Department for Energy Security & Net Zero

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DEEP Report 2.04

Case Study 01BA

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Executive summary

01BA is one of fourteen case study homes retrofitted in the DEEP project. The case studies identify the performance of, and risks associated with, retrofitting solid walled homes. A retrofit was undertaken in stages, reflecting a piecemeal approach to retrofit, followed by undertaking activities that would be required for a whole house approach as a final stage. The data from the case studies is also being used to evaluate modelled predictions of retrofit performance and risk.

Cumulatively, the replacement loft insulation and glazing, new suspended timber ground floor, and external wall insulation (EWI) reduced the heat transfer coefficient (HTC) of the home by (156 ± 15) W/K, or (60 ± 7) %, according to coheating tests. The majority of this, (130 ± 10) W/K, was achieved by the EWI, which also included bay window roof insulation. Calculated U-values suggest heat loss from the bay roof window was reduced from 4 to 0.2 W/K, signifying a small but beneficial retrofit measure. Measured U-values also confirm that a major benefit was achieved by the EWI, suggesting reductions of (119 ± 14) W/K. The EWI also increased the home's EPC from band D to C, and achieved the social housing decarbonisation fund's < 90 kWh/m²/annum target. Post-EWI, surface condensation risks were removed from all wall junctions, except the suspended timber ground floor. However, the EWI retrofit alone cost £37,300 (75 % of the total retrofit cost). This was particularly high as the EWI system was relatively innovative, plus £13,000 of this was related to undertaking remedial works needed to support the retrofit. These findings suggest that solid wall insulation (SWI) is likely to be required to achieve EPC and other policy targets in solid walled homes; however, the costs associated with this retrofit measure can be substantial.

Replacing the existing 150 mm of loft insulation, with newly laid 400 mm mineral wool also achieved a statistically significant reduction in the dwelling's HTC (21 ± 16) W/K, according to the coheating tests. This suggests savings can be achieved from enhancing insulation in lofts which are already considered 'insulated'. It was also the most cost-effective retrofit, despite having to remove and dispose of the existing insulation. More research on the quality of existing loft insulation is needed to understand the national potential of this retrofit measure.

New glazing, external doors, and the addition of suspended timber ground floor insulation did not result in significant changes in the home's HTC, according to the coheating test results; nor did they remove surface condensation risks measured at their junctions. This is despite achieving reductions of (19 ± 4) W/K and (12 ± 1) W/K respectively, according to measured U-values. The collective retrofits reduced air leakage from 14.8 to 12.5 $m^3/(h·m^2)$ @ 50Pa. This is mostly from the new glazing installation and some from the EWI. Infiltration through the suspended timber ground floor was minimised via installation of an airtight membrane, though the blower door test results indicate that this measure did not materially affect the home's airtightness.

RdSAP appears to predict relatively similar heat loss in the uninsulated case study home to the coheating test. However, when the default input assumptions on U-values were replaced with measured data, the EPC estimates were much higher than those measured. This highlights the problems involved in attempting to improve defaults model inputs and the impact this may have on improving model accuracy. When the home was fully insulated, there was less variance in the model predictions, regardless of which input data was used, and predictions were also relatively close to the coheating measured post-EWI HTC.

1 Introduction to 01BA

Case Study 01BA is a two bed 1910 end-terrace in which a whole house retrofit was undertaken. The whole house retrofit was undertaken in stages, reflecting a piecemeal approach to retrofit, with stages comprising of loft insulation, new double glazing and composite doors, ground floor insulation, and external wall insulation (EWI). The performance of each individual retrofit stage was assessed for airtightness, thermal performance, and moisture risk. This case study also provided the opportunity to investigate a traditional retrofit journey that a home may make over several decades, and understand how piecemeal retrofit affects whole house performance. It also explores the impact of installing suspended ground floor insulation when only half the ground floor was of a suspended construction.

1.1 DEEP field trial objectives

01BA is one of 14 DEEP case studies which, collectively, will attempt to investigate the research objectives listed in Table 1-1. (Note that not all the objectives are addressed by each case study.)

Table 1-1 DEEP research objectives

Objective	Rationale
Model input accuracy	Policy relies on models with known limitations; exploring inputs and model robustness will improve policy advice.
Unintended consequence	More retrofit scenarios need modelling to confirm condensation, underperformance, air quality, and comfort risks
Cumulative impact	Piecemeal retrofits are common; clarity is needed on impact of different options including achieving EPC band C.
Fabric vs ventilation	Insulation influences fabric 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 DESNZ, the wider DEEP Steering Group, and Expert QA panel, additional questions have been proposed and the objectives have been refined to develop seven discreet research questions. These are listed below and will be referred to when discussing the findings:

1. *What combinations of retrofits are needed to bring solid walled homes up to an EPC band C? Do these represent value for money and what challenges do they face?*
2. *To what extent do unintended consequences reduce energy efficiency 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 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 01BA will contribute to the formation of a body of evidence from the DEEP project, that may begin to address these questions.

1.3 Case study house information

01BA, shown in Figure 11, is a two-bedroom property in West Yorkshire. It was built in the 1930s, despite neighbouring streets being built around 1910. Therefore, the house's design and construction match that of a 1910s terraced house, rather than a typical 1930s dwelling. The external walls are built of solid 9-inch bricks and the property is an end of terrace. It has three external walls: front, gable, and rear.

Accommodation-wise, to the front, there is a small hallway leading to the stairs and a living room. The living room has a suspended timber ground floor, sealed-up fireplace set within the chimney breast and a rectangular bay window set into the front façade. Externally, corbels are used at the eaves on the front and rear elevation to support the gutter. Doors from the living room lead to the kitchen at the rear of the property and an under-stairs cupboard. While most of the ground floor in the kitchen is solid concrete, unusually, a small portion is suspended timber, indicating that there used to be stairs leading down into the floor void beneath the kitchen and living room. Upstairs there are two bedrooms and a bathroom: bedroom 1 faces onto the street, while bedroom 2 and the bathroom overlook a yard and shared alleyway to the rear. Access to the loft is through the bathroom.

Over 5.3 million new homes were built between 1900 and 1939, representing around 20 % of England and Wales' housing stock [1]. Two-bed terraced homes account for nearly 9 % of all homes: equivalent to around two and a quarter million homes [2]. The results from this case study highlight the challenges faced by homeowners when their homes have a number of construction details (e.g. corbels under gutters and projecting bay window) that may affect how well EWI is installed.

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 1-2 and Figure 1-3 respectively.

Ground floor First floor

Figure 1-3 House plans

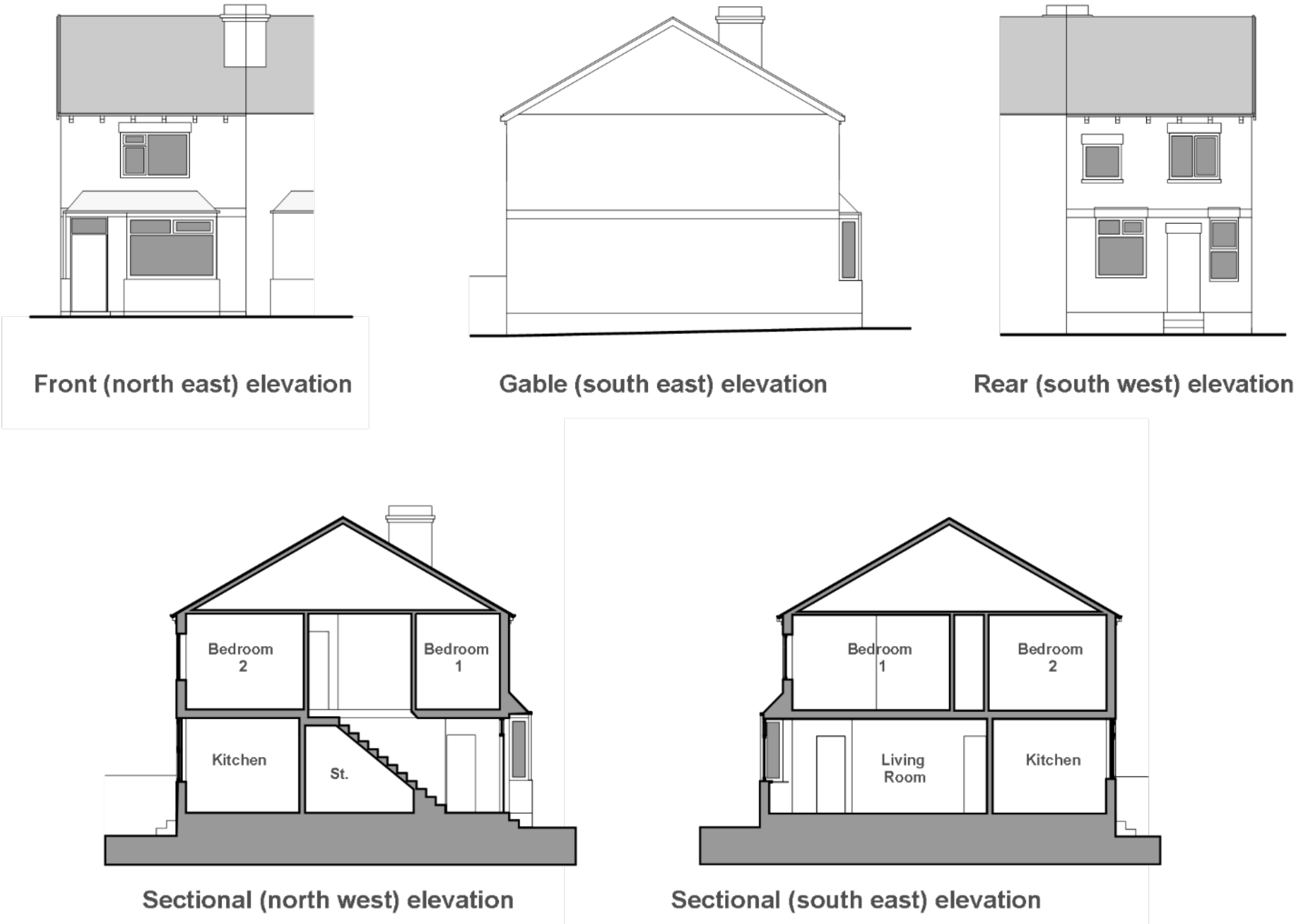


Figure 1-4 House elevations and sections

The dimensions of each element in the home were obtained by measured survey and are listed in Table 1-2. They were used to allocate heat losses as well as generate thermal models in RdSAP, BREDEM, and DSM.

Construction details are summarised in Table 13. Features to note are that the ground floor in the kitchen is solid except for a small section along the gable wall (1.7 m^2) where a stair used to lead down into the floor void, but has since been covered with tongue and groove floorboards.

The house had several projections: a single storey bay window, brick corbels supporting plastic guttering to the front and rear elevations, and the area where the boundary wall intersects with the gable wall at lower level. While the loft was insulated prior to any retrofits taking place, the underside of the roof tiles was not felted.

Table 1-2 House dimensions

Detail	Measurement
Volume	181 m^3
Total floor area	70 m^2
Total heat loss area	159 m^2
Ground floor	35 m^2
Front external wall	15 m^2
Rear external wall	15 m^2
Gable external wall	41 m^2
Windows	13 m^2
Door	4 m^2
Loft	36 m^2
Party walls	46 m^2

The property also had double glazed windows installed. However, upon closer inspection it was clear that the fit was poor, with large gaps present between structural openings and window units. The gaps were packed out with newspaper, covered over with plaster and concealed with plastic cover pieces spanning the window reveals. The external doors were timber with single glazed panels and in poor condition. Hence, the windows and doors were replaced as part of the whole house retrofit.

All kitchen and bathroom fittings had been removed by the landlord prior to handing over to the research team for testing. While direct penetrations to outside were temporarily sealed throughout the retrofit process some unfinished detailing was visible, that would be covered over if the house was in a habitable state, and areas of unplastered brickwork remained where fittings had been removed from the walls (Figure 1-5).

Figure 1-5 Kitchen and bathroom with fittings removed prior to testing

There were no obvious defects in the building elements, apart from a hole in the external wall close to bay window where a section of brickwork was missing. Consequently, part of the inner bay wall and adjacent front-facing external wall in the living room were visibly damp, as shown in Figure 1-6. %WME readings as high as 40 % were observed near the base of the bay wall compared to <5 % on the dry party wall. The section of missing brickwork was sealed, and the fabric dried out prior to any testing taking place.

Figure 1-5 Evidence of damp in baseline case study

1.4 Retrofit approach

The retrofit details and U-values targets for each element are listed in Table 13. The target retrofit U-values listed have been calculated using the BRE calculator and are based on the observed materials and thickness of the existing fabric and knowledge of the insulation being installed. The thermal conductivity of the insulation was provided by the manufacturers and BS EN 12524:2000 was used to determine the thermal conductivity of other construction elements. The plane element U-values included repeating thermal bridges (e.g. floor joists) in accordance with BR443 and BS EN ISO 6946.

Table 1-3 Construction and retrofit summary

Detail	Original construction	Retrofit[1]
Airtightness	14.84 $m^3/h{\cdot}m^2$ @ 50 Pa	None.
Loft	Unfelted roof construction with 150 mm mineral wool insulation between and over first floor ceiling joists	Mineral wool between and over joists 420 mm x 0.040 W/(m^2·K) Design U-value 0.09 W/(m^2·K)
Windows	Poorly fitted uPVC double glazed	uPVC double glazed windows Design WER A and U-value 1.6 W/(m^2·K)
Doors	Timber with single glazed panes	Composite doors Design U-value 0.8 W/(m^2·K)
Front room ground floor and part of kitchen ground floor	Uninsulated suspended timber	Mineral wool roll between joists 175 mm x 0.040 W/(m·K) with airtight barrier membrane Design U-value 0.20 W/(m^2·K)
External wall type	Uninsulated 9-inch solid brick	EWI system (102 mm @ 0.033 W/(m·K) Insulation + 20 mm ventilated cavity + 10mm façade) Design U-value 0.31 W/(m^2·K) 50 mm XPS below DPC 75 mm XPS above and between corbels
Bay window roof	Unfelted roof construction with 15 mm lath and plaster	Mineral wool 200 mm x 0.040 W/(m·K) Design U-value 0.19 W/(m^2·K)

[1] The Design retrofit U-values listed in Table 1-2 are validated by the BRE calculator and are based on the observed materials and thickness of the existing fabric and knowledge of the insulation being installed. The thermal conductivity of the insulation was provided by the manufacturers and BS EN 12524:2000 was used and included calculation of repeating thermal bridges within each plane element calculation (e.g., floor joists).

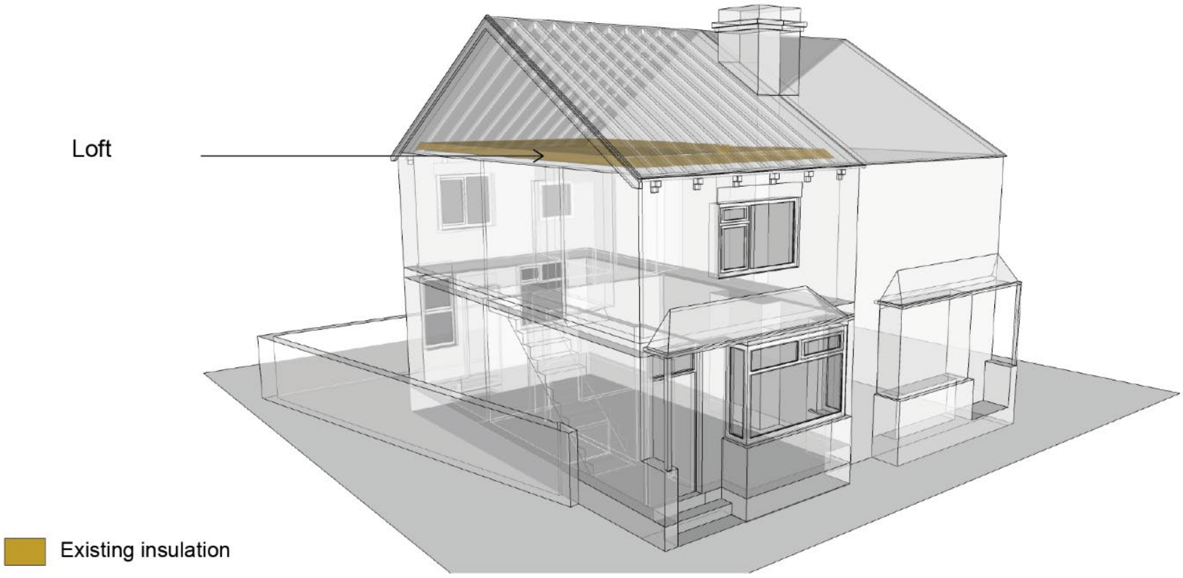
The sequence of the staged whole house retrofit approach is shown and illustrated in Figure 1-7 through to Figure 1-11. Building performance evaluation (BPE) tests, whole house energy modelling and elemental thermal simulations were conducted at each retrofit stage to quantify changes in energy performance and the potential for condensation risk. The specific methodologies for these are described in DEEP Report 2.01.

The codes in Table 14 are shorthand to identify each retrofit stage. As the retrofits are cumulative, the codes are combined to explain which stage is being discussed, e.g. the final code for stage 5 is 01BA.R.G.F.W.

Table 1-4 Phased retrofit stages

	Retrofit stage	Code	Retrofit dates
1	Baseline	01BA.B	October 2020
2	Installation of new loft insulation	01BA.R	November 2020
3	New external windows and doors fitted	01BA.R.G	December 2020
4	Suspended timber ground floor insulated	01BA.R.G.F	January 2021
5	External walls & bay window roof insulated	01BA.R.G.F.W	February 2021

2.04 DEEP 01BA



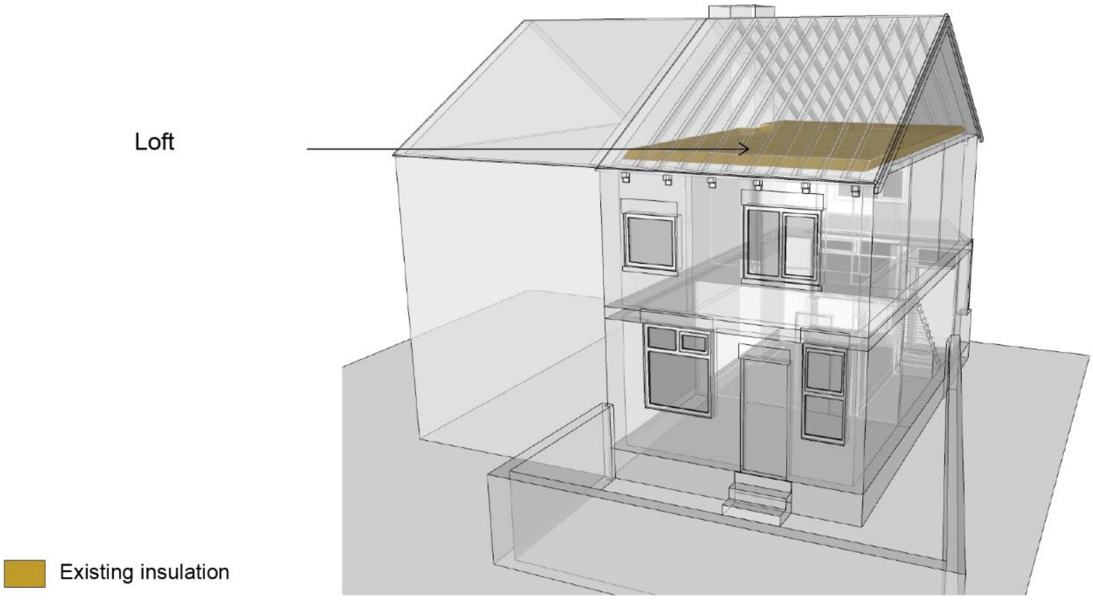


Figure 1-6 Insulation already in the property prior to the retrofits (01BA.B) – front and rear views respectively

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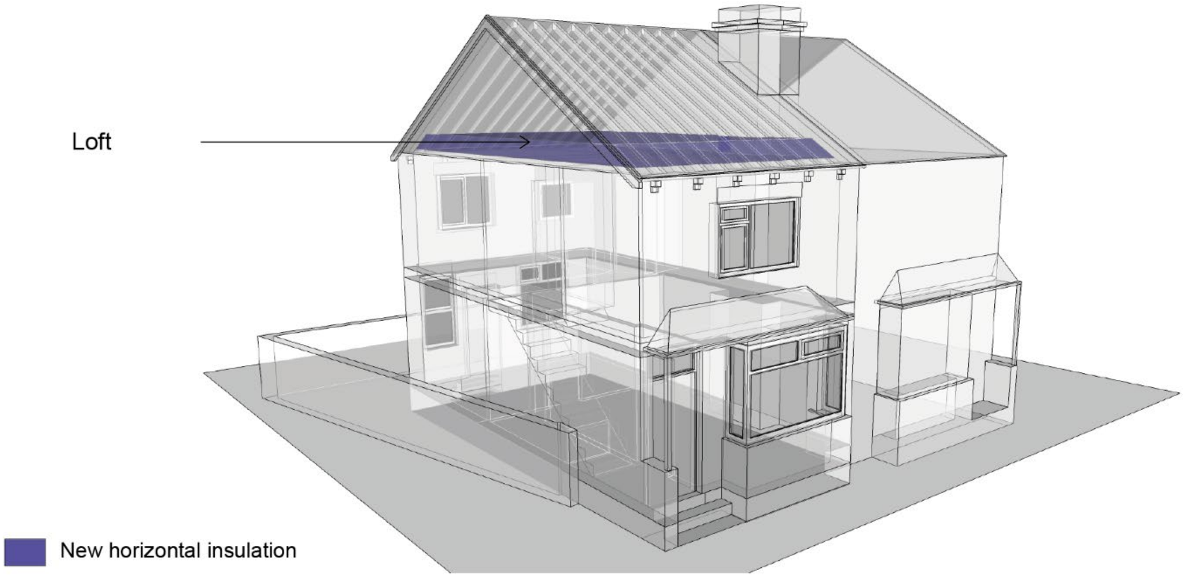

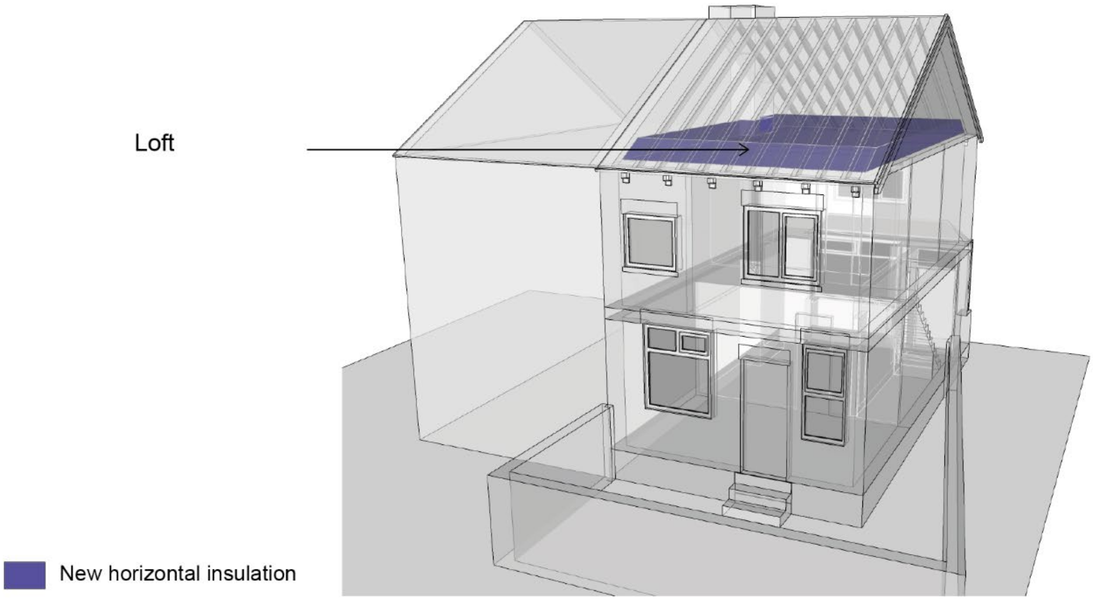

Figure 1-7 Stage 1: Installation of new loft insulation (01BA.R) – front and rear views respectively

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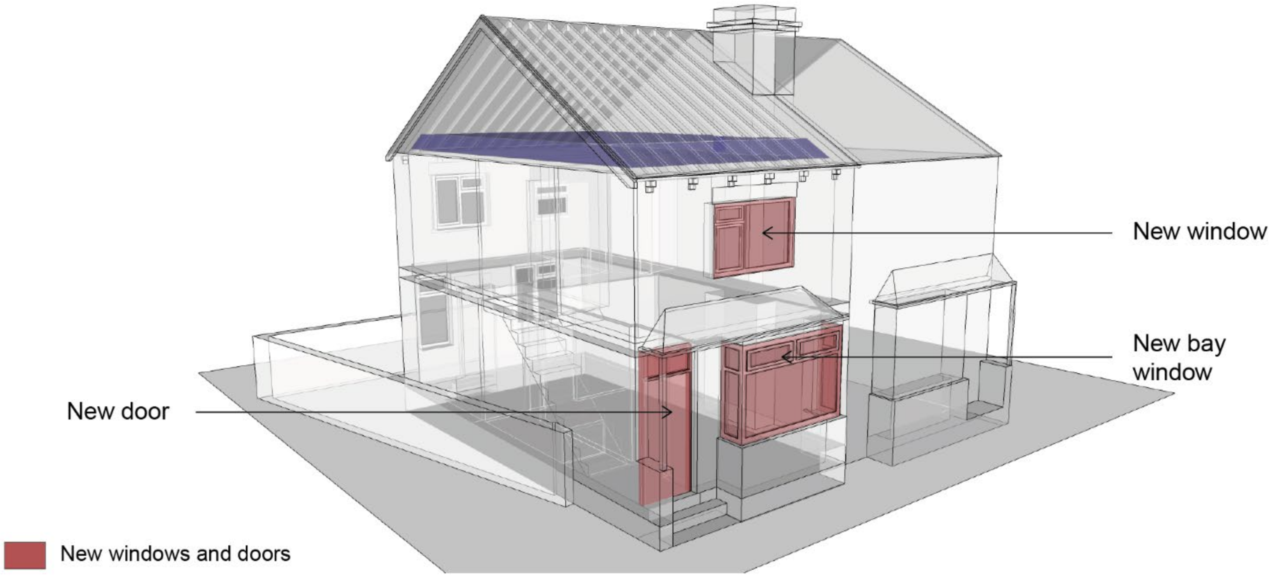


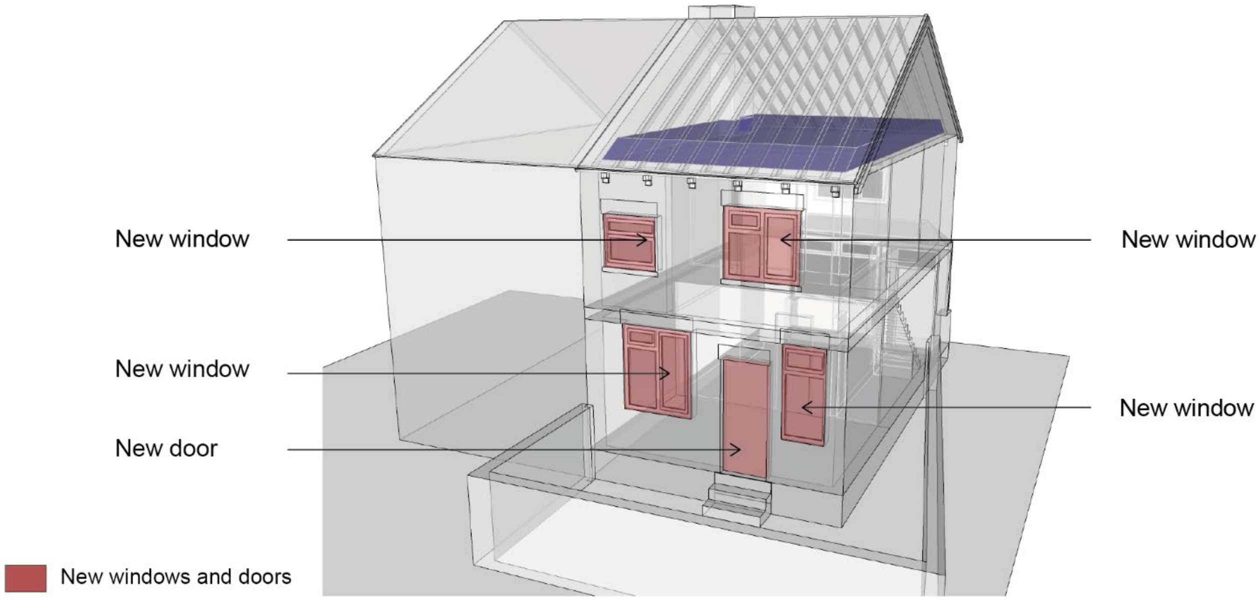
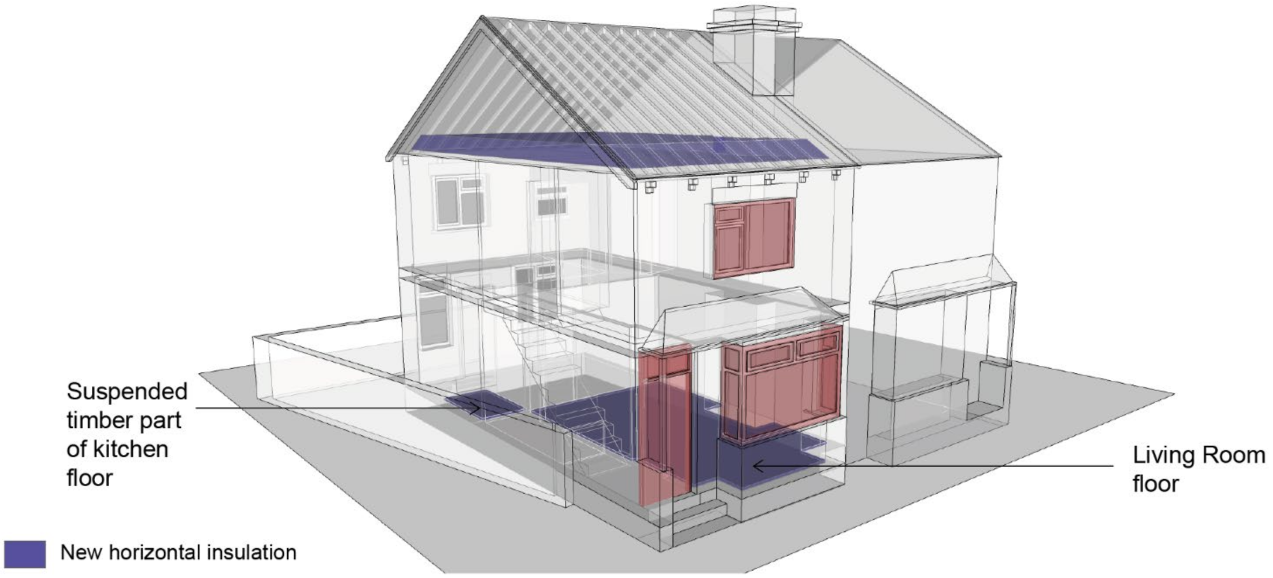


Figure 1-8 Stage 1: Installation of new windows and doors (01BA.R.G) – front and rear views respectively



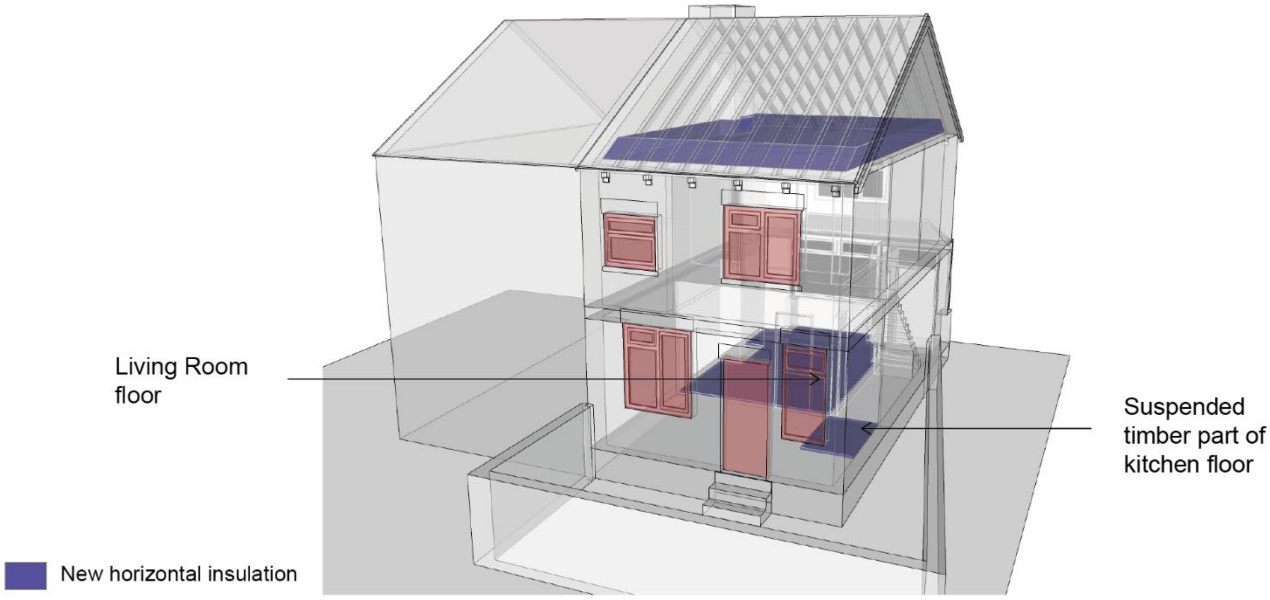


Figure 1-9 Stage 1: Installation of 200 mm insulation to suspended timber floors (incorporating airtightness membrane) in the living room and kitchen (01BA.R.G.F) – front and rear views respectively

2.04 DEEP 01BA

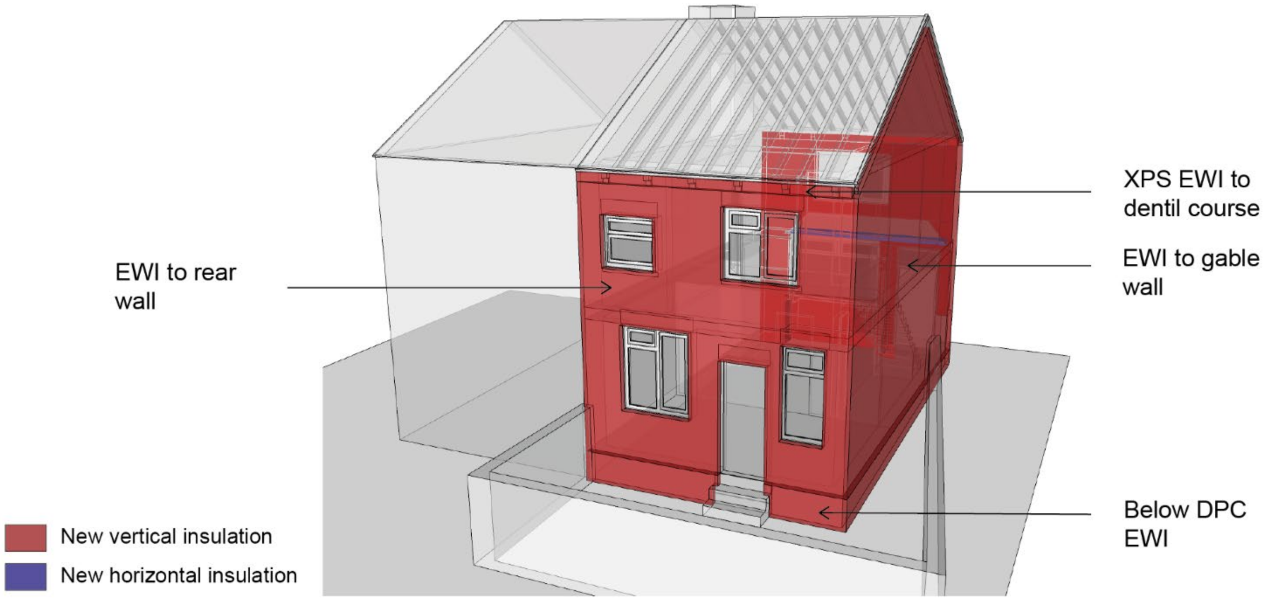


Figure 1-10 Stage 1: Installation of new EWI to front, gable and rear walls, which includes XPS to the corbels and below DPC, plus mineral wool insulation to bay window roof (01BA.R.G.F.W) – front and rear views respectively

The EWI system employed at this property required a digital scan of the property so the brick slip rain-proof cladding boards could be precision cut offsite. However, the system was unable to accommodate period features like the brick dentil course at eaves level. Consequently, the contractor applied a rendered EWI system at the eaves comprising XPS insulation between the soffit and brick corbels, which was tied into the rest of the EWI.

Sequencing was problematic for the glazing retrofit, as it preceded the EWI retrofit. To minimise disruption, the window manufacturer supplied deeper sill covers to ensure each window sill was deep enough to project beyond the external wall once the EWI was installed. This highlights the role sequencing plays in the retrofit process when improvements are made in a piecemeal fashion.

Introduction summary

01BA provided a whole house retrofit terraced solid wall case study. It collected performance and moisture risk data on retrofits: including loft retrofits where old existing loft insulation was removed and replaced; suspended timber ground floors where an airtight membrane was incorporated; and glazing and external doors retrofits where poorly fitted units were replaced with new higher performance units.

It also provided the potential to investigate risk and performance aspects of issues arising from the sequencing of retrofits. The combination of replacing windows and external doors before adding EWI is often faced by homeowners when they choose to carry out retrofits on a piecemeal basis without fully realising the implications that sequencing has on future potential retrofits.

In addition, specifying an offsite EWI system added complications to the installation process, as the property had period brickwork features. This is another potential issue that could be faced by homeowners with older properties.

2 Fieldwork and modelling methods

Building performance evaluation (BPE) tests and modelling activities were undertaken on 01BA at each retrofit stage in accordance with the methodologies listed in DEEP Report 2.01. This section outlines the specific implementation of these methods at 01BA including any variations and additions.

2.1 Environmental data collection

Internal environmental data logging equipment is described in detail in the Report 2.01 DEEP Methods. Internal environmental data collected at 01BA 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 01BA, and included vertical solar irradiance, air temperature, and wind speed. This was supplemented by an external air temperature sensor positioned outside 01BA.

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 13. 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 external walls were also taken for lab analysis of the material properties and to identify the construction layers. The method for this is described in the DEEP Report 4.

2.3 Airtightness and thermography

Blower door tests were successfully completed at all baseline and retrofit stages. Results from these were used to identify changes related to the retrofits and to approximate the average heat loss attributable to air leakage (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. Pulse air tests and CO_2 tracer gas tests were also deployed during the testing programme to compare with the blower door tests results.

2.4 Heat flux measurement and U-values

Twenty-one Hukseflux HFP01 Heat Flux Plates (HFPs) were installed on different elements to: measure the baseline in-situ U-values; to measure improvements achieved by the fabric upgrades, and party wall heat exchange; to calibrate energy and thermal models; and to estimate the plane element fabric heat loss and compare with HTC disaggregation. HFP are listed in Table 1-5 and visualised in Figure 1-12 and Figure 1-13. Thermography was undertaken to identify representative locations for each fabric element and, where possible, multiple locations for each element were measured.

Table 1-5 HFP locations

HFP	Element	Room
L1	Neighbour party wall	Kitchen
L2	Neighbour party wall	Living room
L3	Neighbour party wall	Living room
L4	Solid floor	Kitchen
L5	Suspended ground floor	Living room
AC1	Front wall	Bedroom 1
AC2	Front wall	Bedroom 1
AC3	Gable wall	Bedroom 1
AC4	Gable wall	Bedroom 1
AC5	Neighbour party wall	Bedroom 1
AC6	Chimney breast	Bedroom 1
AC7	Neighbour party wall	Bedroom 1
AC8	Ceiling	Bedroom 1
AC9	Ceiling	Bedroom 1
AC10	Ceiling	Bedroom 1
AC11	Ceiling	Bedroom 1
AC12	Ceiling	Bedroom 1
AC13	Gable wall	Bedroom 2
AC14	Rear wall	Bedroom 2
AC15	Windowpane	Bedroom 2
AC16	Neighbour party wall	Bathroom

Heat flux density from individual HFPs, along with internal and external air temperature data, were used to generate estimated U-values for each element. Where more than one HFP was located on a single element, a simple average was used to obtain a single U-value for the element.

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 an estimate of the whole element U-value.

It is important to note that the estimated in-situ U-values that were derived, were based upon a limited set of measurements, so may not necessarily be representative of the performance of the whole plane element in practice.

Due to the building geometry, a number of the HFPs had to be installed in non-idealised locations. This is not uncommon in the domestic setting, as there is a limited surface area in which to place such sensors. In areas where thermal bridging may be expected, such as near corners, or interfaces between different components and constructions, 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 01BA was a relatively small house with few large, uninterrupted surface areas.

In terms of the glazing, while the BRE calculator has the capacity to calculate the U-value of windows, it requires manufacturer's details of the component parts that make-up the glazing, such as the frame U-value and internal construction to estimate the Ψ-value. These details were not available and so the U-values for the existing windows had to be assumed. This represents an area of uncertainty in the energy models.

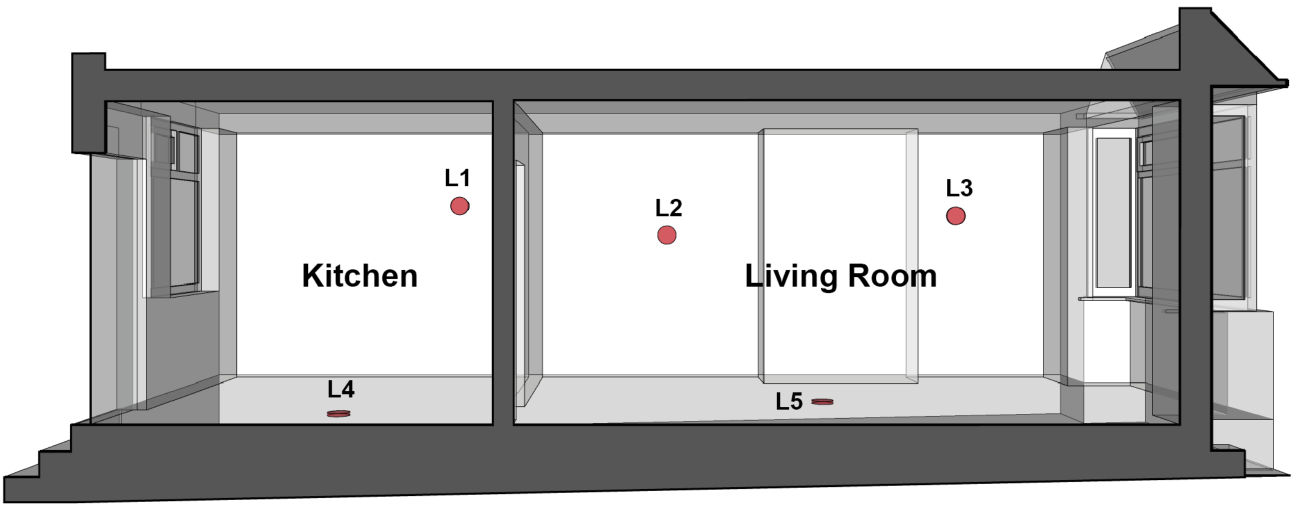
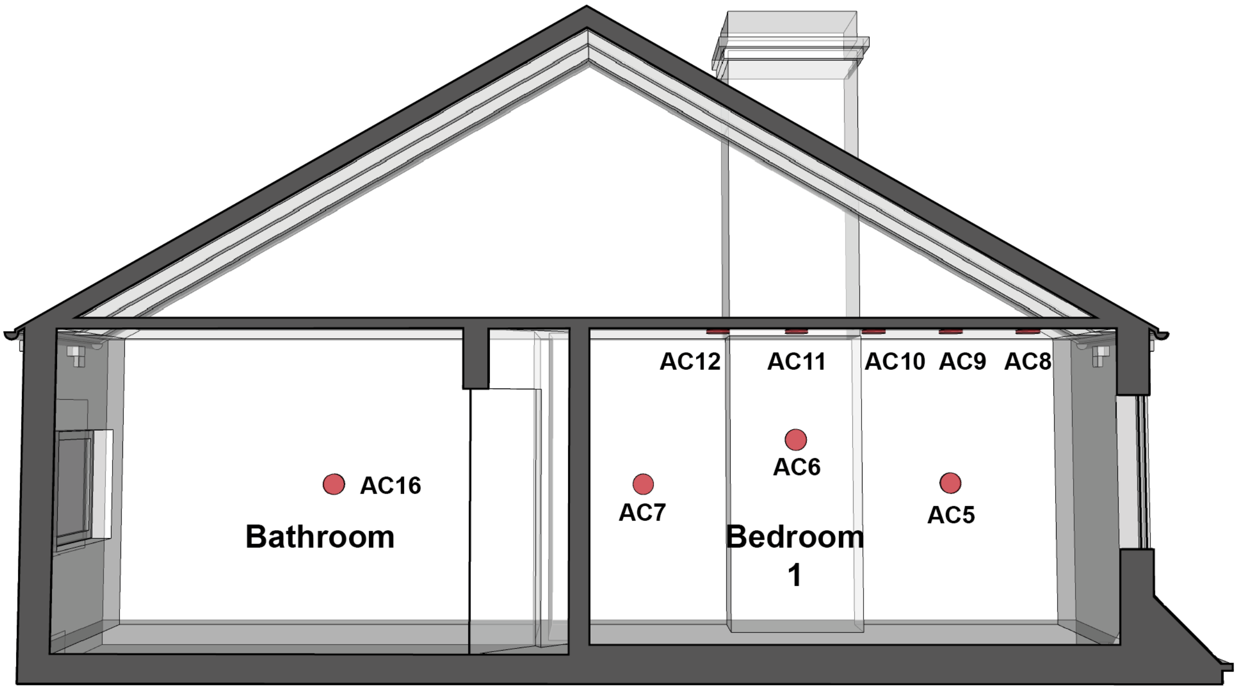


Figure 1-12 Ground floor HFP locations



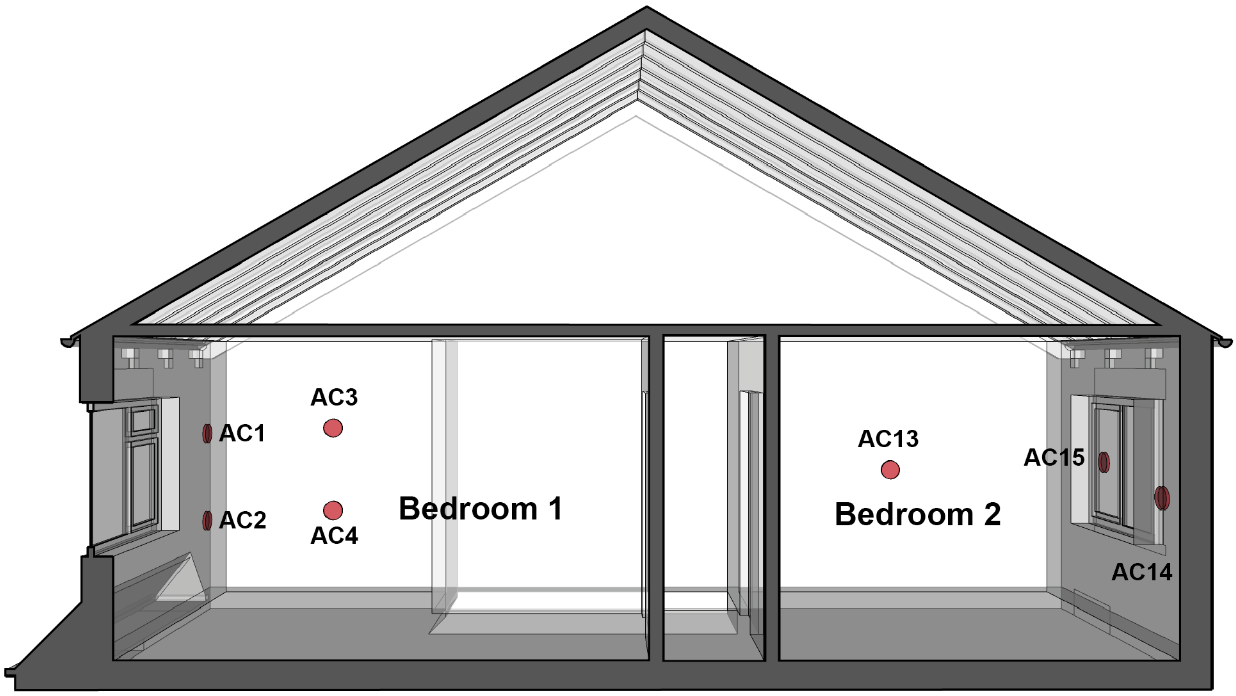


Figure 1-13 First floor HFP locations

2.5 Whole house heat loss coefficient (HLC)

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

2.6 Whole building energy modelling

The modelling methodologies undertaken are explained in detail in the Report 2.01 DEEP Methods. 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 BREDEM predicts. These are also compared with the HTC predicted by DSM (using DesignBuilder software version 7.0.0.088 [3]) at each retrofit stage. Table 1-6 describes the 4-step calibration approach taken to understand how their predictions change as default inputs are overridden.

Table 1-6 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]

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

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

[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

BPE Methodologies summary

A deep dive into the 01BA 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 the retrofits.

Steady-state and dynamic energy models were also developed, to compare predicted results against in-situ measurements. To investigate the appropriateness of using default data in energy models, a four step calibration process was adopted.

These methods collectively investigate the energy performance associated with the retrofits, as well as the usefulness of models to predict these.

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, which would have required longitudinal conditions monitoring pre and post retrofits.

The findings from these case studies, therefore, can provide useful information on the impact of loft, floor, glazing, and EWI retrofits; but data on the implication for indoor air quality and occupant experience needs a holistic longitudinal study to understand the impact of retrofits on these broader issues.

3 Results

This chapter first presents results on the in-situ field trials: airtightness tests; U-values; and the whole house heat loss, as measured by the coheating and QUB tests. It then describes how modelled predictions compared with the measured data, and how successful the four different calibration steps were at improving predicted heat loss, including assessing non-repeating 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 are discussed.

3.1 Airtightness improvements

The base case status of the house had relatively large amounts of air leakage; its infiltration rate was found to be around 15 $m^3/(h·m^2)$ @ 50Pa. For context, the average UK air permeability value for existing homes is estimated to be approximately 11.5 $m^3/(h·m^2)$ @ 50Pa [4] and the limiting value permitted under Building Regulations for new build homes is now 8 $m^3/(h·m^2)$ @ 50Pa [5]. It is important to note that the air permeability rate is not the same as ventilation for fresh air, for which there was purpose provided ventilation. This was via trickle vents on windows, an electrical intermittent extraction fan located in the kitchen, and a wall vent in the bathroom (all of which were retained throughout the retrofit). The results of these tests are illustrated in Figure 3-1.

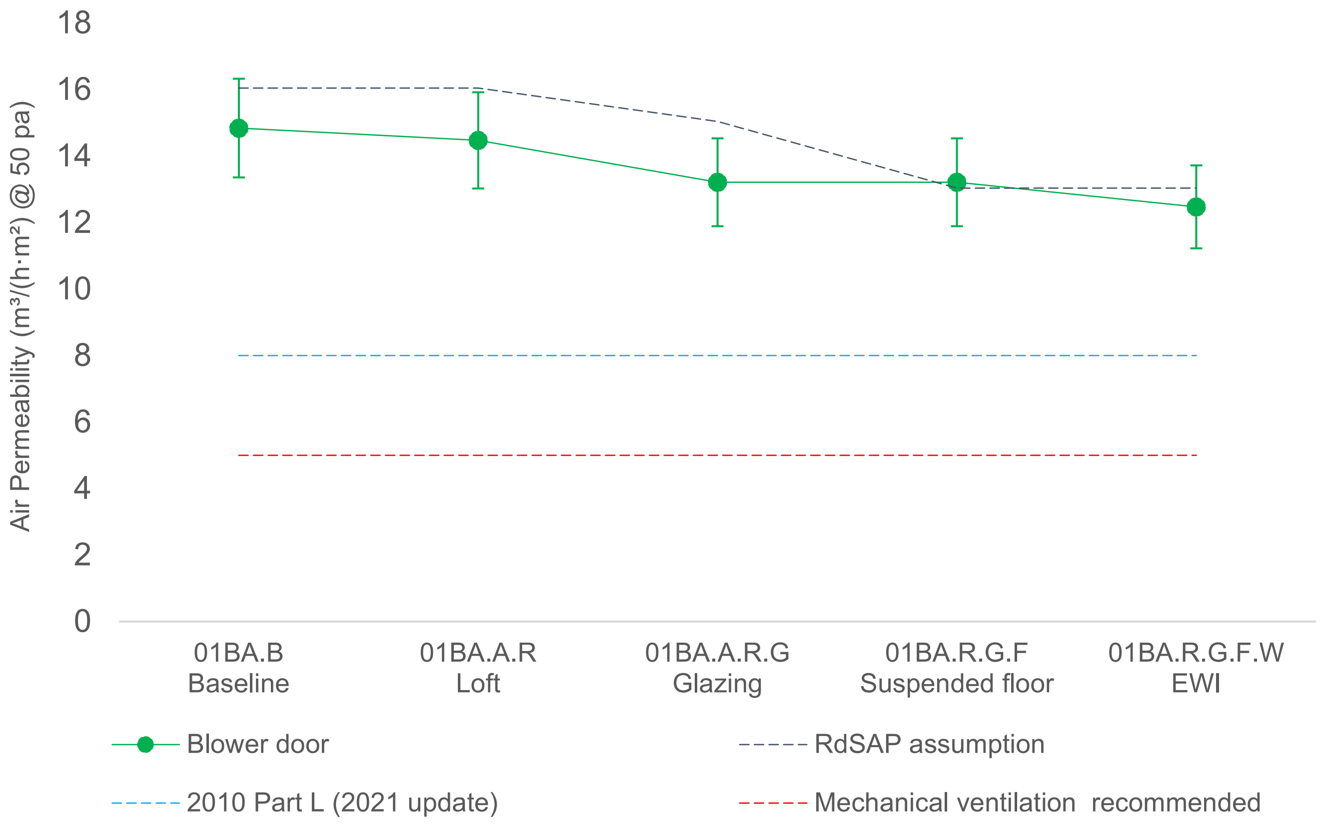


Figure 3-1 Airtightness improvements made at each retrofit stage.

Although no dedicated airtightness retrofit was planned for the house, airtightness measurements were undertaken at each retrofit stage to establish if the measure had an unintended impact on air leakage.

Overall, the infiltration rate in the house was reduced slightly by undertaking the various retrofits from ~15 to 13 $m^3/(h \cdot m^2)$ @ 50Pa, though there remained significant room for further improvement. It is also interesting to note that this case study home had similar levels of airtightness to those predicted in RdSAP, though they are often outside the uncertainty bounds of the test.

Savings were made during the loft, glazing, ground floor ,and EWI retrofits, though these were within the error of the test. This may be because the leaky existing timber loft hatch was replaced with a sealed insulated hatch; and because the seals between the external window and door frames (Figure 3-2) in the original baseline house were particularly poor, and the EWI wrap may have sealed cracks or gaps in the brickwork.

Figure 3-1 Reduction in air leakage from the existing front door (top) and replacement (bottom)

In addition, when the new external windows and doors were installed, the openings around these elements were repaired so that the new frames were better sealed in the external walls, Figure 3-3, although new air paths existed through the new trickle vents.

c

Figure 3-3 Air leakage around the bedroom 2 window frame with the original (top) and replacement (bottom) windows

Treatment of the suspended timber ground floor involved installing under-floor insulation with a vapour permeable membrane and replacing old floorboards with new flooring panels in the living room. This significantly reduced air leakage through the main expanse of the living room floor (Figure 3-4). Air leakage from the suspended floor void remained around the room perimeter and at smaller areas, such as the hall and understairs cupboard, where the existing floorboards remained.

Figure 3-2 Air leakage through the suspended ground floor was reduced with the replacement floor covering

2.04 DEEP 01BA

The kitchen and bathroom fittings had been removed prior to testing, leaving numerous penetrations through the rear external wall. These were temporarily sealed throughout the test periods from inside the property, but infiltration remained throughout all test phases. In the kitchen, the external walls had been dry-lined and air leakage into the void behind the plasterboard was commonplace, appearing to enter this void from both floor and around openings (Figure 3-5).

Figure 3-3 Infiltration in the kitchen into the void behind the dry lining under depressurisation observed at Stage 3 of the retrofit (01BA.R.G)

In the bathroom, the waste and soil pipes and other service penetrations were sealed with tape, but gaps remained around the penetrations, most of which would normally be obscured by boxing and the bath panel (Figure 3-6). As in the kitchen, there were areas of exposed brickwork where plaster had been dislodged when the fittings were removed; air movement into the exposed brickwork could be detected but it was slight compared to the other leakage paths identified.

Figure 3-6 Air leakage around bathroom service penetrations at Stage 1 (01BA.B)

A number of less significant air leakage pathways remained throughout the retrofit process. No specific airtightness measures were undertaken to address service penetrations during the course of the retrofits. Air leakage was detected throughout around the boiler flue, electrical penetrations through the top floor ceiling (Figure 3-7) and to the consumer unit in the cupboard beneath the stairs.

Figure 3-4 Air leakage around electrical penetrations in the landing

The fireplaces in the living room and bedroom 1 both allowed some air leakage, even though the bedroom fireplace had been boarded up (Figure 3-8), which again remained consistent throughout. Indirect leakage paths from the loft were also detected through service conduits and into partition wall voids. Figure 3-9 shows air coming down from the loft into a bedroom 2 partition wall void. The temperature of the infiltrating air reflected the ambient loft temperature rather than the very different wall external temperatures pre and post the EWI installation.

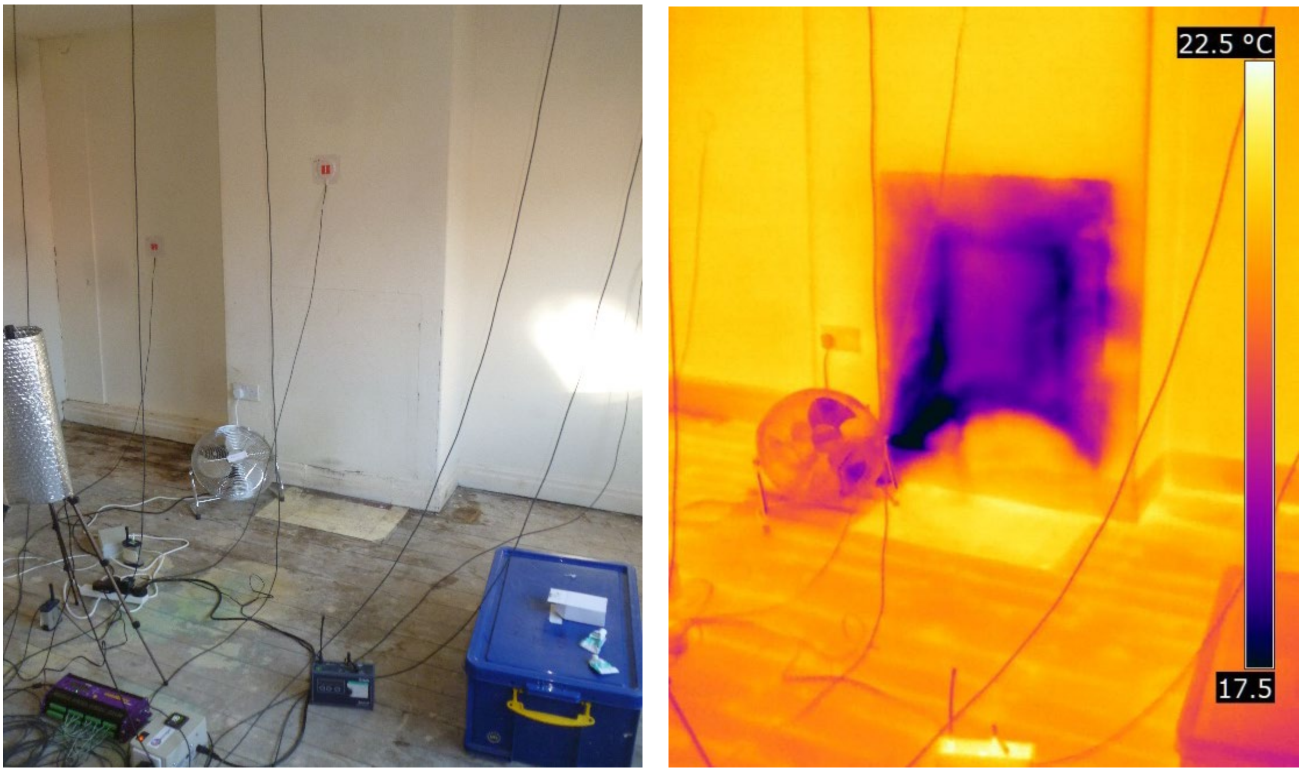


Figure 3-5 Air leakage around the covered fireplace in bedroom 1

Figure 3-6 Air movement into the bedroom 2 partition wall void both pre (top) and post (bottom) EWI retrofit

3.1.1 Alternative airtightness tests

Low pressure Pulse tests were undertaken in the property at a number of retrofit stages. Due to the low level of airtightness, most of these gave invalid results either due to achieving too low a pressure range, the airflow exponent out of range, or both. Where acceptable tests were achieved, albeit with a low pressure range warning, the results did not correspond well to blower door results using the CIBSE TM23:2022 conversion factor ($5.254*(AP_4{}^{0.9241})$ differential [6]. Two acceptable Pulse results were obtained at the 01BA.R and 01BA.R.G.F.W stages (as defined in Table 1-4) recording 5.7 and 5.9 $m^3/(h \cdot m^2)$ @ 4Pa respectively. The CIBSE TM23:2022 conversion suggests that these represent blower door air permeability test results of 26.4 and 27.0 $m^3/(h \cdot m^2)$ @ 50Pa. However, what was actually measured using the blower door on the same days was 14.9 and 12.9 $m^3/(h \cdot m^2)$ @ 50Pa.

Timed CO_2 releases were undertaken in the house following the loft retrofit in December 2020. Analysis of the CO_2 decay indicated ventilation rates of 1.87 and 1.91 h^{-1} in the living room (by the point of release) and 1.03 and 1.19 h^{-1} in bedroom 1. The results suggest that the ventilation rate of the ground floor was substantially higher than that of the first floor. Following releases, the CO_2 concentration peaks upstairs occurred about 20 minutes after the peaks downstairs, suggesting the bulk movement of air from downstairs to upstairs happened at quite a quick rate due to the low level of airtightness experienced in the property.

Following the windows and ground floor retrofit, timed CO_2 releases were repeated. Analysis of the CO_2 decay data indicated a ventilation rate of 0.65 h^{-1} in the living room and 0.72 h^{-1} in the bedroom above. The results suggest that the ventilation rate of the ground floor was now similar to that of the first floor and that both had been significantly reduced in comparison to the earlier measurements. The results suggest that the bulk movement of air from downstairs to upstairs had slowed with the improved airtightness of the property. Consequently, the concentration peaks occurred an hour apart, as opposed to 20 minutes apart. This suggests that although there was only a ~10 % reduction in the overall air permeability of the whole house under the elevated pressure differentials of a blower door test, at non-induced pressures changes in ventilation and infiltration characteristics of the dwelling may be more noticeable.

Co-pressurisation of the test house was performed at the end of the retrofit process. Using two blower door kits, readings were taken simultaneously while the next-door property held at the same internal to external differential pressures (± 1.0 Pa) to remove any drivers for air movement across the party wall during the test. Pressurisation of the test house without co-pressurisation provided a test result of 13.6 $m^3/(h \cdot m^2)$ @ 50Pa; with co-pressurisation this fell to 10.8 $m^3/(h \cdot m^2)$ @ 50Pa: a reduction of >20 %. Although this does not mean that same proportion of air leakage is through party elements under natural conditions, it does show that a significant proportion of air leakage measured with a blower door test is not direct internal to external air exchange.

Airtightness improvement summary

The case study home had relatively high levels of air leakage of 15 $m^3/(h \cdot m^2)$ @ 50Pa. Although no specific measures to reduce air leakage were adopted, the retrofits reduced infiltration slightly: to around 13 $m^3/(h \cdot m^2)$ @ 50Pa. This is still a relatively high amount of infiltration compared to the stock average of 11.5 $m^3/(h \cdot m^2)$ @ 50Pa and the backstop new build Building Regulations standard of 8 $m^3/(h \cdot m^2)$ @ 50Pa. The improvement was collectively achieved via new windows, the new loft hatch, the EWI, and to some extent the suspended timber floor.

3.2 U-value improvements

Three methods were adopted in deriving U-values:

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

All three methods 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, the contribution of fabric elements to the HTC, and the predicted benefit achieved by the various retrofits.

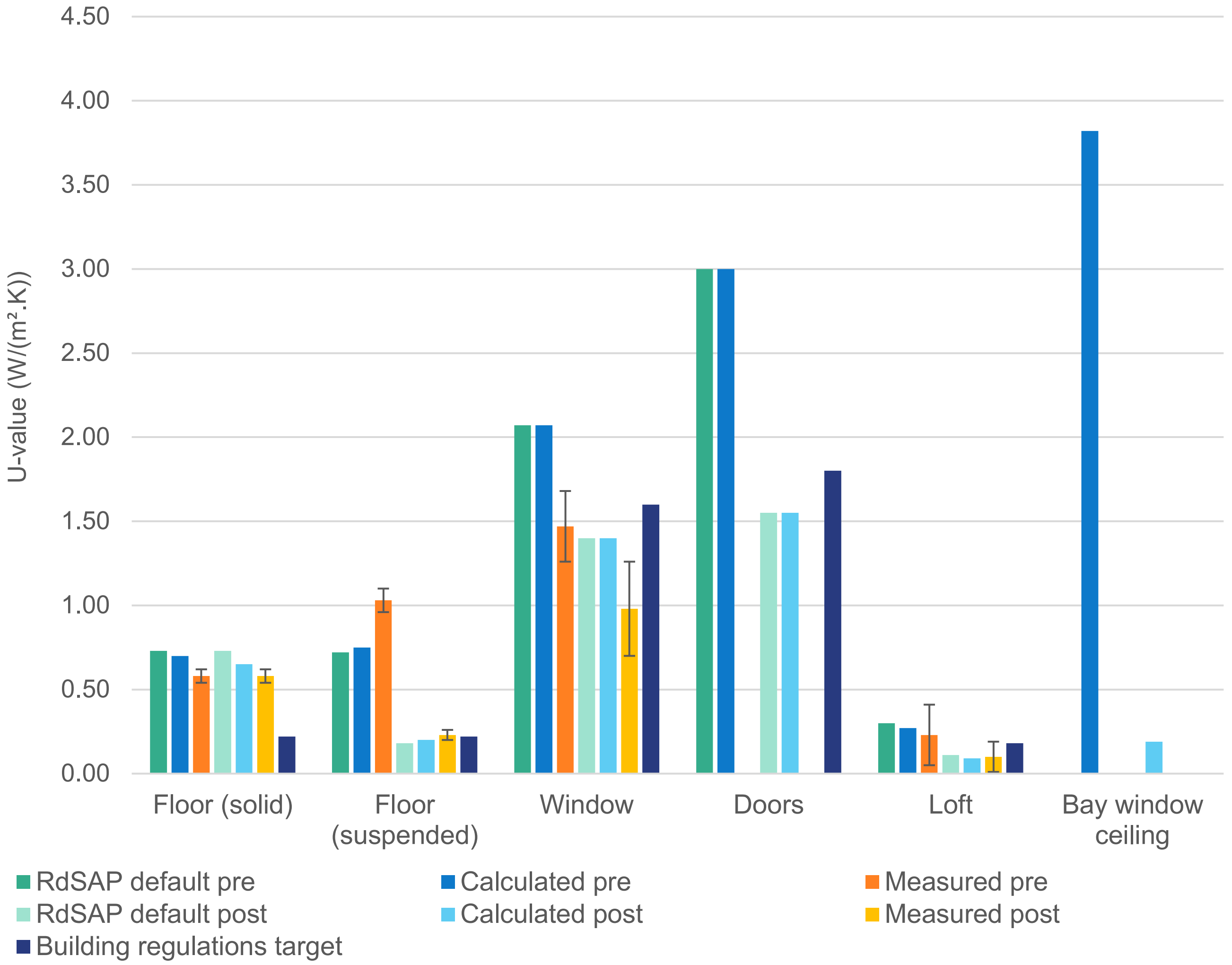


Figure 3-10 Pre- and post- U-values (excluding walls) (W/(m^2·K))

The pre-retrofit U-values that were measured for the solid floor were in line with the calculated and defaults, though the suspended floor was measured to be higher. As can be seen, in Figure 3-10, large reductions of (78 ± 8) % are reported for the suspended ground floor U-values, since this element was previously uninsulated.

However, this may be unlikely to be representative, since this U-value is based on only a single centre room HFP, which is not likely to be accurately capturing the entire suspended timber ground floor heat losses, such as: edge effects, varying ventilation rates or other heterogenous heat losses associated with the suspended timber ground floor. Additionally, only one HFP was placed on the solid ground floor. This was a limitation imposed by the availability of HFPs and the need to capture heat loss from all the other elements in the house. Consequently, ground floor U-values remain an area of significant uncertainty in this case study.

Large improvements were also observed in centre pane window U-value (33 ± 35) %. Both the pre- and post-retrofit U-values were measured to be substantially lower than the defaults and calculated values. Though the measured window U-value is only a centre pane value so does not include the thermal properties of the frame. Additionally, the uncertainty measured is relatively high, as there was only one HFP installed on a window, and glazing is more susceptible than opaque construction materials to variations in external conditions.

The loft insulation also substantially reduced the ceiling U-values by (57 ± 20) %, even though these elements had already previously been retrofitted. This indicates that there may be some benefit in replacing loft insulation that is observed to be disturbed or topping up loft insulation that is less than 150 mm deep.

The bay window roof U-vales were not measured, since there was a limited availability of heat flux plates, and this is a relatively small proportion of the heat loss envelope (<1%). RdSAP does not provide a specific default U-value for the bay window roof either, erroneously assuming it to be the same as the ceiling.

While this may have a marginal effect on whole house heat losses, as can be seen by the calculated U-values, there is scope for substantial heat losses through the element, which may have an impact on surface condensation risks. Insulating this element is predicted to have a 95 % reduction in U-value. The very high starting U-value suggests that bay window roofs are among the worst performing elements in homes. This implies that perhaps it should be more fully considered in RdSAP, as it could be a more common retrofit measure.

Figure 3-11 shows the U-values of the external solid walls, pre- and post-retrofit. The addition of the EWI onto the external walls provided a large improvement of between (77 ± 13) % and (89 ± 13) %.

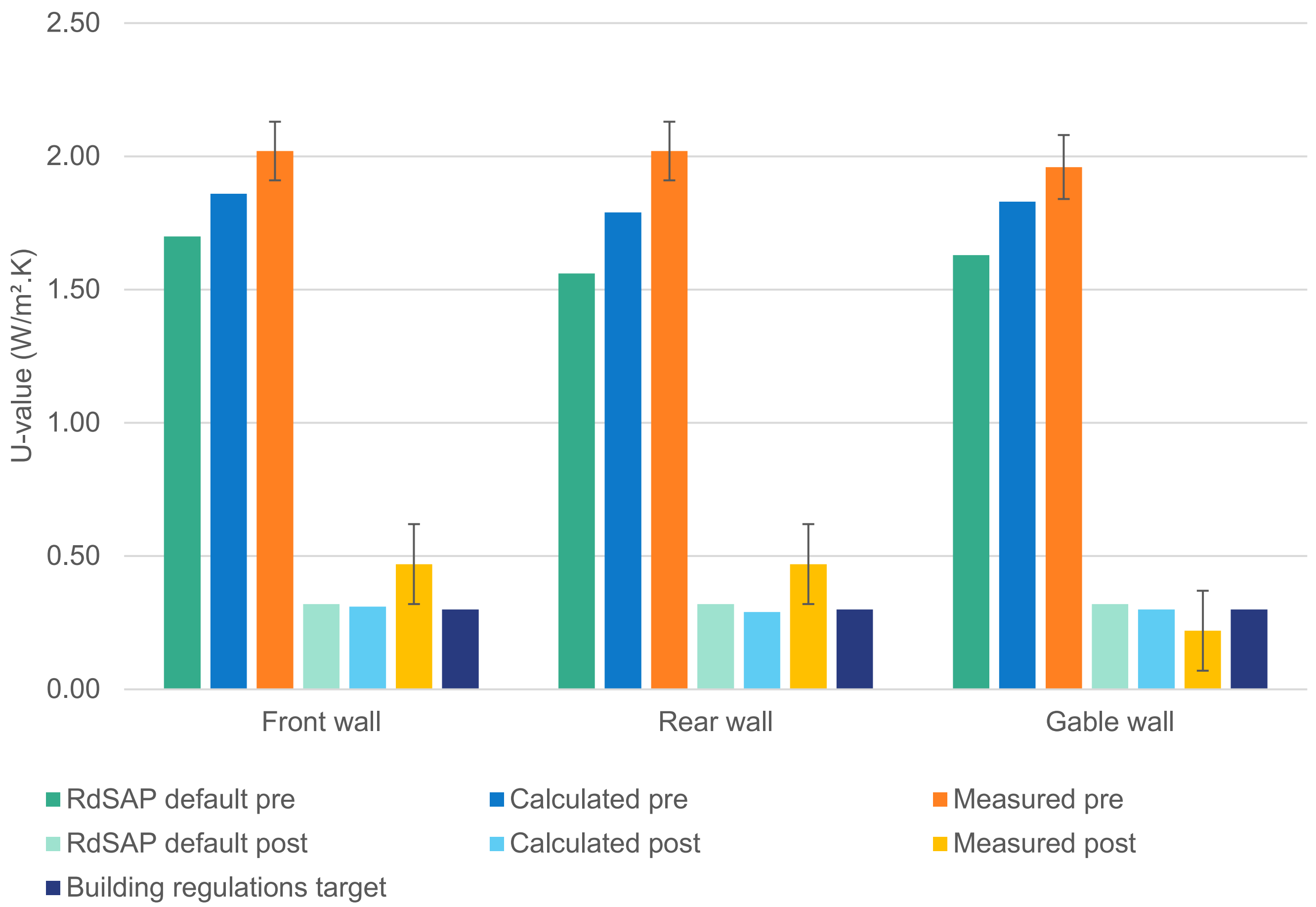


Figure 3-11 Wall pre- and post- U-values (W/(m^2·K))

The pre-retrofit solid wall U-values are slightly higher than they were predicted to be. This is consistent with other DEEP case studies, which have confirmed that there is a large variation in the U-value of uninsulated solid walls. Post-retrofit, the U-values are more aligned with the predictions, which again supports findings in the other DEEP case studies.

A marginally different pre and post U-value is shown for each of the RdSAP external walls (front, rear, and gable), as some of the rooms had drylining, while others did not. RdSAP allows for the drylining to be considered in the U-value calculation, hence, the slightly different default U-values shown in the figures for the different areas of external wall.

The calculated and measured U-values are also both area-weighted to account for different construction types being present and different measured heat flux in different locations respectively. This is partly responsible for the substantially lower U-value measured for the gable wall.

Table 3-1 lists the pre and post U-values for the elements according to RdSAP, the BRE Calculator, and the HFPs. It also identifies the predicted and measured improvements achieved by the retrofits. These confirm that heat loss from all the fabric elements in the home is predicted as having substantial improvement. Even the solid floor, which was not insulated, was calculated as having reduced heat losses since the EWI was likely to reduce heat losses at the edges of the solid floor.

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

	Pre-retrofit U-value			Post-retrofit U-value and % improvement		
	RdSAP default	Calculated	Measured	RdSAP default	Calculated	Measured
Loft	0.30	0.27	0.23 ± 0.18	0.11 (63%)	0.09 (67%)	0.10 ± 0.09 (57 ± 20)%
Glazing[7]	2.00	2.00	1.47 ± 0.21	1.40 (32%)	1.40 (32%)	0.98 ± 0.28 (33 ± 35)%
Doors[8]	3.00	3.00	-	1.55 (48%)	1.55 (48%)	-
Suspended ground floor	0.72	0.75	1.03 ± 0.07	0.18 (75%)	0.20 (73%)	0.23 ± 0.03 (78 ± 8)%
Front wall	1.70	1.86	2.02 ± 0.11	0.32 (81%)	0.31 (83%)	0.47 ± 0.15 (77 ± 13)%
Rear wall	1.56	1.79	2.02 ± 0.11	0.32 (79%)	0.29 (84%)	0.47 ± 0.15 (77 ± 13)%
Gable wall	1.63	1.83	1.96 ± 0.12	0.32 (80%)	0.30 (84%)	0.22 ± 0.15 (89 ± 13)%
Bay window roof[9]	-	3.82	-	-	0.19 (95%)	-
Solid ground floor[10]	0.73	0.70	0.58 ± 0.04	-	0.65 (7%)	-

In Table 3-2 the predicted performance of each of the retrofits is compared to the values that were measured. The RdSAP and calculated U-values frequently disagree with the measured values, but by differing amounts. These incorrect U-values can lead to incorrect predictions of U-value improvement. We therefore define both 'performance gaps' and 'prediction gaps' as follows and calculate their values in Table 3-2:

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

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

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[7] Post-retrofit RdSAP Default and Calculated U-values are obtained from supplier's documents.
[8] No HFP recordings were obtained for the doors. Post-retrofit RdSAP Default and Calculated U-values are obtained from supplier's documents.
[9] RdSAP does not include bay window roof. No HFP recordings were obtained for the bay window roof.
[10] There were no solid ground floor retrofits. The Calculated U-value reduction is related to the increased wall thickness post wall retrofit stage.

This analysis suggests that the loft performance was in line with expectations, since the gaps are within the uncertainty of the measurement. The same is true of the new double glazing. The floor U-value, however, appears to present a performance gap, though it is important to remember that only centre room HFPs were used to estimate the floor U-value and so these values should be treated with caution. No gaps can be calculated for the doors or the bay window roof since, as discussed, the U-values for these elements were not measured.

More certainty can be given to the wall U-value measurements undertaken and these seem to suggest that there may have been a performance gap with the EWI. While the front external wall gaps shown are not statistically significant, the rear and gable walls indicate that the EWI performed better than predictions (a negative gap value). However, it is unlikely that the performance of the insulation is greater than its potential technical improvement. Instead, these negative values are likely due to the higher measured U-values for these elements before the retrofits.

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

Element	RdSAP default predicted reduction (W/(m²·K))	Calculated predicted reduction (W/(m²·K))	Measured reduction (W/(m²·K))	RdSAP defaults prediction gap (W/(m²·K))	“as-built” performance gap (W/(m²·K))
Roof	0.19	0.18	0.13 ± 0.20	0.06 ± 0.20	0.05 ± 0.20
Glazing[11]	0.67	0.67	0.49 ± 0.35	0.18 ± 0.35	0.18 ± 0.35
Doors[12]	1.45	1.45	-	-	-
Suspended timber ground floor	0.54	0.55	0.80 ± 0.08	-0.26 ± 0.08	-0.25 ± 0.08
Front external wall	1.38	1.55	1.55 ± 0.19	-0.17 ± 0.19	0.00 ± 0.19
Rear external wall	1.24	1.50	1.55 ± 0.19	-0.31 ± 0.19	-0.05 ± 0.19
Gable external wall	1.31	1.53	1.74 ± 0.19	-0.43 ± 0.19	-0.21 ± 0.19
Bay window roof[13]	-	3.63	-	-	-

[11] Post-retrofit RdSAP Default and Calculated U-values are obtained from supplier’s documents.
[12] No HFP recordings were obtained for the Doors. Post-retrofit RdSAP Default and Calculated U-values are obtained from supplier’s documents.
[13] RdSAP does not include Bay window roof. No HFP recordings were obtained for the Bay window roof.

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

Table 3-3 shows the impact the improvement in U-values have had on plane element fabric heat loss, i.e. considering the U-values and relative size of heat loss area of each element. As can be seen, a dramatic reduction in heat loss is predicted to have been achieved by the retrofits, equivalent to (158 ± 27) W/K. The measured U-values suggest the loft heat losses have halved following the existing loft insulation being replaced. Substantial reductions in the U-value of the floor were measured (19 ± 3) W/K, despite the solid floor portion of this element receiving no retrofit. However, this estimate may not be robust, since it is based on two centre room HFPs, and so do not consider ground floor edge effects.

Interestingly, insulating the bay window roof, even though this was less than 1 % of the heat loss area, may have reduced fabric heat loss by as much as the loft insulation (4 W/K). This suggests this could have potential as a standalone retrofit measure. More information on the existing level of insulation in bay window roofs may be needed to understand the impact this could have on other house types in the UK housing stock.

The external windows and doors heat losses have reduced by around a third, even though double glazing had been installed in the past. However, there is relatively large uncertainty associated with these values since they are based on a single centre pane HFP and the door values are calculated not measured. Regardless, this suggests upgrading decades-old double glazing and external doors could reduce heat loss in homes. This may become more important in the future as solid walls are insulated, since the fenestrations will be responsible for proportionally larger amounts of whole house heat loss.

The most dramatic reduction was observed in the external wall heat losses, which were expected to reduce by around 84 %. The reduction achieved is so impactful since the home has a large gable wall, and therefore, a large heat loss area for this element from which savings could be made, coupled with a large reduction in wall U-values of between 79 % and 84 %. Installing EWI on end-terrace homes, therefore, may provide one of the most profound strategies for heat loss reductions for retrofit policy. The findings suggest that increasing the proportion of solid wall insulation installations taking place, could increase the impact of retrofits taking place in the UK housing stock.

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

Element	Pre-retrofit (W / K)	*Proportion of heat loss*	Post-retrofit (W / K)	*Proportion of heat loss*
Roof	8 ± 6	*(4 ± 3)%*	4 ± 3	(6 ± 5)%
Solid & suspended ground floor	31 ± 2	*(14 ± 1)%*	12 ±1	(21 ± 2)%
Doors[14] & windows	31 ± 3	*(14 ± 1)%*	19 ± 4	(33 ± 6)%
Walls	141 ± 8	*(66 ± 4)%*	23 ± 11	(40 ± 16)%
Bay window roof[14]	4	*2%*	0.2	0.4%
Total	**215 ± 19**	**-**	**57 ± 19**	**-**

[14] Only calculated values are available

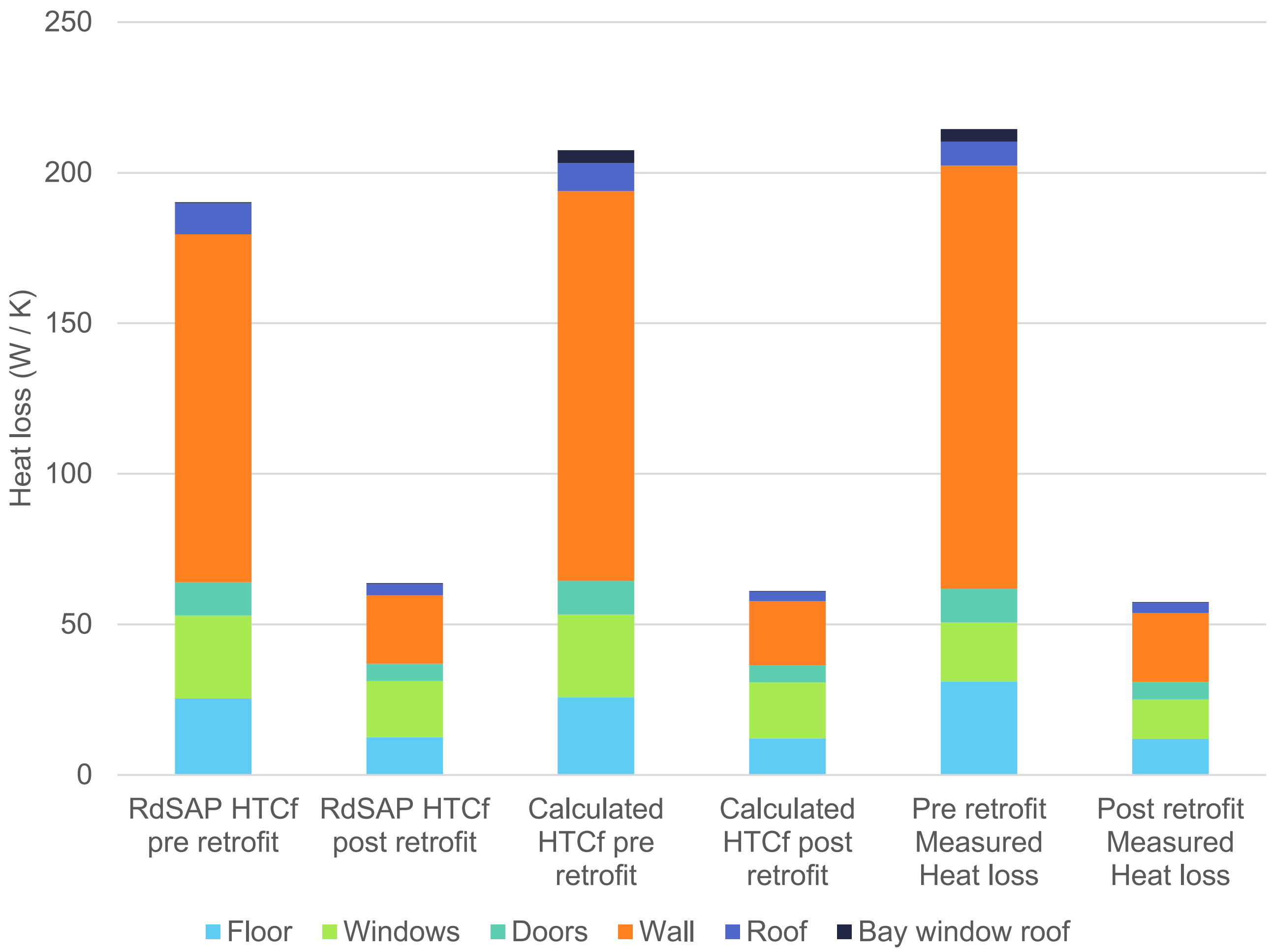


Figure 3-7 Measured heat loss of fabric elements pre- and post-retrofit

U-value improvement summary

The fabric retrofits have dramatically reduced heat loss from the case study home. The EWI was the most effective retrofit, which reduced the plane element fabric heat loss of the external walls by 84 %. The uninsulated external wall U-values were measured to be higher than predicted, though when insulated, the predictions and measurements were more similar.

The whole ground floor U-value could not be accurately measured owing to a lack of HFPs. The indicative centre room U-value suggests a significant improvement in performance was achieved. The same is true for the window U-values, which centre pane HFPs predicted could reduce HTC by (12 ± 5) W/K, but this does not consider the frame heat losses. Thus, the improvements in these elements should be treated with caution.

Insulating the bay window roof at the same time as the EWI was calculated to have a 95 % reduction in U-value. This means that, even though the element was <1% of the heat loss area of the home, installing insulation here is predicted to reduce HTC by 4 %: about as much as replacing and enhancing the home's loft insulation. However, this was not confirmed through in-situ measurements.

3.3 Whole house heat loss (HTC) improvement

The total measured heat loss from the base case dwelling and retrofits are shown in Table 34, which indicates that the cumulative benefit of the retrofits has reduced the HTC by (156 ± 15) W/K, or (60 ± 7) %. The EWI and bay roof insulation had overwhelmingly the largest reduction of (130 ± 10) W/K, or (55 ± 5) %, and the loft replacement also had a reduction of (21 ± 16) W/K, or (8 ± 6) %. This is much larger than the 4 W/K predicted saving from the U-value estimates.

Table 3-4 Test house HTC after each retrofit stage

Retrofit	HTC (W/K)	HTC uncertainty	HTC reduction (W/K)	Percentage reduction
01BA.B Baseline	262	14 (5%)	-	-
01BA.R Replacement loft insulation	241	7 (3%)	21 ± 16	(8 ± 6)%
01BA.R.G New windows and doors fitted	228	16 (7%)	13 ± 17	(5 ± 7)%
01BA.R.G.F Suspended timber ground floor insulation	236	9 (4%)	-8 ± 18	(-4 ± 8)%
01BA.R.G.F.W EWI & bay roof insulation	106	5 (5%)	130 ± 10	(55 ± 5)%
Total	-	-	**156 ± 15**	**(60 ± 7)%**

As can be seen in Figure 3-13, the uncertainty values of the coheating test were generally lower than the previously estimated uncertainty of 8 % to 10 % for the test.

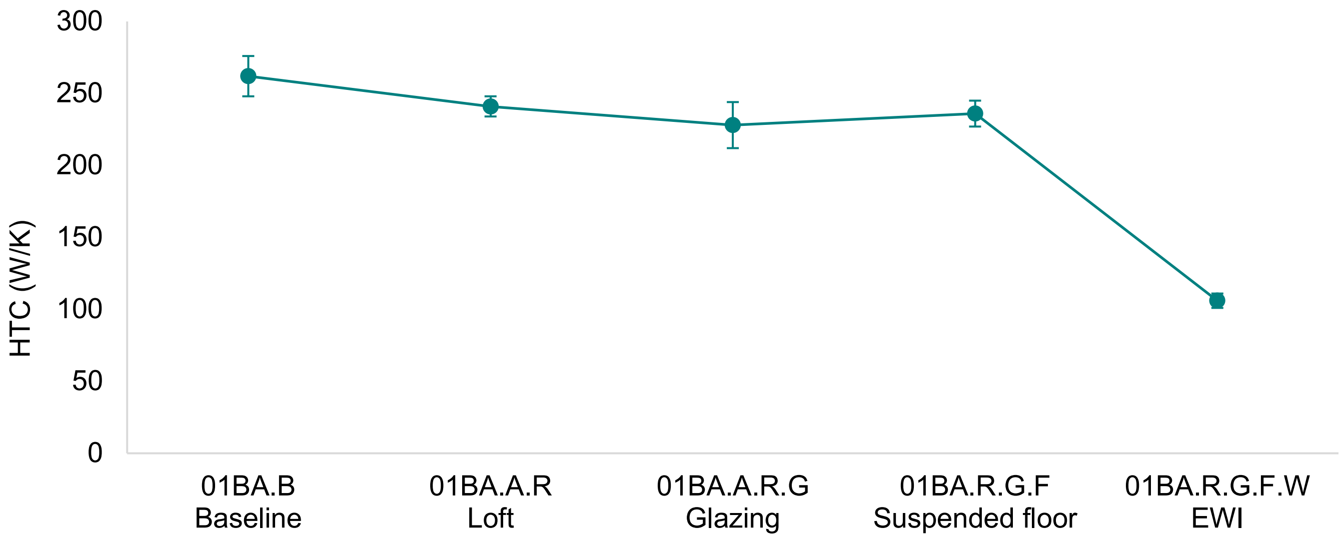


Figure 3-13 Coheating HTC at each retrofit stage

Despite the low uncertainty, the floor and glazing retrofits individually did not achieve a statistically significant change in HTC. Cumulatively, when combined, the loft, windows and doors, and floor retrofits are measured to reduce HTC by (10 ± 6) %, which is greater than the saving achieved by the loft insulation alone. The success of the individual retrofits is discussed in the following sections.

3.3.1 Ventilation heat loss reductions

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

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

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

As previously mentioned, there was no specific retrofit aimed at reducing air leakage in the home, yet the retrofits did result in an unintended measured reduction in infiltration from 15 to 13 $m^3/(h \cdot m^2)$ @ 50Pa. This is the equivalent to an approximated drop in HTC_v from 37 to 31 W/K which, although only small (~2% of the overall baseline HTC), is a similar reduction in HTC to that expected from the loft retrofit based upon the in-situ measured U-values.

The implication is that specific airtightness retrofits that attempt to maintain the integrity of an airtightness barrier in homes may be needed if meaningful reductions in ventilation heat loss are to be achieved. Therefore, relying on retrofits to incidentally improve airtightness is not a reliable approach to achieve reductions in ventilation heat losses, and a more strategic and targeted approach is required.

If not addressed in whole house retrofits, ventilation heat losses can ultimately become one of the largest heat loss mechanisms in a home. For instance, if the n/20 rule of thumb is appropriate for this house: air leakage, which was initially only responsible for ~14 % of the baseline HTC, becomes responsible for almost a third of the total heat loss in the retrofitted home. 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 [7]]. Investigation using a larger sample set would be required to identify an alternative rule of thumb for UK archetypes.

3.3.2 Roof heat losses: 01BA.R

Observation of the original loft insulation installed within the home found that it had been somewhat disturbed by storage of items, resulting in compressed and dislodged insulation in places. In addition, debris had settled on top of the mineral wool. which may have also had an adverse impact on its performance.

The first fabric retrofit undertaken on this dwelling was therefore to remove the old approximately 150 mm of old mineral wool loft insulation and replace it with new 400 mm of mineral wool, installed 200 mm between and 200 mm across the ceiling joists. In addition, the existing loft hatch was not suitable for gaining safe access, and so a new opening with a new sealed and insulated loft hatch was installed instead, as shown in Figure 3-14. This achieved superior thermal performance. Also visible is that the new loft insulation is better fitted, as less thermal bridging can be seen at the wall to ceiling junctions.

The coheating test results confirmed that a reduction in HTC of (21 ± 16) W/K ((8 ± 6) %) was achieved by these improvements.

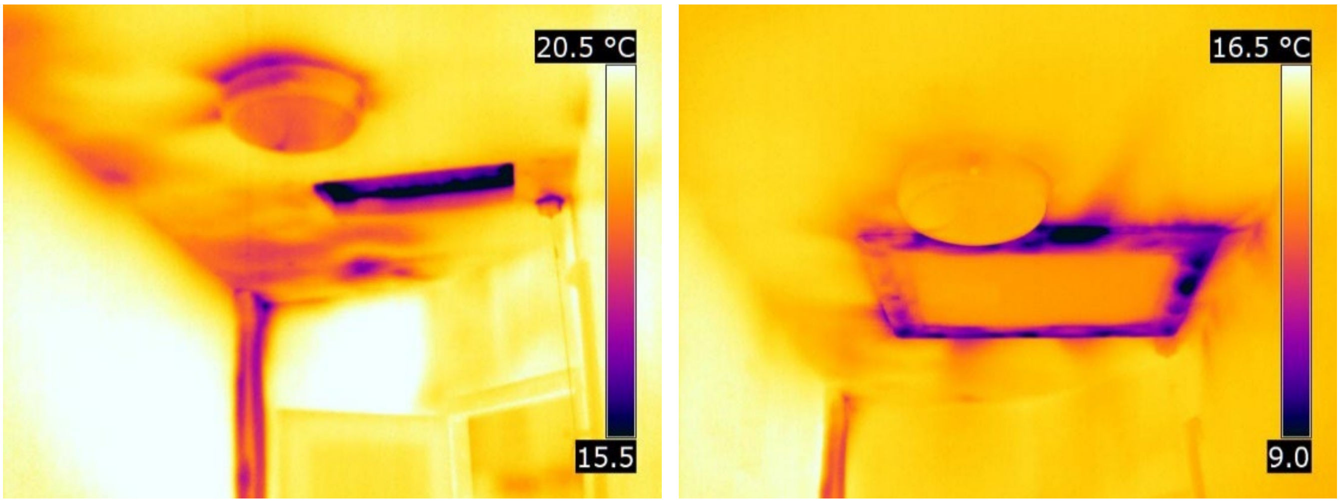


Figure 3-14 Comparison of old loft hatch (left) and new loft hatch (right) under depressurisation

Whilst direct heat losses into the loft through the horizontal ceiling were clearly reduced, other heat loss mechanisms existed and are harder to quantify. Figure 3-15 illustrates one of these additional mechanisms. In this example, air inside the chimney bypasses the insulation layer located at the ceiling level both before and after the loft retrofit, although the additional depth of the retrofitted insulation lengthens the thermal bridge at the base of the chimney stack and along the party wall. The images also illustrate a thermal bypass at the intersection between the party wall and the first floor ceiling. Ventilation of unused chimneys is recommended to avoid moisture and condensation issues; for heat loss reduction the preferred solution would be to remove the chimneys and chimney breasts entirely, an option often not undertaken (and not considered here) due to the associated costs and level of disruption.

Figure 3-15 Comparison of original loft insulation (top) and new (bottom) showing bypassing and bridging at the chimney breast and the intersection between the party wall and the first-floor ceiling.

3.3.3 New glazing heat losses: 01BA.R.G

The original uPVC double glazed windows were over a decade old and incorporated only very small openable areas, which may have implications for achieving adequate summertime cooling. The original doors were timber and in relatively poor condition. The next retrofit was therefore to upgrade these fenestrations, with new A rated double glazed windows and composite doors as shown in Figure 3-16.

Figure 3-16 Comparison of old windows and doors (top) and replacements (bottom) on the front façade during coheating phases

Both the measured U-value improvements and the coheating test results are indicative that there may have been a heat loss reduction from this retrofit stage, though due to the large uncertainties associated with this test (7 %), the change measured in the HTC of (13 ± 17) W/K ((5 ± 7) %) was not shown to be statistically significant. Since 01BA is an end-terrace home, comprising a large gable wall with no openings, as expected, the total external glazing and door area to heat loss area was relatively small (8 %). Consequently, replacing these elements was only expected to make a proportionally smaller impact on the total HTC, than would be the case in a mid-terraced home or flat.

The blower door test results for this retrofit stage reduced the air permeability slightly from 14.5 to 13.2 $m^3/(h \cdot m^2)$ @ 50Pa, though this is just within the uncertainty of the test. It is also important to note that despite there being particularly large air gaps between the external walls and the old windows and door frames pre-retrofit, only a small reduction in air leakage was measured post-retrofit. Nevertheless, the reduction from this retrofit would have contributed to a drop in the HTC.

3.3.4 Suspended timber ground floor heat losses: 01BA.R.G.F

01BA has a part solid and part suspended timber ground floor, a common feature in UK solid walled homes. Insulating the suspended timber element in this case study did not result in a statistically significant reduction in HTC. This is not surprising, given that only the living room floor was suspended timber. This made up 66 % of the floor area and only 15 % of the total heat loss area in the home.

The measured U-values indicate that the centre room heat loss was substantially reduced; however, this is not reflective of the entire suspended timber ground floor heat losses. More research is needed to understand heat losses associated with suspended timber ground floors and how they are affected by retrofits.

It is noteworthy that this retrofit did not result in a measurable reduction in the airtightness of the home. An air barrier membrane was specified as part of the suspended timber ground floor retrofit (Figure 3-17); however, it appears this was only partially successful. A reduction was observed through the living room floor, but not the hall and understairs cupboard. This suggests that a partial under floor membrane is not particularly effective since it changed the air leakage pathways and leakage points, rather than minimising air leakage overall. Reducing infiltration through the ground floor has been noted as being an important component of the ability of ground floor retrofits to reduce heat losses. More research into air leakage through suspended timber ground floors and how this can be minimised during retrofits is needed.

Figure 3-17 The airtight membrane was laid over and between floor joists in the living room (left hand side) and before the mineral wool insulation added (right hand side)

3.3.5 External wall and bay window roof heat losses 01BA.R.G.F.W

The major retrofit success associated with this case study home was the EWI shown in Figure 3-18, which achieved a substantial reduction in overall HTC of (130 ±10) W/K (55 ± 5) %. The main reasons for this large reduction can be attributed to the fact that the home was an end-terrace with a very large gable wall, meaning there was a large area of external wall that was insulated as part of the retrofit, accounting for almost 45 % of the entire dwelling heat loss area.

Figure 3-18 The EWI installation process. The steel section frame was put up (left hand side), then covered with a membrane and injected with insulation (middle). Finally, the pre-made rainscreen panels were added (right hand side).

The results indicate that the EWI only resulted in a minimal reduction in the infiltration in the home, meaning that all the HTC savings were made via improvements to the fabric thermal resistance. This suggests that either the main air leakage points and pathways within the dwelling were not associated with the solid external wall, or that those leakage points and pathways attributable to penetrations in the external wall were not sealed or diminished by the installation of the EWI.

It is also important to note that the bay window roof was also insulated at the same time, as shown in Figure 3-19. This was a particularly poorly performing element when uninsulated, according to the calculated U-values, and so it is probable that insulating here will contribute substantially to reducing the heat loss via this element.

However, as this element only represents a relatively small heat loss area, it is likely to have had only a small contribution to the whole house HTC reduction measured. More significantly, the bay roof retrofit will have reduced the risk of the occurrence of surface condensation on the ceiling, which is discussed further in Section 3.5.

Figure 3-19 The bay window roof before rainscreen panels were added (left hand side) and internally, prior to insulation being installed (right hand side).

There were several other interesting features of note, particularly those areas of the dwelling that were insulated with an 75 mm XPS foam, below the DPC and the corbels at the eaves (Figure 3-20), since the same system that was used for the rest of the house could not be used to insulate these areas.

Figure 3-20 EWI was installed up to the underside of the corbels, where an insulated render based EWI system was used to accommodate the brickwork feature.

In addition, the bay window had a sloping roof, which meant that it was not possible to install EWI on the external wall above the bay window. The extent of the heat loss was not possible to visualise or measure owing to there being a large radiator located in the bay, limiting access to install HFPs or use thermography.

Although the implications of this on overall dwelling heat loss may be relatively small, since its contribution to the overall heat loss area is minimal, there may be implications in terms of surface condensation risk, which are again discussed in Section 3.5. However, since a radiator was located here, the risk that condensation may manifest would be limited.

The cumulative HTC reductions as measured by the coheating tests are show in Figure 3-21. This illustrates the scale of savings made, and that almost all the retrofit savings were achieved by the EWI retrofit. The uncertainty in the test makes it difficult to have certainty on the specific benefits of each of the other specific retrofits.

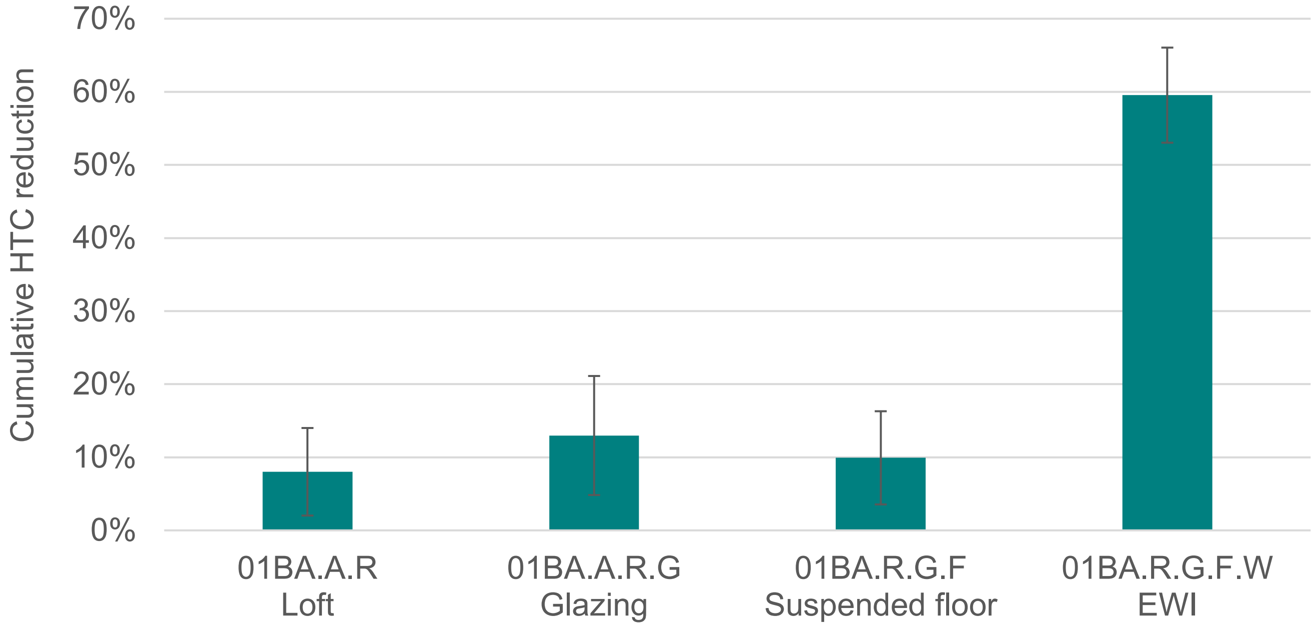


Figure 3-21 Cumulative HTC savings from each retrofit stage

Whole house heat loss improvement summary

This section shows that the retrofits reduced the HTC of the home by (156 ± 15) W/K (60 ± 7) %. Almost all of this improvement was due to the EWI retrofits reducing the HTC by (130 ± 10) W/K, or (55 ± 5) %.

As the largest fabric element of this home was the external walls, it's not surprising that by insulating them with EWI, there was substantial heat loss reduction overall.

Additionally, the results suggest that installing EWI may be the only sensible retrofit approach to achieve the heat loss reductions required to meet policy targets in solid walled homes like 01BA.

The loft retrofit also reduced the HTC, by (21 ± 16) W/K ((8 ± 6) %), even though it was already insulated to some degree. The suspended timber ground floor and glazing retrofits did not make significant changes to the HTC, though the savings associated with these measures may have been masked due to the slightly higher uncertainty associated with these tests.

Infiltration was reduced by the collective loft and glazing retrofits, though the suspended timber ground floor and EWI did not affect air leakage pathways.

3.4 Measured, calculated, and modelled retrofit performance

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

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

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

HTC_b (non-repeating thermal bridging heat losses) can be calculated by modelling each junction in thermal bridging software; though it is erroneously often assumed to be the remainder once the HTC_v and 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 annual average approximation which may not be appropriate for different building types or for different levels of wind exposure, geography, or topography. Thus, the HTC_v can only be an approximation.
- HFP placements may not be representative or comprehensive of whole element heat loss, so the HTC_f may be imperfectly estimated.
- Point thermal bridges are not considered.
- 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, and only quasi steady-state conditions being possible.

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

Following this, the measured HTC is compared to the different energy models at each retrofit stage assuming each of the four calibration steps described in Section 2.6 in this report and in more detail in Report 2.01 DEEP Methods.

3.4.1 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 3-22.

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 plane fabric element by its measured U-value ($W/(m^2 \cdot K)$); the HTC_v is derived using in Equation 1; and the HTC_b is derived from the assumed y-value used in RdSAP software for homes like 01BA.

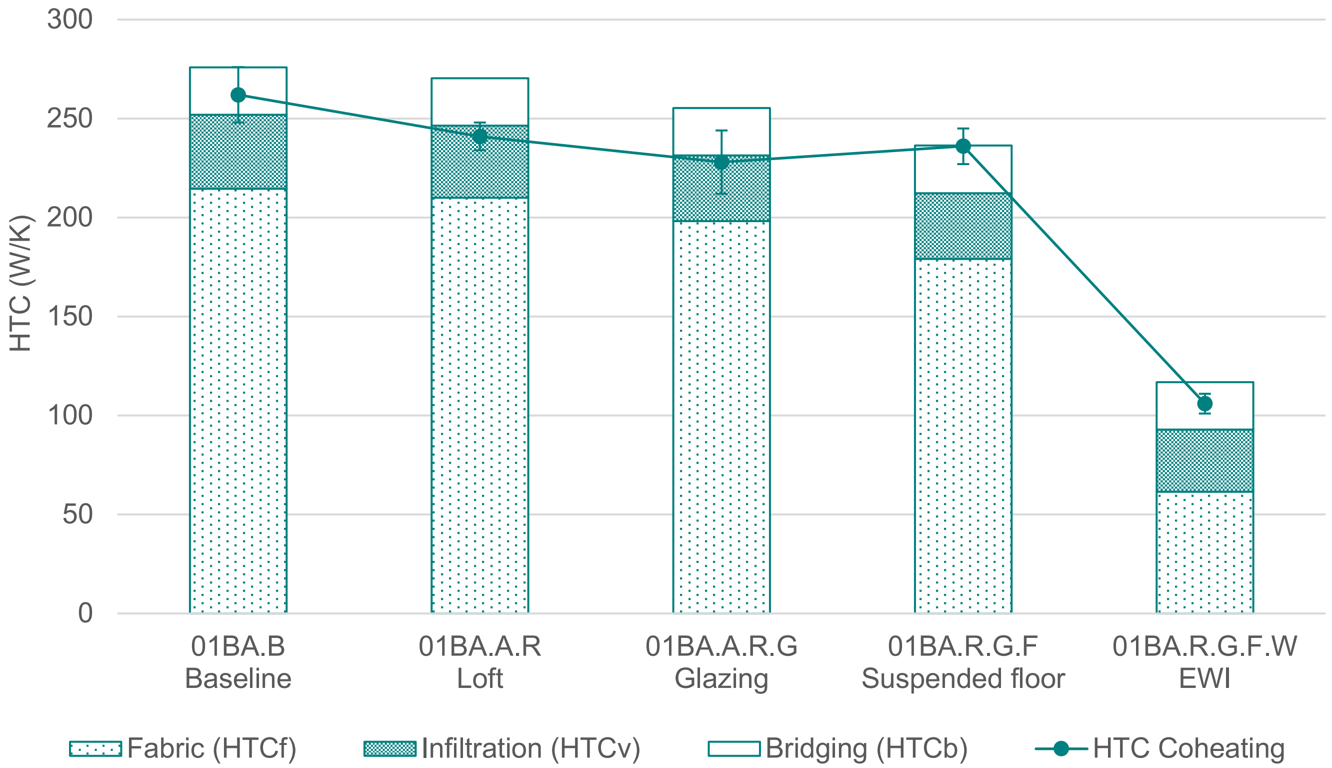


Figure 3-22 Calculated vs measured HTC

The HTC measured by the coheating test is shown to be in good agreement with the aggregate of the HTC_f, HTC_v and HTC_b, except with the loft and glazing retrofit stages. The reasons for this deviation may be due to uncertainties in the coheating test or in the closing-the-loop disaggregated approach, including:

- The thermal bridging heat loss is taken from the EPC model and so not calculated for each junction meaning the HTC_v is an area of uncertainty.
- The n/20 rule of thumb for estimating background ventilation heat losses for this type of house may not be appropriate, specifically this home had an adjoining dwelling and so the blower door test result included some inter-dwelling air exchanges, thus overestimating the HTC_v.
- Heat flux density plates are not be able to capture heterogeneity in heat loss from plane fabric elements (repeated, or local bridges, or local bypasses), meaning U-values and HTC_f may be overestimated in this house.
- Point thermal bridges are not considered, which would lead to an overestimation of HTC_f.

The proportion of heat lost via fabric, infiltration and bridging varies according to the retrofit stage as shown in Table 3-5. It is clear that the fabric remains the largest contributor to the HTC in all of the retrofit stages, despite the significant reduction in heat loss achieved by the EWI.

Heat losses associated with air leakage and thermal bridging therefore become proportionally more significant after EWI is installed, even though they do not have a large absolute change, as the rest of the house is retrofitted.

In reality, it is likely that the thermal bridging heat loss will have changed over the course of the retrofit. However, in EPCs, where the HTC_b has been derived in this case study, the y-value remains constant regardless of what fabric improvements have taken place, and so this remains an area of uncertainty in this analysis.

Table 3-5 Whole house heat loss via disaggregated methods

Retrofit stage	HTC_f W/K	HTC_v W/K	HTC_b W/K
01BA.B Baseline	211 (77 %)	37 (14 %)	24 (9 %)
01BA.A.R Loft insulation replacement	206 (77 %)	36 (14 %)	24 (9 %)
01BA.A.R.G Glazing replacement	164 (77 %)	33 (13 %)	24 (9 %)
01BA.R.G.F Suspended timber floor insulation	175 (75 %)	33 (14 %)	24 (10 %)
01BA.R.G.F.W EWI & bay window roof insulation	57 (51 %)	31 (28 %)	24 (21 %)

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

3.4.2 Measured vs. modelled HTC calibration step 1

The measured HTC values for each retrofit stage are plotted against the HTC values predicted by the uncalibrated models using default RdSAP input data in Figure 3-23. The results of this comparison are as follows:

- DSM substantially underestimates the HTC compared to the steady-state models in all of the retrofit stages apart from the EWI where it is over estimated owing to lower space heat demand.
- Although the coheating test measured an increase in HTC for the suspended ground floor retrofit, this was within the uncertainty of the test method, and is in contrast to the small, predicted reductions in HTC attributable to this retrofit.
- The scale of the cumulative retrofit reductions achieved, and specifically the EWI retrofit, are similar to (slightly less) that which was measured.
- The reductions predicted in the steady-state models for the suspended timber ground floor and glazing retrofits are either within (or only just outside) the uncertainty of the test until the final EWI stage. It is important to note that this perceived accuracy has been arrived at by chance, i.e. when the default U-values are updated in the following steps, the steady-state model predictions get further away from the coheating result.
- Although the DSM had a much lower starting base case than the other models, once all of the retrofits were undertaken, the results from all of the models converged, such that was significantly less difference in the total HTC between all the models.

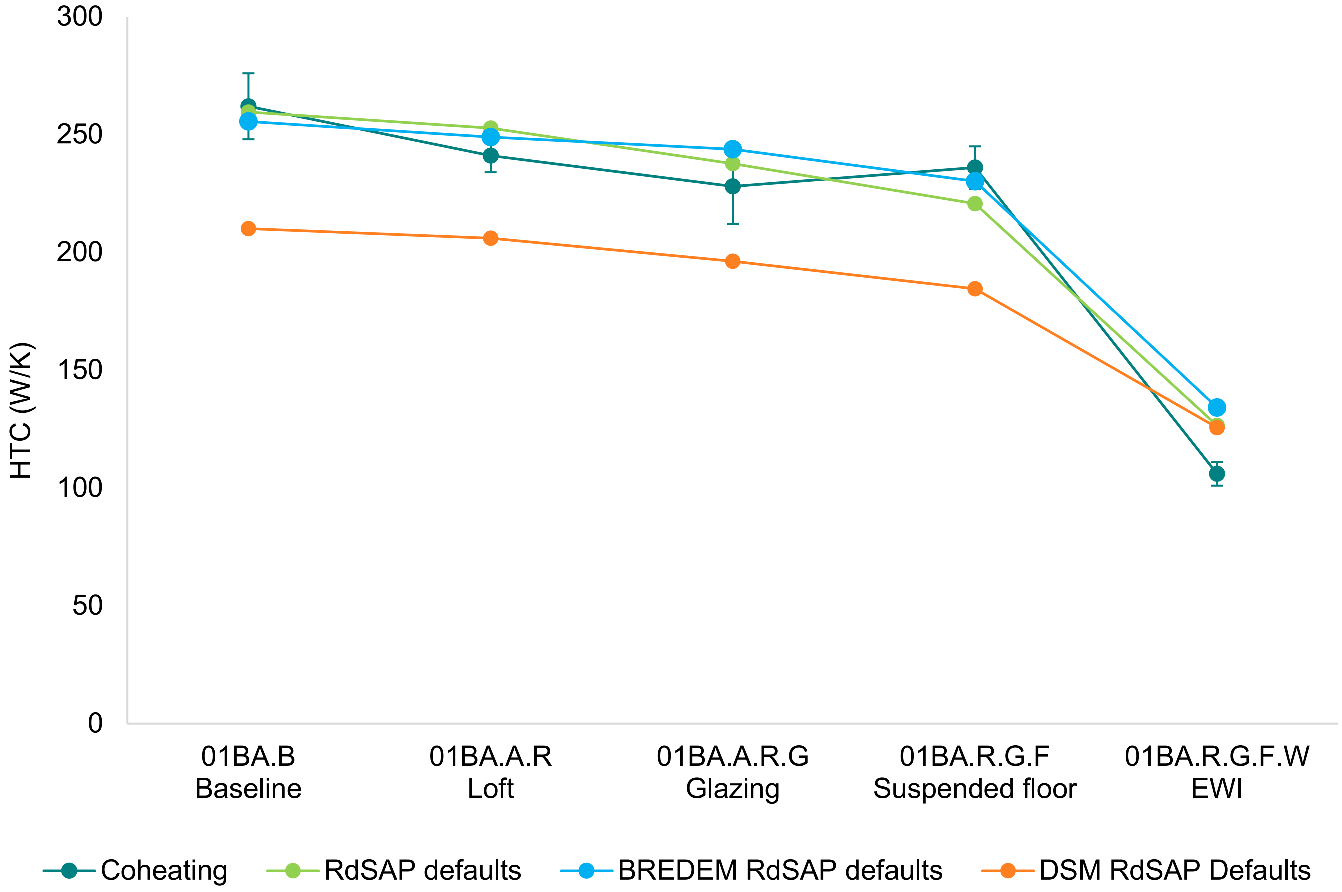


Figure 3-23 Measured vs modelled HTC calibration step 1: default data

3.4.3 Measured vs modelled HTC calibration step 2: measured infiltration

In this first calibration step, the models used infiltration rates derived from the blower door test, as this data was the most likely and most cost-effective measurement data to be acquired in practice. The impact of this compared to the previous calibration stage can be seen in Figure 3-24:

- RdSAP is not included in this step as infiltration cannot be altered in the software.
- A relatively small reduction in HTC is observed in this stage since the default infiltration rate of the house was relatively similar to that which was measured.
- This reduction brings the steady-state predictions for the loft, glazing, and EWI retrofit stages more in line with the measured values. However, all the other stages, including the base case, and all the DSM predictions move marginally further away because they were already lower than the coheating measurements.

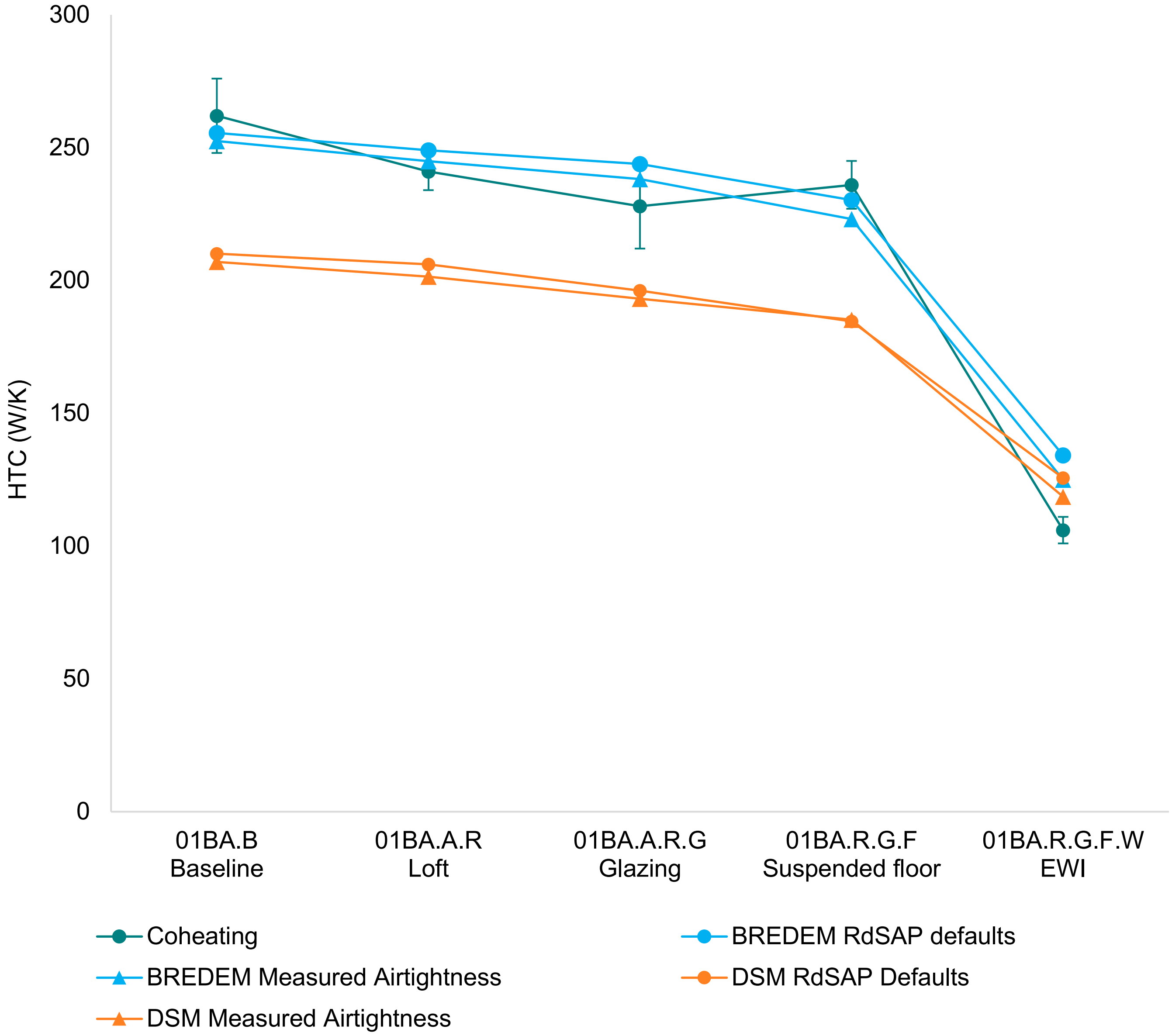


Figure 3-24 Measured vs modelled HTC calibration step 2: measured infiltration

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

In this step, the models included U-values defined using the BRE calculator which requires more detailed surveys, often requiring assumptions or destructive investigations to establish the nature and thickness of construction layers. The impact of this compared to the previous calibration stage can be seen in Figure 3-25:

- RdSAP is not included as only measured U-values can be used in the software.
- The calculated uninsulated external wall U-values were marginally higher than the defaults, and so the HTC predictions in all models increase in this stage for all stages apart from the EWI retrofit.
- Following the EWI retrofit, as the insulated calculated external wall U-values were marginally better than the defaults, the results obtained from all the models converge towards the measured value obtained from the coheating test.

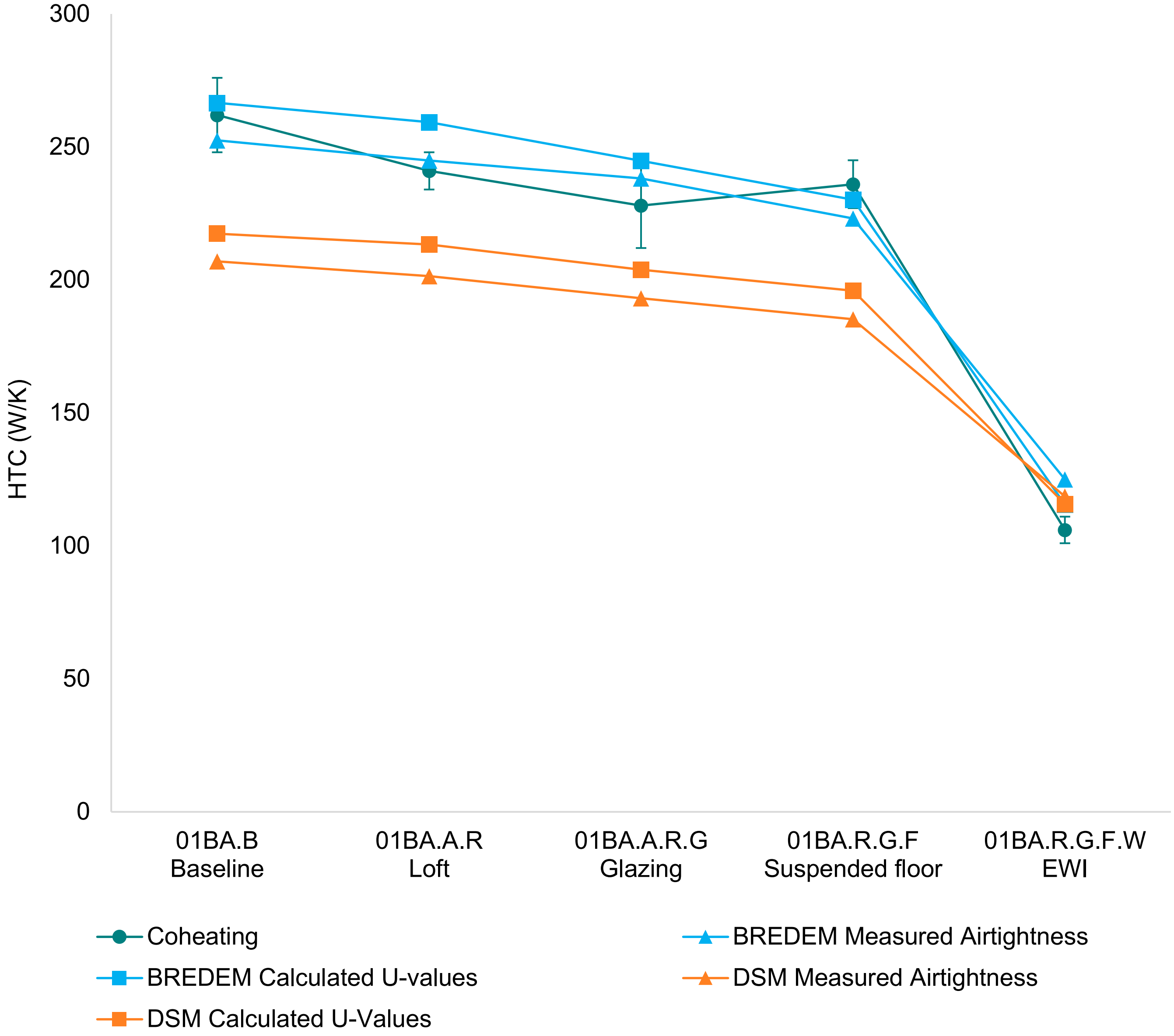


Figure 3-25 Measured vs modelled HTC calibration step 3: calculated U-values

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

In this step, the models used measured U-values, which requires resource intensive in-situ testing. The impact of this compared to the previous calibration stage is shown in Figure 3-26:

- The measured U-value for the uninsulated external wall was higher than was calculated and so the HTC in all models increased.
- After the EWI retrofit, the difference between the measured and calculated wall U-values was negligible, so the modelled predictions and measurements were similar.
- Using the measured U-values in the RdSAP software resulted in a substantial increase in the home's predicted HTC by around 11 % for all retrofit stages (apart from the EWI), since the default U-value was underestimating the plane element fabric heat losses for these retrofit stages.
- After calibrating the model, the predicted HTCs diverged further away from the measured HTCs in all stages (apart from the EWI) than when using default input values. This suggests that in those retrofit stages where the defaults were predicting an HTC that was similar to the coheating HTC, this was occurring by chance.
- The thermal bridging for this home had been taken from the RdSAP default, thus it is not known if calculated thermal bridging values would bring the predicted HTC into better alignment with the coheating HTC, though in other DEEP case studies the thermal bridging heat losses have been observed to be higher than in the RdSAP y-values for uninsulated homes, and lower in insulated homes.

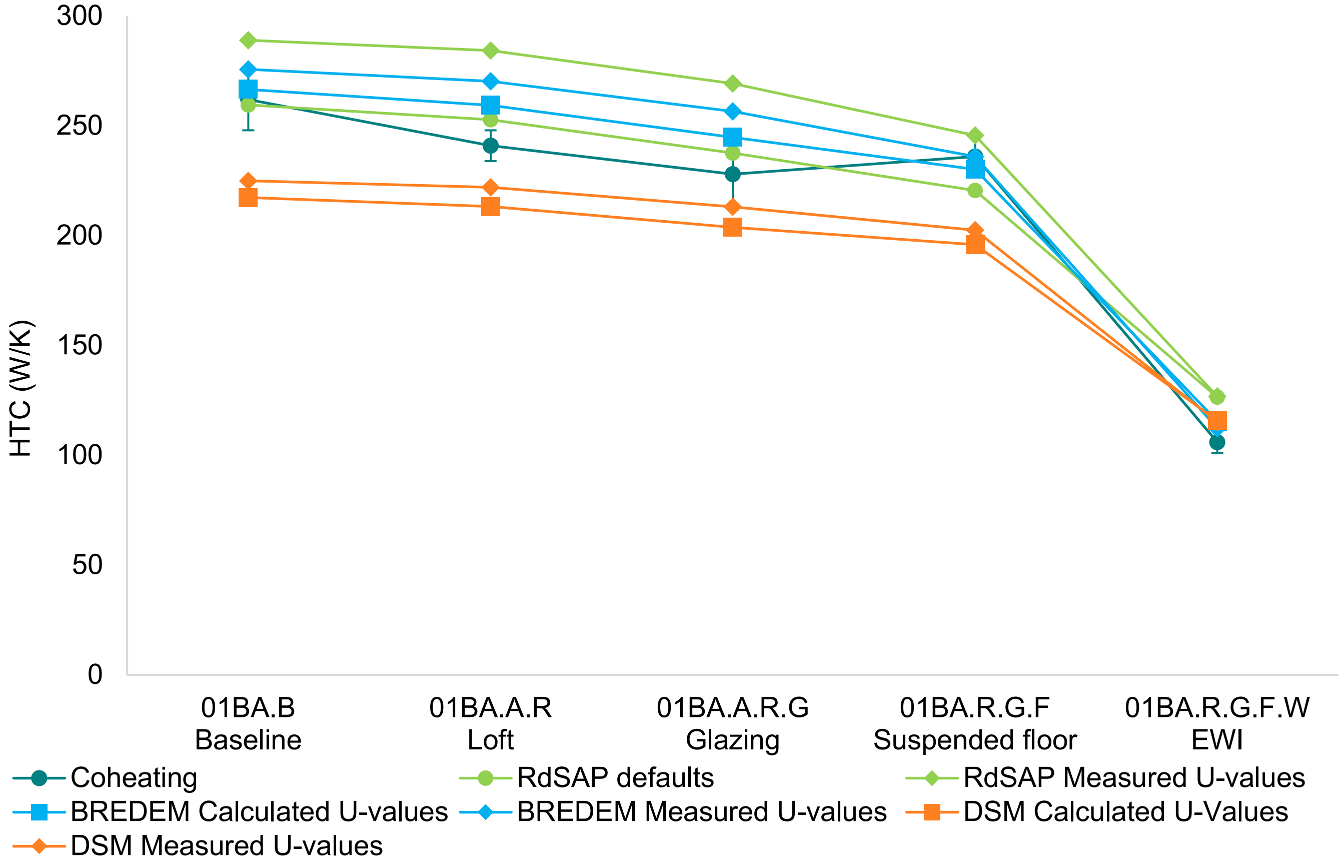


Figure 3-26 Measured vs modelled HTC Calibration step 4: measured U-values

Measured versus modelled HTC summary

The closing-the-loop analysis shows that the disaggregated HTC prediction based on measured U-values, infiltration, and calculated non-repeating thermal bridging heat loss was broadly similar to the HTC measured by the coheating test. The results were often within uncertainty limits associated with the coheating test. However, the assumed y-values in RdSAP were used to estimate thermal bridging heat losses.

At first glance, the steady-state model using RdSAP defaults appears to be a relatively good predictor of HTC. However, when the defaults are replaced with measured airtightness results and in-situ U-values, the HTC predictions diverge further away from the measured results for the majority of the retrofit stages. This suggests that the result from the defaults gave a result similar to the coheating test somewhat by chance.

The savings predicted by all the models appear to be in line with those that are measured. However, perhaps they provide more insight into the level of saving achieved by each individual retrofit, since the uncertainty of the coheating test for the glazing and suspended ground floor retrofit tests was relatively high.

This result suggests that there is much more uncertainty around the performance of uninsulated external walls than for insulated external walls. This is because the thermal insulation proportionally provides the greatest amount of thermal resistance in the insulated external walls, and is much greater than the thermal resistance of the uninsulated wall. This has an implication for the accuracy of EPCs for uninsulated external walls and predicting retrofit performance and savings.

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

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

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

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

This is significant when considering the success of retrofits and calculating paybacks or impacts on EPC levels and fuel poverty for policy evaluation, as RdSAP age-band default data were found to underestimate baseline EPC scores, and thus overestimate retrofit savings. This suggests that the current defaults contained within RdSAP are overly pessimistic.

3.5.1 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 [8]. The impact of the retrofits on EPC in this case study, as predicted by each model at each calibration stage is shown in Figure 3-27. Space heating demand predicted by DSM is the only output that differs in the comparative EPC calculations.

- The baseline home was judged to be a band D by steady-state and DSM models.
- The loft and glazing retrofits alone were not enough improvement for the home to achieve a band C in the steady-state models but were sufficient for the DSM.
- The DSM models predicted higher SAP scores than the steady-state models in all but the EWI retrofit; and even predict that the home could be a band C when the ground floor retrofit was included.
- Following the EWI retrofit, all the models agree that the home will be at EPC band C, indicating that only retrofitting the external walls is likely to achieve policy targets for solid externally walled homes.

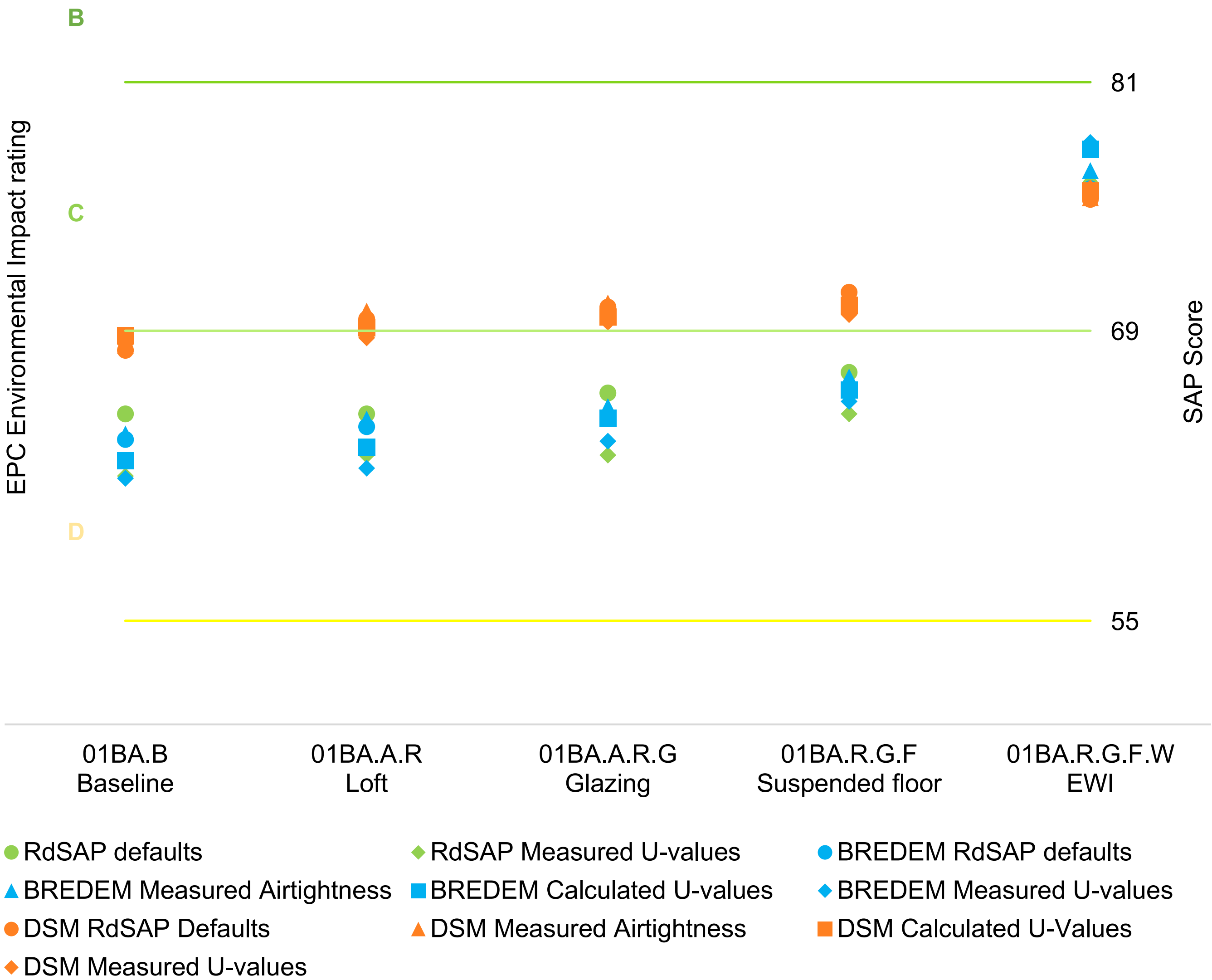


Figure 3-27 Predicted impact of retrofits on EPC band

3.5.2 Impact of retrofits on annual space heating

The Social Housing Decarbonisation Fund (SHDF) Wave 1 evaluates retrofit success by setting an annual space heating target of 90 kWh/m² for retrofits [9]. The predicted annual space heating demand for the case study retrofits is shown in Figure 3-28.

- The DSM model predicts substantially lower space heating requirements than the steady-state models.
- The glazing, ground floor, and airtightness retrofits result in a small reduction in space heating demand, but are insufficient to reduce the space heating requirement to the SHDF target of 90 kWh/year using any of the models
- All the models agree that the final EWI retrofit will achieve cumulative savings sufficient to bring the home below the SHDF target.
- In eight out of the ten models, including the RdSAP used to generate the EPC, the EWI alone would have just been sufficient to achieve the SHDF threshold, without the other retrofits.

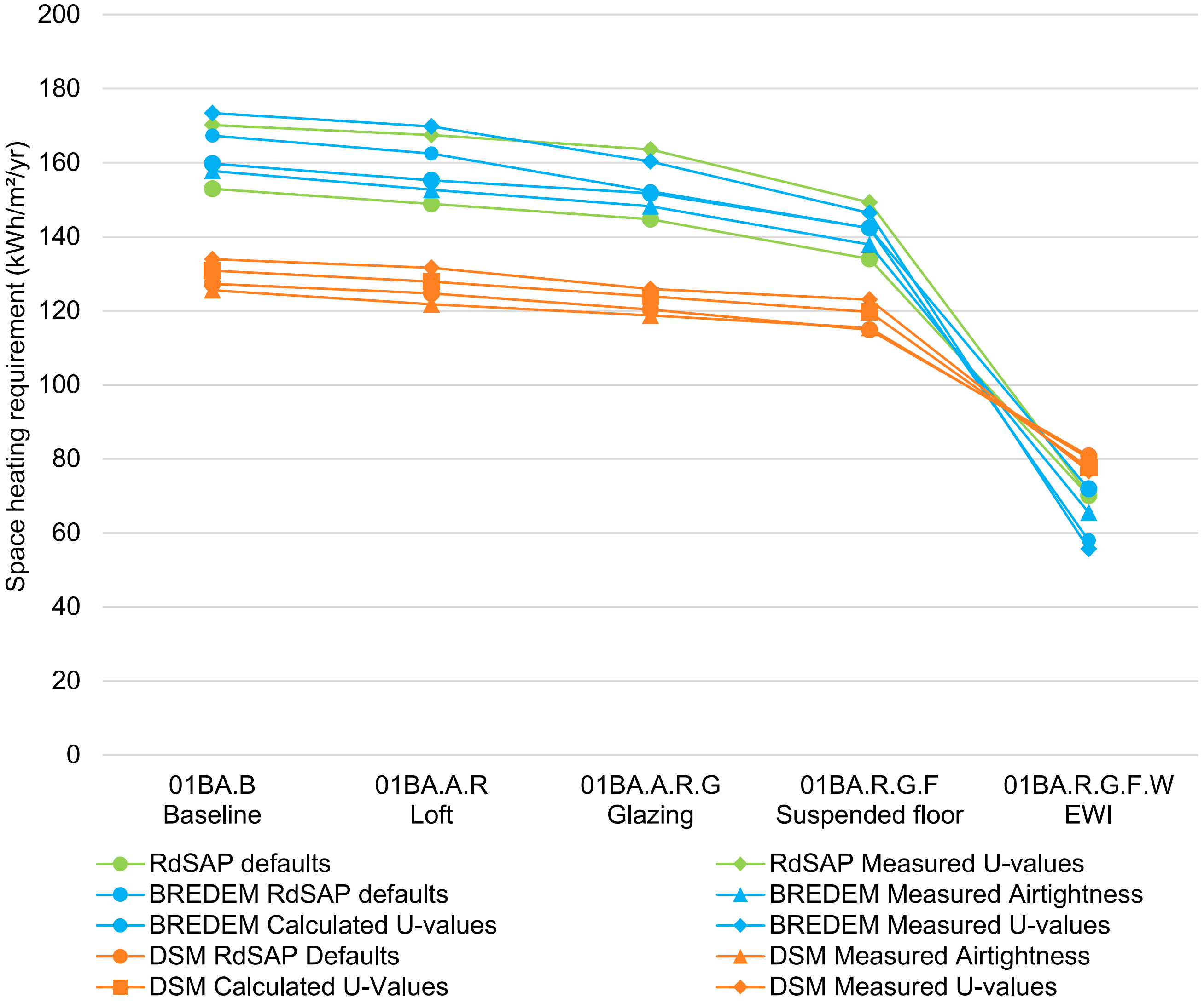


Figure 3-28 Predicted cumulative reduction in annual space heating demand

3.5.3 Impact of retrofits on CO_2 emissions

Space heating homes is responsible for around 15 % of the UK's CO_2 emissions [10]. 01BA's CO_2 emissions were predicted to be reduced by between 8 % and 36 % depending on which model and inputs were assumed. The savings achieved by each retrofit are shown in Figure 3-29.

- The retrofits have reduced the CO_2 emissions of the home by between 29 % and 46 % depending on which model and assumptions are used.
- Almost all the CO_2 savings are predicted to be achieved by the external wall retrofit in all of the models.
- The steady-state models predict greater overall CO_2 emissions than the DSM models. This is due to the fact that the baseline CO_2 emissions attributable to these models is much higher in the first place.
- The steady-state models predict substantially more savings from the external walls and the ground floor retrofit than the DSM models.
- The models with measured airtightness and calculated or measured U-values tend to show greater savings, since the defaults used in RdSAP assumed a better performing house than was found.

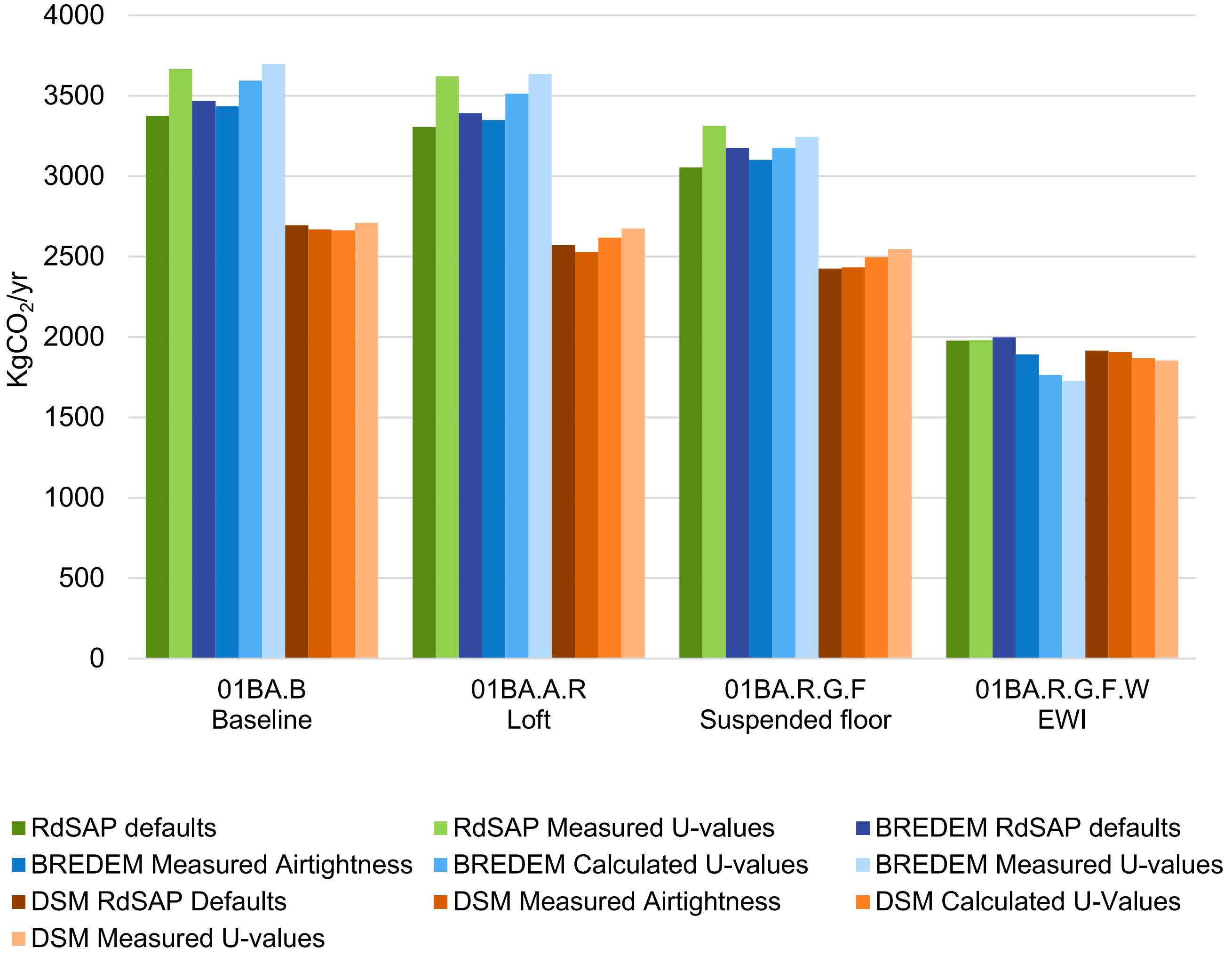


Figure 3-29 Annual CO_2 emission after each individual retrofit

3.5.4 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 DEEP Report 2.01 Methods, and are summarised here:

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

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

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

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

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

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

Weather
Due to the temporal resolution and variability of weather, it is not possible to match to the BREDEM inputs in the same way as the internal gains. The weather file used in the DSM was selected due to the close similarities between monthly average external temperature values (CIBSE Test Reference Year file for Leeds [11]) as discussed in the DEEP Methods 2.01 Report.

Differences specific to 01BA
For the 01BA baseline scenario, using measured infiltration rate and U-values, BREDEM predicts a space heating demand that is 5,005 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 the calculate the HTC. Using

an unrestricted version of 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 8,195 kWh, compared with the DSM estimate of 7,083 kWh, meaning that BREDEM predicts a demand that is greater by 1,112 kWh. The BREDEM calculations can be further normalised by using the DSM volume of conditioned space (6.89 m^3 less in the DSM model). Following this final adjustment, the BREDEM estimate is 799 kWh higher than the DSM output. In the case of 01BA, the DSM included solar heat gains that are 546 kWh greater than in BREDEM.

The largest area of exposed envelope is the gable wall which faces towards the south-east. The visualisations presented in Figure 3-30 illustrate the external surface temperatures on indicative days when there are low, medium, and high amounts of solar irradiation. This also plays a role in the forecast overheating, as discussed in the following section of this report.

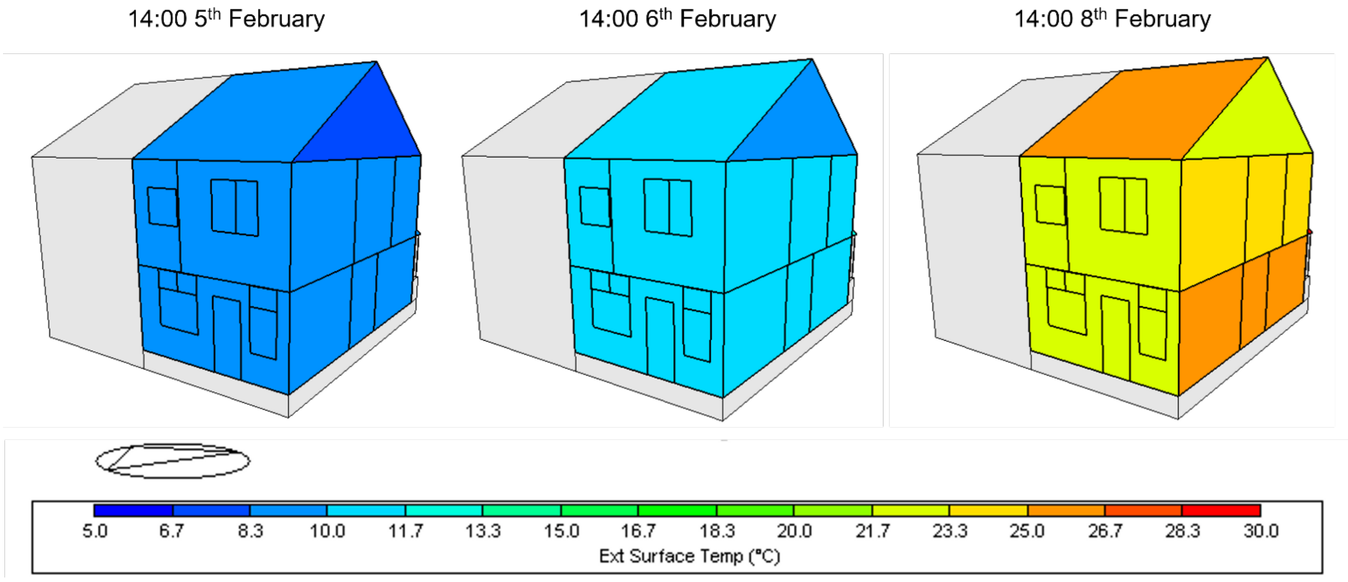


Figure 3-30 Comparison of hourly external surface temperature in DSM model

Predicting EPC band, space heating and carbon reductions summary

The models confirm the measured results that EWI retrofit is by far the most significant retrofit; suggesting that this is the only retrofit that would bring the home up to an EPC C rating if using steady-state models. However, since DSM assumes lower space heating, the dynamic modelling suggests the home may have achieved a C after the loft and glazing retrofits.

Conversely, all models agree that the EWI is the only retrofit that could bring the home below the SHDF target of 90 kWh/m²/year. Similarly, the EWI is predicted to be responsible for 90 % of the estimated of the annual fuel bill savings and up to 80 % of the CO_2 savings.

This indicates that for homes like 01BA, EWI may be the only viable option to achieve current policy ambitions; and that the benefits of retrofits other than wall insulation less certain, and may not meaningfully contribute to achieving national retrofit targets.

3.6 Overheating risk of retrofitting

As part of the overall DEEP project, Loughborough University have carried out parametric analysis of overheating scenarios, using a 10-year weather data file. The overheating analysis in this section is complementary to this work and uses the overheating assessment method from CIBSE TM59, which is cited within the PAS2035 guidance [12].

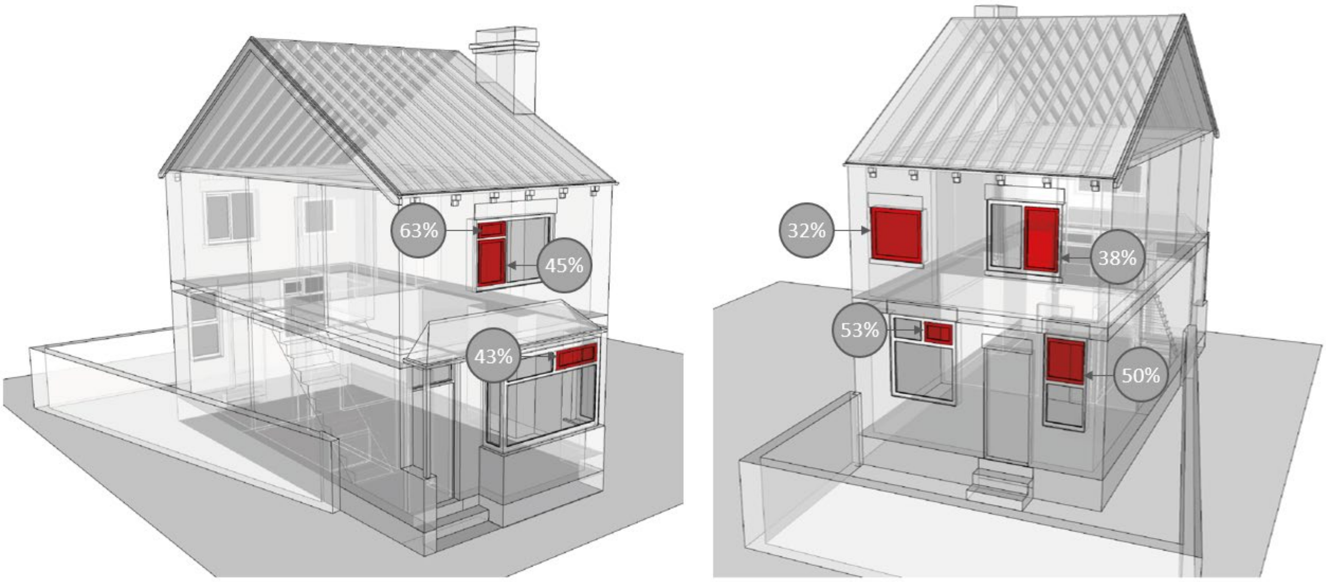
Two metrics are used to assess whether the dwelling will overheat. The first is taken from another CIBSE publication, TM52: The limits of thermal comfort: avoiding overheating in European buildings [13]. The two assessment criteria are defined as follows:

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

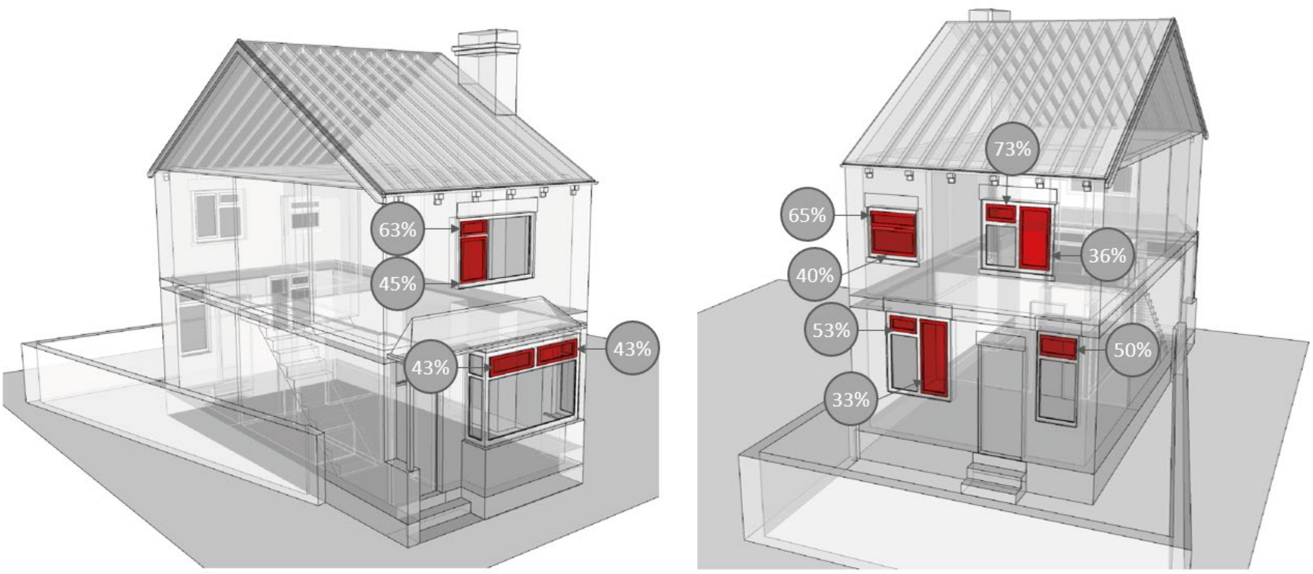
B. For bedrooms only: to guarantee comfort during the sleeping hours the operative temperature in the bedroom from 10 pm to 7 am shall not exceed 26 °C for more than 1 % of annual hours. (Note: 1 % of the annual hours between 22:00 and 07:00 for bedrooms is 32 hours)

Overheating assessment has been carried out at each stage of the retrofit. Following the TM59 guidance, the initial assessment was completed using the CIBSE Design Summer Year 1 (DSY1) file for a 2020s high emission scenario at the 50th percentile, for Leeds in this instance. There are three different DSY files available for the 14 UK regional locations. They use actual year weather data that simulate different heatwave intensities: DSY1 represents a moderately warm summer; DSY2 represents a short, intense warm spell; and DSY3 a longer, less intense warm spell [11].

Assessment was also carried out for future weather scenarios, using the DSY1 files for the 2050s and 2080s high emission scenarios at the 50th percentile. As with all naturally ventilated homes, it is the percentage of openable area in the windows that has the strongest influence on overheating risk. These are illustrated in Figure 3-31.



(a) pre-retrofit



(b) post-retrofit

Figure 3-31 Percentage of opening area for openable windows

Overheating risk in 01BA is predicted as being significant in the pre-retrofit baseline model, with only the north-east facing living room considered to not overheat in the current climate scenario. The living room is also protected from the conducted solar heat gain onto the south-east facing gable wall as the hallway separates this space from the wall.

All other occupied spaces include large sections of the gable wall in their envelope. It is also important to note that the window opening areas in the baseline model are relatively small.

Increasing insulation in the loft space has a very small impact on overheating, reducing it slightly under Criteria A (Figure 3-32) but with no impact on assessment under Criteria B (Figure 3-33).

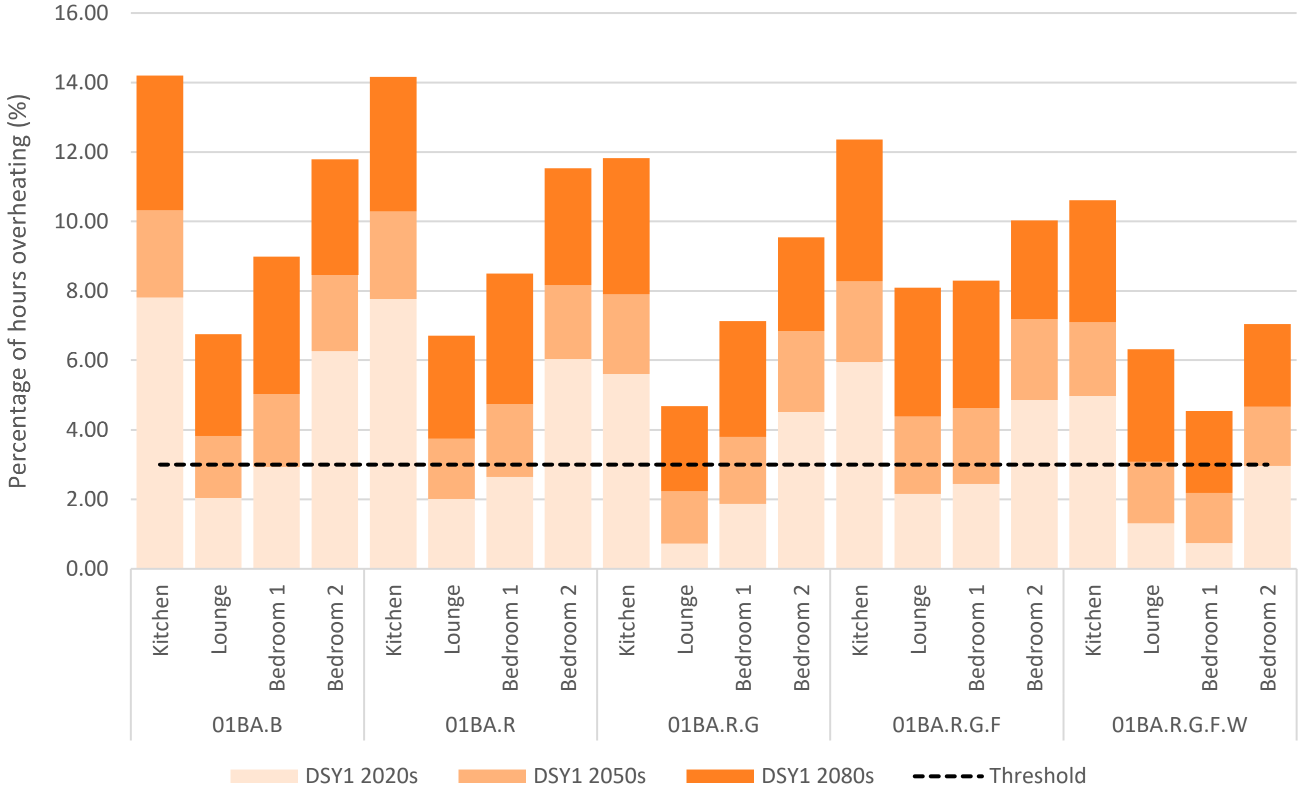


Figure 3-32 Modelled overheating under TM59 Criteria A

As with other DEEP case studies, retrofitted glazing with larger openable areas helps to reduce overheating for both criteria and means that the living room and bedroom 1 are considered to be comfortable in the current climate scenario, although all bedrooms are still considered at risk of overheating during the night when internal doors are closed.

In keeping with other results, the introduction of floor insulation increases the risk of overheating, due to the ground temperatures being cooler than air temperatures during hotter periods.

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EWI again leads to a reduction of overheating risk, which is amplified due to the large south-east facing gable wall; the EWI helps to significantly reduce conducted heat and decouples the thermal mass from external heat sources. All models indicate a significant risk of overheating in future climate scenarios so shading devices should be considered as part of future retrofit measures.

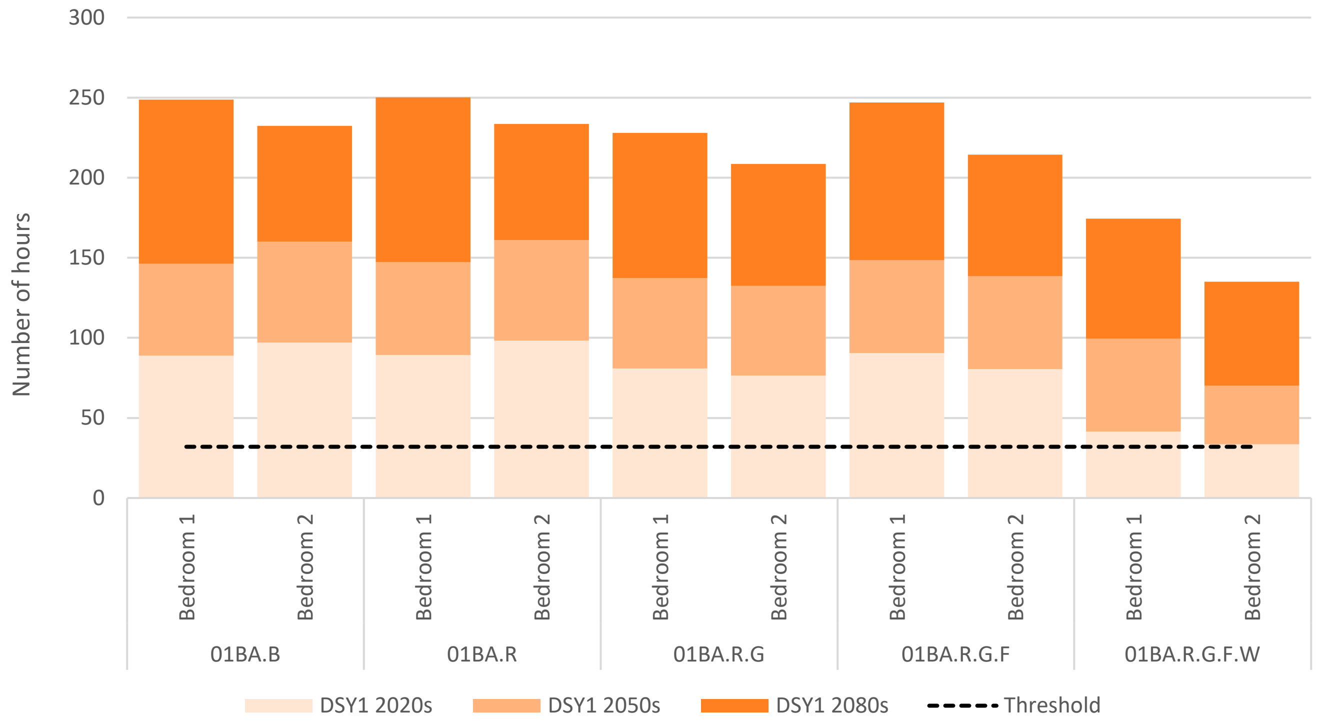

Figure 3-33 Modelled overheating under TM59 Criteria B

Overheating risk of retrofit summary

The uninsulated south-east facing gable wall plays a significant role in the overheating risk modelled for 01BA and the introduction of EWI reduces this considerably. Larger openable areas in the retrofitted windows also help to address overheating risk, although only to acceptable levels in the living room and one bedroom under Criteria A.

All spaces are considered to be at risk of overheating under the 2050 and 2080 climate scenarios, indicating that other mitigation measures will be required for the dwelling to be comfortable during future heatwaves

3.7 Retrofit surface condensation risks

Surface temperature measurements were taken in several locations throughout the test house, focusing on sites where thermal bridges and discontinuities of insulation were expected to pose a risk of surface condensation.

T-type thermocouple temperature sensors were placed on the building fabric to investigate how the floor and wall retrofits affected surface condensation risks. These were monitored during the coheating periods for the glazing, ground floor, and wall retrofits. The sensors in the living room were removed to allow retrofit works and subsequently placed back on the building fabric. Due to the nature of the works sensors located in bedroom 1 did not need to be moved between phases.

Temperature factors were used to indicate whether a location is at risk of surface condensation, a temperature factor below the critical temperature factor of 0.75 is considered to be at risk.

Temperature factor (f_{Rsi}) is calculated using the following 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).

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

3.7.1 Living room – external wall to suspended floor junction

Surface temperature sensors were placed on the external wall flanking the bay window in the living room and below the window sill of the bay window. It was anticipated that the introduction of suspended ground floor insulation would induce a thermal bridge at the external wall to suspended ground floor junction, and subsequently the introduction of EWI may also affect thermal bridging at this junction.

A sensor was also placed below the window sill, as it was anticipated that the introduction of EWI would impact the level of thermal bridging around the window to external wall junctions. The positioning of the temperature sensors can be seen in Figure 3-34.

During the window retrofit stage, sensor 3 was not able to provide sufficiently stable readings. This is likely due to air infiltration at this junction. Following the installation of the suspended timber ground floor insulation, the air infiltration at this junction likely reduced, resulting in stable enough conditions to satisfy the averaging method.

Post floor retrofit, the calculated f_{Rsi} of 0.46 indicates that surface condensation may be a risk at the external wall to suspended timber ground floor junction. The installation of the suspended timber ground floor insulation had no effect on the temperature factors calculated for all of the other sensors in the living room.

Figure 3-34 Position of thermocouple sensors in living room. Left: sensors on external wall. Right: sensor below window sill.

The installation of EWI improved the values for f_{Rsi} at all points in the living room. For sensor locations 1, 2 and 4, the values of f_{Rsi} prior to the EWI retrofit were above the critical threshold of 0.75, implying there was no risk of surface condensation formation.

The EWI caused the external wall to suspended timber ground floor junction to increase the f_{Rsi} from 0.46 to 0.56. However, this still represents a risk of condensation formation as shown in Table 3-6.

Table 3-6 Living room temperature factors (red indicates risk of surface condensation)

	1- External wall	2- External wall above skirting board	3- External wall to Floor Jct.	4- Below window sill
	f_{Rsi}	f_{Rsi}	f_{Rsi}	f_{Rsi}
01BA.R.G New windows and doors fitted	0.81 ± 0.05	0.63 ± 0.16	Fail	0.80 ± 0.07
01BA.R.G.F Suspended timber ground floor insulation	0.82 ± 0.09	0.62 ± 0.04	0.46 ± 0.06	0.77 ± 0.06
01BA.R.G.F.W EWI & bay roof insulation	0.92 ± 0.01	0.79 ± 0.05	0.56 ± 0.06	0.85 ± 0.02

3.7.2 Bedroom 1 – External wall to party wall corner

Temperature sensors were installed at the junction between the front external wall and party wall with the neighbour at ground floor level, as shown in Figure 3-35.

Figure 3-35 Bedroom 1 - front wall to party wall junction, surface temperature sensors.

The installation of suspended timber ground floor insulation had no significant effect on the temperature factors in the front bedroom, as these parts of the building fabric were not directly affected by the work. As can be seen in Table 3-7, prior to the EWI retrofit, the external wall and the external wall to party wall junction have values of f_{Rsi} below 0.75, indicating that they are at risk of surface condensation, though the party wall itself does not appear to be at risk. After the installation of the EWI, all of the sensor locations at the junction and on the external wall experienced an uplift in their values of f_{Rsi} to above 0.75, indicating that EWI was effective in removing condensation risk from the external wall and party wall junction. The party wall itself was not significantly affected, although it rose marginally.

Table 3-7 Bedroom 1 - front wall to party wall junction temperature factors (red indicates risk of surface condensation)

	1 Party wall	2 Ext. wall / party wall jct.	3 Ext. wall	4 Ext./party wall jct. below skirting board
	f_{Rsi}	f_{Rsi}	f_{Rsi}	f_{Rsi}
01BA.R.G New windows and doors fitted	0.95 ± 0.01	0.69 ± 0.06	0.73 ± 0.05	Fail
01BA.R.G.F Suspended timber ground floor insulation	0.94 ± 0.03	0.67 ± 0.04	0.71 ± 0.04	0.65 ± 0.09
01BA.R.G.F.W EWI & bay roof insulation	0.96 ± 0.01	0.81 ± 0.04	0.93 ± 0.02	0.80 ± 0.06

3.7.3 Bedroom 1 – external corner

Temperature sensors were placed on the external wall corner junction between the front wall and gable wall of the dwelling, as shown in Figure 3-36.

Figure 3-36 Bedroom 1 - external corner junction surface temperature sensors

Table 3-8 confirms that before EWI was fitted, the front external wall and the corner junction had values of f_{Rsi} below 0.75, indicating that they were at risk of surface condensation. The gable wall had an f_{Rsi} of 0.75 prior to the EWI retrofit, while this may mean it is assessed to not be at risk, it is important to consider that the uncertainty of the value calculated means that the gable wall may still be at risk of surface condensation. Following the installation of the EWI, all of the surface temperature sensors at the external wall junction were uplifted beyond the 0.75 critical temperature factor, suggesting that EWI was successful in removing surface condensation risks on the walls and at the wall junction.

Table 3-8 Bedroom 1 - external corner temperature factors (red indicates risk of surface condensation)

	1 External wall	2 External wall to gable wall	3 External to gable wall below skirting	4 Gable wall
	f_{Rsi}	f_{Rsi}	f_{Rsi}	f_{Rsi}
01BA.R.G New windows and doors fitted	0.69 ± 0.05	0.56 ± 0.09	0.52 ± 0.09	0.75 ± 0.07
01BA.R.G.F Suspended timber ground floor insulation	0.68 ± 0.05	0.57 ± 0.08	0.52 ± 0.08	0.75 ± 0.07
01BA.R.G.F.W EWI & bay roof insulation	0.92 ± 0.02	0.88 ±0.03	0.77 ± 0.04	0.95 ± 0.01

3.7.4 Bedroom 1 – window and ceiling

Surface temperature sensors were placed to investigate condensation risk around the junction between the external wall and the window, and external wall to ceiling junction Figure 3-37.

Figure 3-37 Bedroom 1 window and ceiling surface temperature sensor locations.

These are common locations for thermal bridging risk due to the potential for discontinuities of the insulation layer i.e. between the loft insulation as well as the EWI window reveals. The results of the analysis are contained within Table 3-9.

The results show that the window jamb had a different risk between the glazing and floor retrofits, though it is likely this is due to uncertainty in the measurements, since this junction was not affected by the floor retrofit.

Prior to the fitting of the EWI; the window jamb (1), window frame to wall junction (2), and the wall to ceiling junction (3) had values of f_{Rsi} below 0.75: indicating that these locations were at risk of condensation formation. Following the installation of EWI, these three monitored locations experienced an uplift in the value of f_{Rsi} to above the 0.75 threshold, suggesting that EWI was successful in removing the condensation risk at the window and ceiling junctions.

It is interesting to note, however, that the f_{Rsi} actually fell for the ceiling sensor location 4. The reason for this is not known, however, this drop is not sufficient be a condensation risk.

Table 3-9 Bedroom 1 window and ceiling temperature factors (red indicates risk of surface condensation)

	1 Window jamb	2 External wall window jamb	3 External wall ceiling	4 Ceiling
	f_{Rsi}	f_{Rsi}	f_{Rsi}	f_{Rsi}
01BA.R.G New windows and doors fitted	0.78 ± 0.04	0.72 ± 0.04	0.65 ± 0.06	0.89 ± 0.02
01BA.R.G.F Suspended timber ground floor insulation	0.72 ± 0.03	0.70 ± 0.04	0.65 ± 0.03	0.88 ± 0.03
01BA.R.G.F.W EWI & bay roof insulation	0.88 ± 0.04	0.90 ± 0.02	0.94 ± 0.01	0.78 ± 0.04

Retrofit surface condensation risk summary

The base case ground floor to external wall junction was considered at to be at risk of surface condensation. The suspended timber ground floor insulation did materially impact on risks though did not remove the condensation risk.

EWI has generally increased surface temperatures in the home, and specifically improved the f_{Rsi} of the external walls; as well as the external wall junctions with the party wall, the external corner, and window junctions; eliminating pre-existing risk from these locations.

Additionally, the EWI removed the condensation risk from the intermediate floor to wall junction in the bedroom. Also, although it improves surface temperatures at the ground floor to wall junction, the increase was not sufficient to remove the existing risk.

Further, it was measured as reducing the f_{Rsi} at the wall to ceiling junction, but this was not shown to result in a condensation risk.

The risk assessment here is based on measurements undertaken during quasi-steady-state conditions of the coheating test. Thus, there are some areas of uncertainty including air movement affecting sensors, as well as the accuracy of the sensors themselves.

Additionally, the descriptions of risks are only based on point of measurements, meaning they can only be indicative of general conditions at these locations, rather than providing a comprehensive evaluation of all surface condensation risks in the home. Similarly, caution should be applied if attempting to generalise the results for this one case study to other homes.

3.8 Retrofit costs and fuel bill savings

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

Cost data presented here may not be representative for the national retrofit market; since retrofit tends to be labour intensive there are variations across the country based on regional differences in construction labour markets. The data discussed here originate from a single contractor in the North of England and relates to only one house type and a limited range of retrofit specifications. Decoration costs were excluded from the costs reported here since the landlords were undertaking their own decent homes repairs following the retrofits and would take on some of the decoration work. However, costs associated with decorating were outside the scope of this project; these have been found to represent around 14 % of the cost of IWI [14].

The costs of the 01BA retrofits are outlined in Table 3-10 and Table 3-11. The total retrofit cost was £50,580, with around three quarters of the costs being attributable to the EWI.

Table 3-10 Costs of retrofits

Retrofit	Retrofit activity	Retrofit costs	Additional enabling work required	Enabling work costs
01BA.R Loft replacement	Install new 420 mm mineral wool between and over rafters	£ 2,075	Removal of existing debris and insulation	£ 585
01BA.R.G New glazing and external doors	Remove & replace all windows and external doors	£ 6,800	Plasterwork to 'make good' repairs, additional repairs to existing ventilation in bathroom and damaged brickwork	£ 420
01BA.R.G.F Suspended timber ground floor insulation	Lift & refit floorboards Insulate 175 mm between joists Remove & refit skirting Fit airtight barrier membrane	£ 2,500	New floor needed Disposal of old floorboards and skirting	£ 900
01BA.R.F.W EWI	Scan of Gable wall and installation of EWI Insulate bay window roof	£ 24,000	Removal & replacement of garden wall Temporary security fencing Extra scaffold and materials. Above corbel and DPC insulation Gas safe engineer check External plumbing and electrical works	£ 13,000

There was large amount of enabling costs (a third of the total costs) associated with the EWI retrofit, including the removal and rebuilding of a garden wall (£~5,000) which was adjoining the home's external wall, and extra rental time of scaffolding. There were only marginal other enabling costs, such as additional waste clearing from the loft and additional plaster work around windows, for the other retrofit measures. In total, enabling costs made up 30 % of the overall retrofit costs. This is a substantial amount, in addition to the cost of the retrofits themselves, and has implications for budgeting or economic forecasting for retrofits. However, it should be noted that such costs would have been lower if the removal and rebuilding of the garden wall was not required.

Table 3-11 details the costs of the retrofits, three quarters of which were incurred to install the EWI. The system chosen by the landlord was substantially more expensive than alternatives, as it involved scanning the building, and bespoke panels being made off site, which was more time consuming to install and costly to produce than alternatives. It is not known if this system will become cheaper to install than a rendered system as the installers gain more experience.

The ground floor and glazing retrofits were in line with benchmarks, though the loft was higher, since this involved removing the existing insulation and debris in the loft, plus installing a new loft hatch. The EWI system and the associated enabling costs were substantially higher than benchmarks. This indicates that EWI could be expected to be installed much more cheaply if an alternative EWI system is used, and there are fewer site-specific enabling costs.

Also shown is the split between labour and materials costs for each retrofit. As can be seen, there is a large variation in where the costs are incurred. This is important when considering how the future costs of retrofits can be reduced. The material costs of this EWI system and the glazing were the dominant costs for the retrofits, indicating there may be opportunities for cost savings from economies of scale or manufacturing these items more cheaply. The loft and flooring retrofits had a more even split between labour and materials.

Table 3-11 Assessment of cost of retrofit

Retrofit	Labour	Materials	Total cost	% of total	Cost / element area (£/m²)	Benchmark (£/m²) [15]	Cost per W/K reduction
01BA.R	56%	44%	£2,660	5%	£ 75	£ 20 - £ 40	£ 127
01BA.R.G	21%	79%	£7,220	14%	£ 802 per window & door	£300 - £1,000 per window	-
01BA.R.G.F	47%	53%	£3,400	7%	£ 97	£ 95	-
01BA.R.G.F.W	37%	63%	£37,300	74%	£ 519	£ 55 - £180	£ 287
Combined	**36%**	**64%**	**£50,580**				**£ 193**

An attempt has also been made to evaluate the relative costs of the retrofits according to how much they reduced heat losses (HTC). As shown, the loft retrofit, despite having relatively small absolute savings still appears the most cost effective, followed by the EWI, where despite the large costs incurred, substantial HTC reductions were achieved. No significant change in HTC was measured for the glazing and suspended ground floor retrofits, hence it was not possible to provide a cost saving in W/K. The following section discusses how the retrofits affect annual fuel bills.

3.8.1 Predicted fuel bill savings

The impact of the retrofits on household dual fuel bills is shown in Figure 3-38 using the SAP fuel prices of 3p per kWh gas and 13p per kWh electricity. These values do not reflect current fuel prices and are shown only as an illustration.

- Almost all the savings are predicted to be achieved by the EWI retrofit.
- The DSM models predict significantly lower fuel bills than the steady-state models before EWI is installed because the because the space heating demand is lower.
- There is a relatively large variation in the predicted savings that will be achieved by the EWI of between £82 and £245, with the models used for EPCs predicting three times more savings than the DSM since it predicts higher space heat demand. This has implications for finance mechanisms that rely on cost savings to fund retrofits.
- The models suggests that the loft,glazing, and suspended timber ground floor retrofits combined, only marginally reduced bills by between £26 and £73.

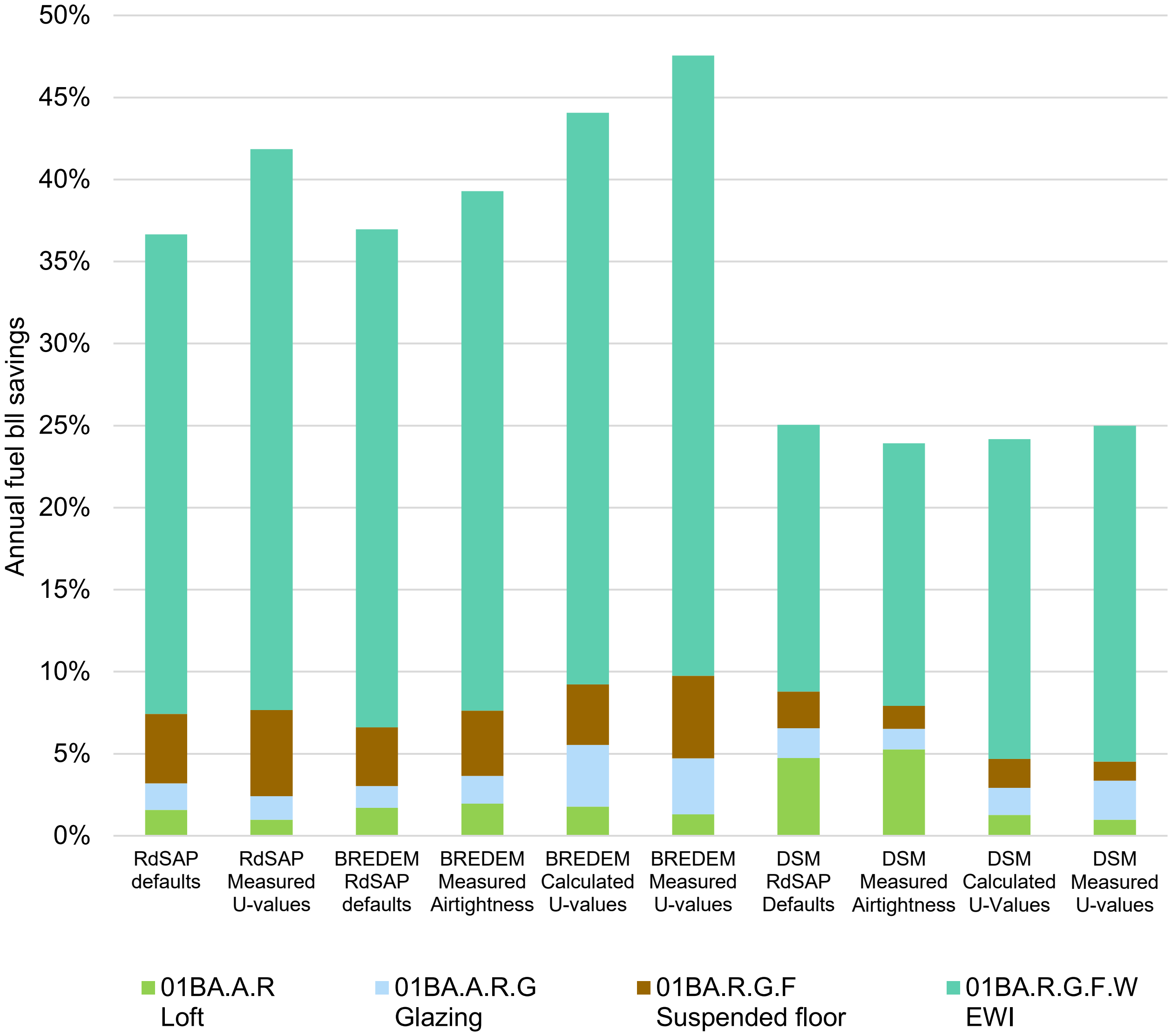

Figure 3-38 Predicted annual fuel bill savings achieved by the retrofits

Retrofit costs summary

The retrofit costs in this case study are substantially higher than they may normally be; in part owing to it being a non-standard, one-off retrofit installation, therefore no economies of scale and so on, could be achieved.

However, there was also a high degree of remedial activity required, especially removing and rebuilding a garden wall, which is important to consider in retrofit policy since the underlying condition of the home tends to be unknown before work commences.

Another reason for the relatively high costs is that the EWI system chosen was more expensive than alternatives. Additionally, there was a need to install XPS in addition to the main EWI system to account for the brick corbels at the eaves. Adaptations made onsite to EWI may be necessary where solid walls have architectural features and this can again add substantial additional costs.

The annual fuel bill reduction estimates suggest that only the EWI would be expected to make a substantial reduction in fuel bills. However, the range of savings predicted are not only relatively high, but more importantly, varied significantly between £82 and £245. This has significant implications for expected paybacks for the retrofits, and any policy of finance mechanisms that rely on fuel bill savings predicted by EPCs.

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

4 Conclusions

Loft insulation
Lofts are regarded as low hanging fruit in terms of retrofit options for the UK housing stock, with the majority considered to be already insulated. Indeed, this case study home had an insulated loft with 150 mm mineral wool insulation. Topping-up the loft insulation in homes has often been disregarded as a retrofit, owing to the law of diminishing returns.

Loft insulation, however, can often be imperfectly installed and is at risk from disruption either when services in the loft have been altered, or for storage of items by householders; as was the case in this case study. Removing the insulation at 01BA and replacing this with 400 mm of mineral wool, and fitting a new, sealed and insulated loft hatch, statistically significantly reduced whole house heat loss by (21 ± 16) W/K ((8 ± 6) %). This also appeared to be the most cost-effective retrofit, despite the need to remove the incumbent loft insulation.

Modelled savings resulting from the loft retrofit were much smaller only 3 to 8 W/K (1 to 3 %), which is only equivalent to between £7 and £31 per annum. Despite this, the DSM model predicted that this would be sufficient to increase the EPC of the home to a band C, though not in the steady-state models. Since modelled savings are lower, this indicates that substantial benefit may have been achieved by the retrofit in reality, as the retrofit is likely to have addressed areas where insulation was previously disrupted or obstructed by storage of items, coupled with having a new loft hatch. These issues are not conventionally considered in energy models, as only the increase in insulation thickness is: i.e. EPCs assume perfect installation quality. This case study indicates that loft installation may not be imperfectly installed or may have been disturbed over time.

More research is needed to understand if similar improvements are achieved in other house and loft types. Overall, although lofts may be considered insulated, if they have disturbed or only ≤150 mm of loft insulation, significant reductions could still be made through loft retrofits.

A rated glazing and external doors
Replacing the old glazing and the wooden external doors in 01BA did not result in a statistically significant change in the overall HTC of the home as the change was (13 ± 17) W/K or (5 ± 7) %, i.e. the change was within the uncertainty of the test. The U-value measurements also had some uncertainty over them since they were only based on centre room values. However, these also indicate a reduction of the order of (12 ± 4) W/K ((5 ± 2) %) was made.

Thermography suggests that installing the new glazing reduced air leakage, though the reduction in infiltration measured by the blower door tests was just within the error margin of the test method. The models predict HTC reductions of between 5 % and 15 % depending on which inputs are used. This equates to cost savings between £7 and £28 per annum, which is not sufficient for the steady-state models to improve the EPC band of the home to a C, as only 1 SAP point was gained. The findings suggest that the retrofit is likely to reduce heat loss, but that it was perhaps not cost-effective and may not be able to achieve substantial improvements to EPCs.

Suspended timber ground floor insulation
Insulating the suspended timber ground floor and installing a partial airtightness membrane appears to not have had a measurable impact on the whole house heat loss; the difference in HTC reported was within the certainty of the test (an increase of (8 ± 18) W/K). The reason for this may be because the suspended timber ground floor was only 15 % of the heat loss area,

and, despite an airtight membrane being installed, there was no change in the airtightness of the home according to the blower door test, suggesting that a partial membrane was not successful. More research is needed into complex heat transfer mechanisms taking place that were circumvented by this measure, and which may explain why no measurable reduction in the HTC was observed from the installation of the insulation.

It may be slightly surprising that no reduction in heat loss was recorded since the centre room HFPs indicated a (78 ± 8) % reduction in U-value, equivalent to a heat loss of (19 ± 2) W/K, though this does not account for edge effects. More research is needed to understand how to measure and model suspended timber ground floor heat losses; and evaluate the benefit of ground floor retrofits in different house types, to evaluate the potential for ground floor insulation as a retrofit measure.

External wall insulation
The EWI retrofit resulted in a substantial reduction in U-values of between 1.55 ± 0.19 W/(m^2K) (77 ± 13 %) and 1.74 ± 0.19 W/(m^2K) (89 ± 13 %), which equates to an overall reduction in heat loss of 138 ± 14 W/K. The scale of the reductions suggested by undertaking the EWI retrofit (including insulating the bay window roof) is comparable to that measured by the coheating test, a reduction in the HTC of 130 ± 10 W/K (55 ± 5 %).

The findings suggest that, should a standalone retrofit be carried out on a property such as this, EWI is the only retrofit capable of achieving EPC and SHDF policy targets. This indicates that investment towards poorly performing solid walled homes like 01BA should be focussed on external or internal wall insulation, as a priority over investing in other retrofit options.

This saving came at a considerable cost of £ 37,300. A large proportion of which was attributable to the significant remediation work required, including removing a garden wall that was attached to the external wall, and installing XPS to decorative brickwork at the roof eaves. Both measures combined accounted for over a third (35 %) of the EWI costs. However, it is important to note that the EWI stage was the only retrofit that saw the EPC improve to a band C in the steady-state models, rising between 4 and 12 SAP points, depending on which models and input assumptions are used.

Bay roof insulation
Although the bay roof was less than 1 % of the dwellings overall heat loss area, it was thought to have by far the highest uninsulated U-value, calculated to be 3.8 W/($m^2 \cdot$K), and therefore likely to pose a surface condensation risk. When insulated, the heat losses were expected to drop from 4 to 0.2 W/K (i.e.,from 2 % of the total HTC to just 0.4 %). This suggests that there may be some benefit in insulating bay window roofs as a standalone retrofit measure even where EWI is not being installed. Bay windows are relatively common to several archetypes in the UK; however, it is not known to what extent these may have insulated roofs. More information on bay window roof compositions and levels of insulation is required to understand how much potential this measure has nationally.

Accuracy of models
When the default values assumed in RdSAP are used, the steady-state model predictions of HTC, which are used when calculating the EPC, match relatively well with the HTC measured by the coheating test.

However, when the default U-values are replaced with measured U-values, the steady-state predicted heat losses drift away from that which was measured. This is because the baseline walls had much higher heat losses than was expected. This suggests that the EPC arrived at an ‘accurate’ heat loss predication in this case study, by chance. Post-EWI retrofit, the models converge around a similar heat loss estimate, which is also much closer to the coheating measured HTC value. This concurs with other DEEP case studies, suggesting that variance in the model predictions is relatively large in uninsulated external solid walled homes, though less problematic when these homes are insulated.

Condensation risk
The EWI retrofit was successful in removing the existing surface condensation risks from the external wall and from the external wall to party wall junction, the external wall corner, the wall to windows junctions, and the wall to intermediate floor junctions. However, neither the suspended timber ground floor insulation, nor the later addition of the EWI, removed the existing surface condensation risk from the external wall to suspended timber ground floor junction. It is not known what the risk would have been if the ground floor had been uninsulated with the EWI installed since the ground floor insulation was insulated first.

Results from different external solid walled homes with different construction details and retrofit specifications are needed to generalise these results. However, it appears that EWI is effective at increasing surface temperatures generally and removing surface condensation risks from most locations. More research is needed to understand suspended timber ground floor to wall junction surface condensation risks under different retrofit scenarios.

Retrofit Costs
The most cost-effective retrofit was supposed to be the loft insulation, even though this required the existing insulation to be removed and disposed of. Although the costs generally are not representative of commercial retrofit projects, it is useful to consider that additional enabling works constituted a significant proportion of the overall cost, accounting for just under 30 % of the total retrofit costs. Including these costs in budgets and forecasts for retrofit is necessary to provide realistic estimates of retrofit costs. The EWI was highly successful in reducing heat loss though even without the enabling costs this was still an expensive retrofit at £ 24,000, though alternative, less innovative EWI systems would be cheaper to install.

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