Department for Energy Security & Net Zero

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DEEP Report 2.11

Case Study 07LT & 09LT

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Prepared for DESNZ by

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Executive summary

07LT and 09LT are two of fourteen case study homes retrofitted in the DEEP project. The case studies have been used to identify the performance of, and risks associated with, retrofitting solid walled homes. The data have also been used to evaluate the accuracy of the modelled predictions of the retrofit performance and risk.

In 07LT and 09LT, the whole house heat loss reductions achieved by the retrofits according to the coheating tests were (42 ± 36) W/K or (12 ± 10)%, and (10 ± 15) W/K or (4 ± 7)%, respectively. Greater savings were measured in 07LT, probably because it is an end-terrace. The presence of a gable wall gives 07LT a greater heat loss area, which could be fitted with insulation during a room-in-roof retrofit.

The energy performance certificate (EPC) model suggests that much higher savings would be achieved in 07LT and 09LT, of 17% and 22%, respectively, mostly due to the simplified room-in-roof assumptions which predict much higher fabric heat losses than measured. When the default assumptions were updated with measured airtightness and U-values, the HTC reduction predictions ranged from 10 % to 12 % and for 09LT from 7 % to 13 %, more in line with that measured. It is likely, therefore, that EPCs overpredict the benefit of room-in-roof retrofits.

Despite both neighbouring homes being EPC band D pre-retrofit, the same retrofit interventions resulted in 07LT remaining band D, while 09LT moved up to band C. This can occur because EPC band ranges are relatively large, and the band ranges may need to be refined to improve the transparency and understanding of the ratings.

Both homes had airtightness levels around 12 ($m^3/m^2 \cdot hr$) @ 50Pa before the retrofits took place. The room-in-roof retrofit in 09LT had the additional benefit of improving the airtightness of the home by around 17 %, yet in 07LT no benefit was measured, since the new access hatches had not yet been fully installed and sealed due to time pressure, highlighting the importance of ensuring airtightness strategies are incorporated into retrofit specifications.

The general airtightness improvements, which included sealing around the floor perimeters and direct penetrations through the walls, had a negligible impact on either home. Although direct air leakage was in some instances addressed, the complex air leakage pathways found in these homes meant that the improvements often resulted in air leakage paths being redirected rather than eliminated. The implication is that homes with complex air leakage pathways may require new, continuous airtightness barriers to be installed if infiltration rates are to be improved.

The rooms-in-roof were found to be at risk of overheating, and the retrofits reduced this risk by reducing solar gains entering the home, though it could not be eliminated.

The costs associated with the retrofits in 07LT and 09LT were significant, at £32,166 and £36,736, respectively. 96% and 90%, respectively, of these costs were incurred by the room-in-roof retrofit alone. Around a third of these costs were for enabling works. For instance, the homes had leaking roofs and undersized roof timbers, and the retrofits required scaffolding, radiators to be removed, additional plastering, cleaning and decorating work and bespoke joinery. The issues faced in this case study provide useful insights, but more data are needed to make broader generalisations for the housing stock. However, a proportion of homes would need a similar scale of enabling works, which makes household and national retrofit policy budgeting problematic and uncertain.

1 Introduction to 07LT and 09LT

Case studies 07LT and 09LT are adjoined end-terrace and mid-terrace 1890s solid walled homes. As a pair, they offered the opportunity to install identical retrofits, consisting of room-in-roof insulation, general airtightness sealing and timber sash window refurbishment. The retrofit work in both houses followed the PAS 2035 retrofit approach.

1.1 DEEP field trial objectives

07LT and 09LT are two of 14 DEEP case studies. DEEP has the research objectives listed in Table 1-1, though not all 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 would improve policy advice.
Unintended consequences	More retrofit scenarios need modelling to confirm condensation, underperformance, air quality and comfort risks.
Cumulative impact	Piecemeal retrofits are common. Clarity is needed on the impact of various 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 the benefits of floor retrofits may increase installation from 0.5 % of Energy Company Obligation (ECO) measures.
Airtightness retrofit	Infiltration undermines retrofits, balancing airtightness and indoor air quality is an unexploited ECO opportunity.
Neighbour risk	We investigate whether whole house or staged retrofits affect the condensation risk for neighbours.

1.2 Case study research questions

Over the course of the three-year project and following advice from the Department for Energy Security and Net Zero (DESNZ), the wider DEEP Steering Group and expert QA panel, the objectives have been refined and the seven discreet research questions listed below have been developed:

1. *What combinations of retrofits are needed to bring solid walled homes up to EPC band C? Do these represent value for money and what challenges do they face?*
2. *To what extent do unintended consequences reduce energy efficiency savings and increase moisture risks when insulating solid walled homes?*
3. *Are methods to reduce the potential risk of unintended consequences when retrofitting solid walled homes effective and appropriate?*
4. *How significant is airtightness in domestic energy efficiency and is improving airtightness a practical, low risk retrofit measure for inclusion in domestic energy efficiency policy?*
5. *How accurate can the 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 quick U-building (QUB) tests as alternatives to the blower door test and the coheating test?*

Data collected from case studies 07LT and 09LT do not answer all these research questions but contribute to the formation of a body of evidence from the DEEP project that can begin to address them.

1.3 Case study house information

Shown in Figure 1-1, 07LT and 09LT are three and four-bedroom houses, respectively. Located in West Yorkshire. Both homes were built before 1890 and the solid external walls are made from 9-inch bricks. Both dwellings were built as mid-terraced homes. However, 05LT was demolished in the 1960s and a new gable wall was added to the side elevation of 07LT, making it an end-terrace. Each house has a basement and chimney stack, although the fireplaces have been sealed.

Both properties are split into two flats, with the lower flat comprising the ground floor accommodation and the upper flat on the first and second floors. However, as both houses are large and have sizable two-storey offshoots, only the thermal envelopes of the main buildings are considered, and the accommodation has been relabelled accordingly. The parts of the dwellings included in this research are outlined in red in Figure 1-3 to Figure 1-5.

Both houses have a similar layout at ground and first floor level, with a hallway and two reception rooms on the ground floor, and a landing, two bedrooms and a kitchen at the first floor level. 07LT has a storeroom accessed from the main staircase which sits above the rear offshoot at first floor level and a sealed sash window in the external wall above the storeroom door. For comparison, the main staircase at 09LT has a stained glass, single glazed un-opening rooflight in the ceiling and is open to a bathroom and WC above the offshoot at first floor level. On the second floor, 07LT has a bedroom and bathroom, each with a window sharing a dormer, in contrast to 09LT, which has two bedrooms, each lit with a single openable rooflight.

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This is a typical construction for the area, though less so nationally. Over four million homes in England and Wales were built before 1890, representing 16 % of England and Wales' housing stock [1]. Four-bed terraced houses account for around 2 % of all homes, thus there may be around 83,000 homes similar to 07LT and 09LT [2], although many may not have basements. While it is unlikely that the results from 07LT and 09LT would be directly transferrable across all terraced properties in general, the features of these case studies do, however, enable a deeper understanding of airtightness, heat loss across party walls and the impact of room-in-roof retrofits.

Figure 1-1 Case study houses (07LT on the left and 09LT on the right)

Figure 1-2 Case study houses site location plan

Floor plans, elevations and sections are shown in Figure 1-3, Figure 1-4 and Figure 1-5, respectively.

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Figure 1-3 House floor plans

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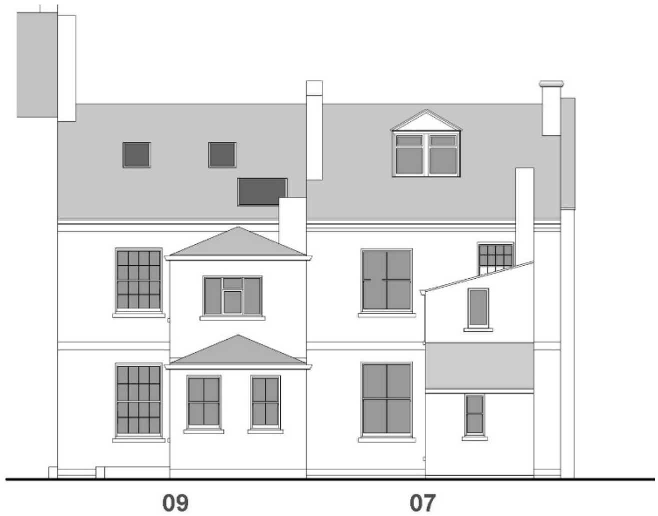
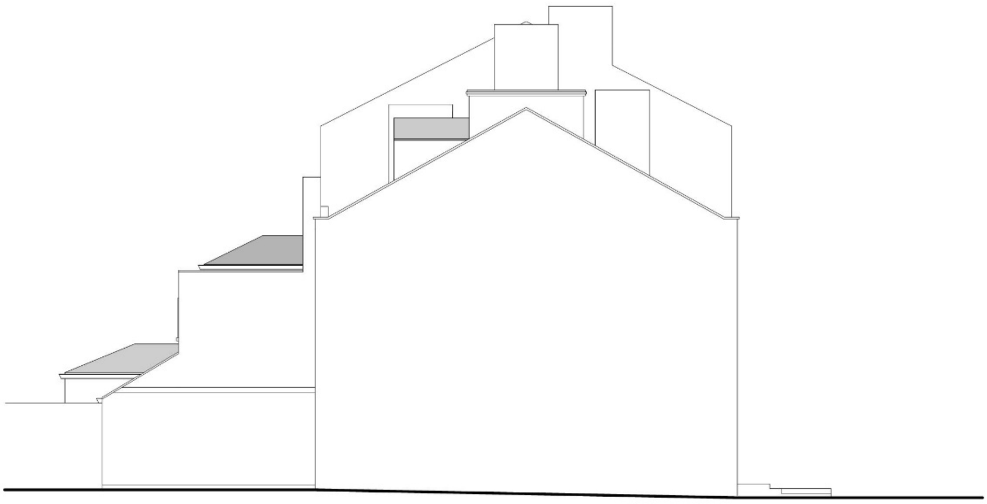
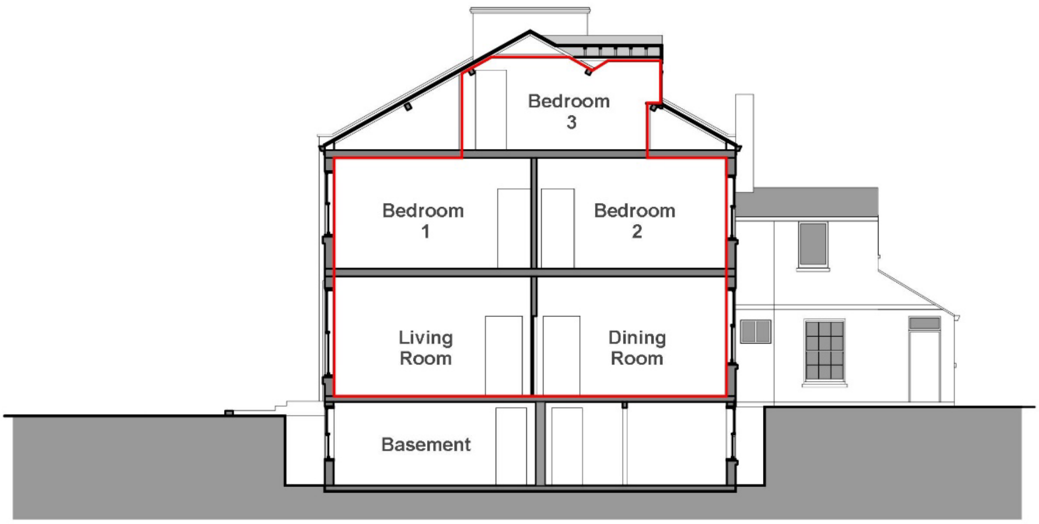
Front (east) elevation



Rear (west) elevation



Side (south) elevation of 07LT



Section through 07LT facing south

Figure 1-4 Front, side and rear elevations plus a sectional elevation of 07LT

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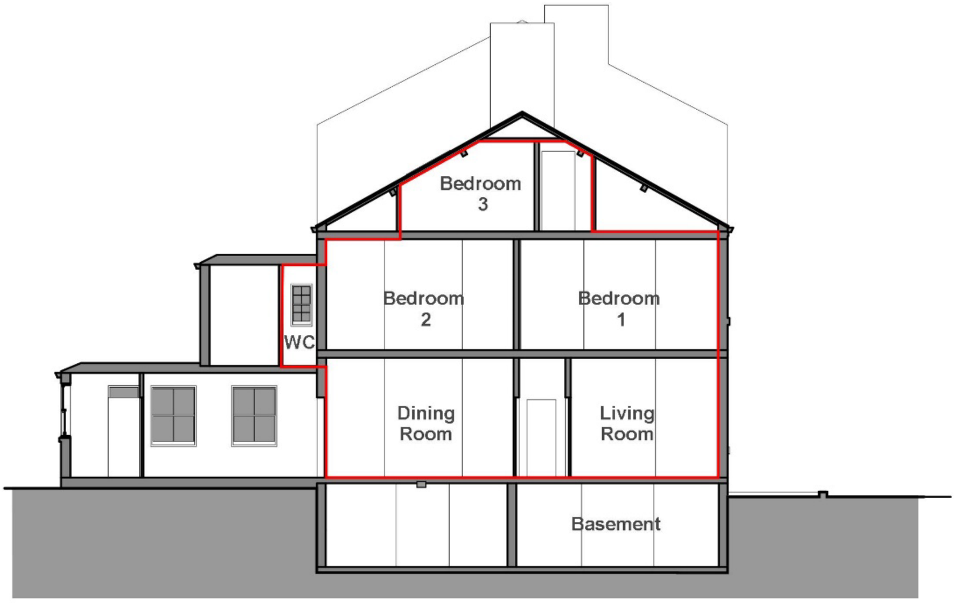
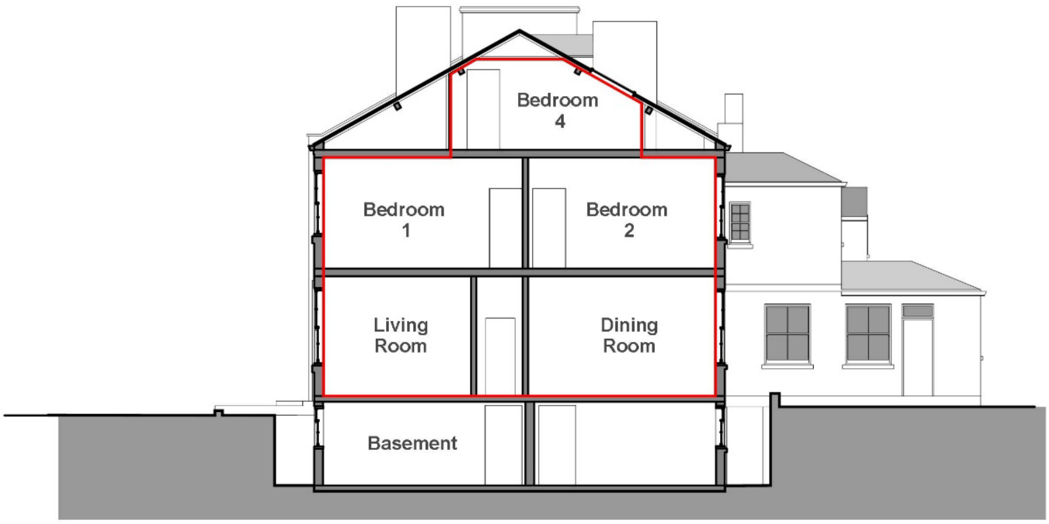


Section through 09LT facing north



Section through 09LT facing south

Figure 1-5 Sections through 09LT

The dimensions of each element in the home are listed in Table 1-2 and were used to allocate heat losses as well as generate thermal models in the reduced data Standard Assessment Procedure (RdSAP), Building Research Establishment Domestic Energy Model (BREDEM) and Dynamic Simulation Modelling (DSM).

Table 1-2 House dimensions

Detail	Measurement (07LT)	Measurement (09LT)
Volume	*451.19 m^3*	*456.86 m^3*
Total floor area	*150.25 m²*	*153.44 m²*
Total heat loss area	*287.60 m²*	*204.55 m²*
Ground floor	59.87 m²	60.08 m²
Gable external wall	76.26 m²	N/A
External walls (front and rear)	48.02 m²	47.45 m²
Windows	15.02 m²	15.37 m²
Door	2.53 m²	2.53 m²
Sloping roof	16.12 m²	15.88 m²
Ceiling to loft void	11.71 m²	15.13 m²
Dormer roof	2.74 m²	N/A
Dormer cheek	2.62 m²	N/A
Stud wall	21.30 m²	20.15 m²
Ceiling to eaves void	31.41 m²	27.96 m²
Party wall	99.39 m²	179.82 m²

The construction details are summarised in Table 1-3. A feature to note is the single glazed roof light above the main stair in 09LT, which is framed out in the loft space above and capped off with another roof light in line with the roof tiles. Also, the doors to the offshoot rooms were sealed during testing.

Once the room-in-roof retrofit work started, roof leaks were detected around the staircase wall in both homes, the corridor stud wall at 07LT, and the corner of the Bedroom 4 party wall and the stud wall where the chimney stack comes up in 09LT. This meant roofing repair works had to be carried out in tandem with the retrofit, which added complication to an already challenging retrofit programme.

1.4 Retrofit approach

The retrofit details and U-value targets for each element are listed in Table 1-3.

Table 1-3 Construction and retrofit summary

Detail	Original construction	Retrofit[1]
Airtightness	12.32 $m^3/(h·m^2)$ @ 50Pa (**07LT**) 12.30 $m^3/(h·m^2)$ @ 50Pa (**09LT**)	General sealing of air leakage paths and single-glazed sash windows repairs
Room-in-roof (**07LT**)	a) Gable wall, 825 mm of several layers of brick and mortar, + 10 mm of plaster finish (bathroom) b) Front and rear stud walls, uninsulated c) Dormer cheeks, uninsulated stud wall d) Ceiling to eaves, insulated with 270 mm mineral wool between and above joists e) Ceiling to loft voids, cold roof, insulated with 250 mm mineral wool between and above joists f) Sloped ceiling (front and rear), uninsulated rafters g) Dormer flat ceiling, uninsulated	a) Internal wall insulation (IWI) on existing wall (60 mm wood fibre board @ 0.044 W/(m·K) Target U-value 0.34 $W/(m^2·K)$ b) Insulation to stud wall 60 mm wood fibre @ 0.038 W/(m·K) on top of studs as IWI + 80 mm wood fibre @ 0.038 W/(m·K) between studs Target U-value 0.25 $W/(m^2·K)$ c) Insulation to dormer cheeks 40 mm wood fibre board @ 0.044 W/(m·K) on top of studs as IWI + 40 mm wood fibre board @ 0.044 W/(m·K) between studs Target U-value 0.44 $W/(m^2·K)$ d) Existing mineral wool insulation cleared and re-laid Target U-value 0.14 $W/(m^2·K)$ (no change to the existing estimation) e) Insulation between and above joists 134 mm wood fibre board @ 0.044 W/(m·K) on top of joists + 80 mm wood fibre insulation @ 0.038 W/(m·K) between studs Target U-value 0.19 $W/(m^2·K)$ f) IWI above rafters 30 mm wood fibre board @ 0.044 W/(m·K) + 100 mm wood fibre insulation @ 0.038 W/(m·K) as IWI on rafters Target U-value 0.28 $W/(m^2·K)$ g) Insulation between and above joists 60 mm wood fibre board @ 0.044 W/(m·K) on top of joists + 80 mm wood fibre insulation @ 0.038 W/(m·K) between studs Target U-value 0.29 $W/(m^2·K)$

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

Detail	Original construction	Retrofit[1]
Room-in-roof (**09LT**)	a) Front stud wall, with 75 mm mineral wool between studs	a) Insulation to stud wall 60 mm wood fibre @ 0.038 W/(m·K) on top of studs as IWI + 80 mm wood fibre @ 0.038 W/(m·K) between studs Target U-value 0.25 W/(m²·K)
	b) Rear stud wall, uninsulated	b) Insulation to stud wall 60 mm wood fibre @ 0.038 W/(m·K) on top of studs as IWI + 80 mm wood fibre @ 0.038 W/(m·K) between studs Target U-value 0.25 W/(m²·K)
	c) Ceiling to eaves, lath and plaster ceiling, insulated with 300 mm Mineral wool between and above joists	c) Existing mineral wool insulation cleared and re-laid Target U-value 0.13 W/(m²·K)
	d) Ceiling to loft voids, cold roof, insulated with 250 mm mineral wool between and above joists	d) Insulation between and above joists 140 mm wood fibre board @ 0.044 W/(m·K) on top of joists + 75 mm wood fibre insulation @ 0.038 W/(m·K) between studs Target U-value 0.19 W/(m²·K)
	e) Sloped ceiling (front and rear), uninsulated rafters	e) IWI above rafters (large bedroom) 70 mm wood fibre board @ 0.044 W/(m·K) + 60 mm wood fibre insulation @ 0.038 W/(m·K) as IWI on rafters IWI above rafters (landing) 60 mm wood fibre board @ 0.044 W/(m·K) + 80 mm wood fibre insulation @ 0.038 W/(m·K) as IWI on rafters Insulation above and between rafters (small bedroom) 60 mm wood fibre @ 0.038 W/(m·K) + 80 mm wood fibre insulation @ 0.038 W/(m·K) between rafters Average target U-value 0.28 W/(m²·K)

The sequence of the staged whole house retrofit approach is shown and illustrated in Figure 1-6 and Figure 1-7. Building performance evaluation (BPE) tests, whole house energy modelling and elemental thermal simulations were conducted at each retrofit stage to quantify changes in energy performance and the potential for condensation risk. The specific methodologies for these are described in the DEEP Methods 2.01 Report.

The codes in Table 1-4 are shorthand to identify each retrofit stage to aid the discussion and presentation of results. As the retrofits are cumulative, the codes are combined to explain which stage is being discussed.

Table 1-4 Phased retrofit stages

	Retrofit Stage	Code	Retrofit Dates
1	Baseline	B	October 2021
2	Room-in-roof insulation	R	December 2021
3	Airtightness improvements	A	March 2022

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

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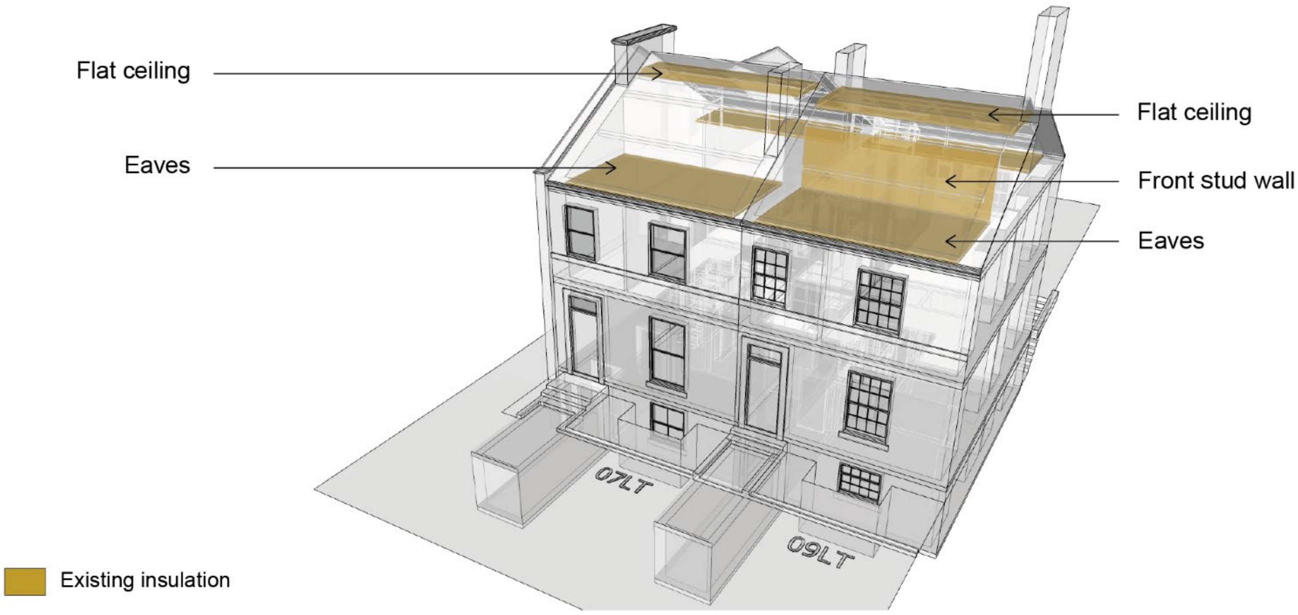

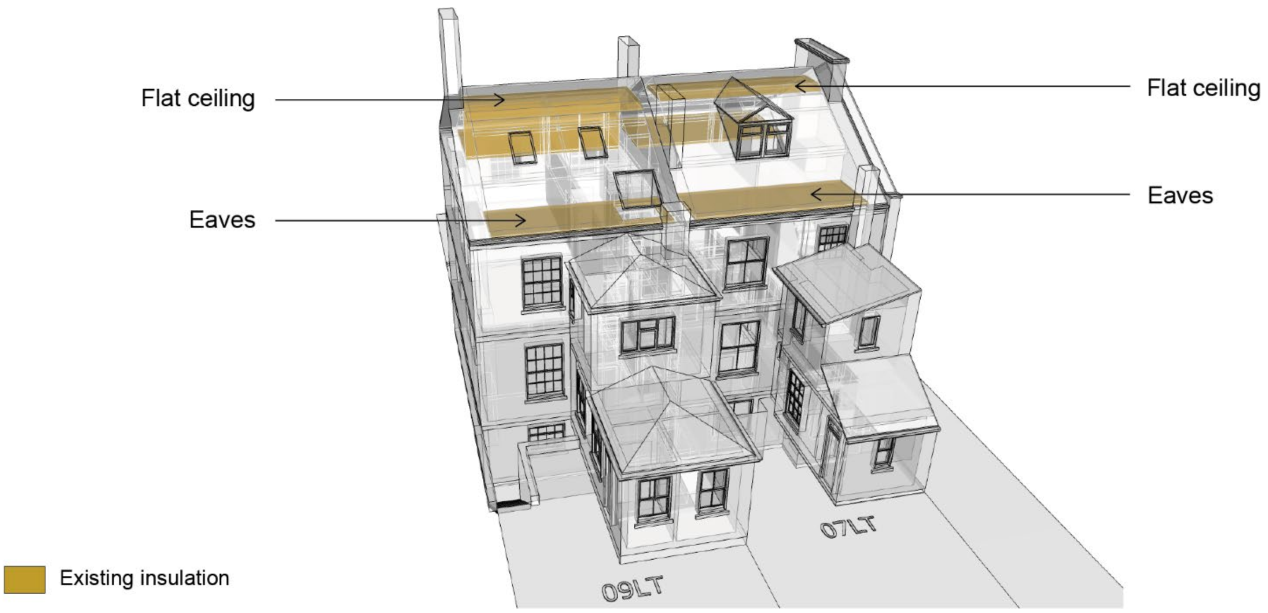

Figure 1-6 Stage 1: Insulation already in the property prior to the retrofits – front and rear (07LT.B and 09LT.B)

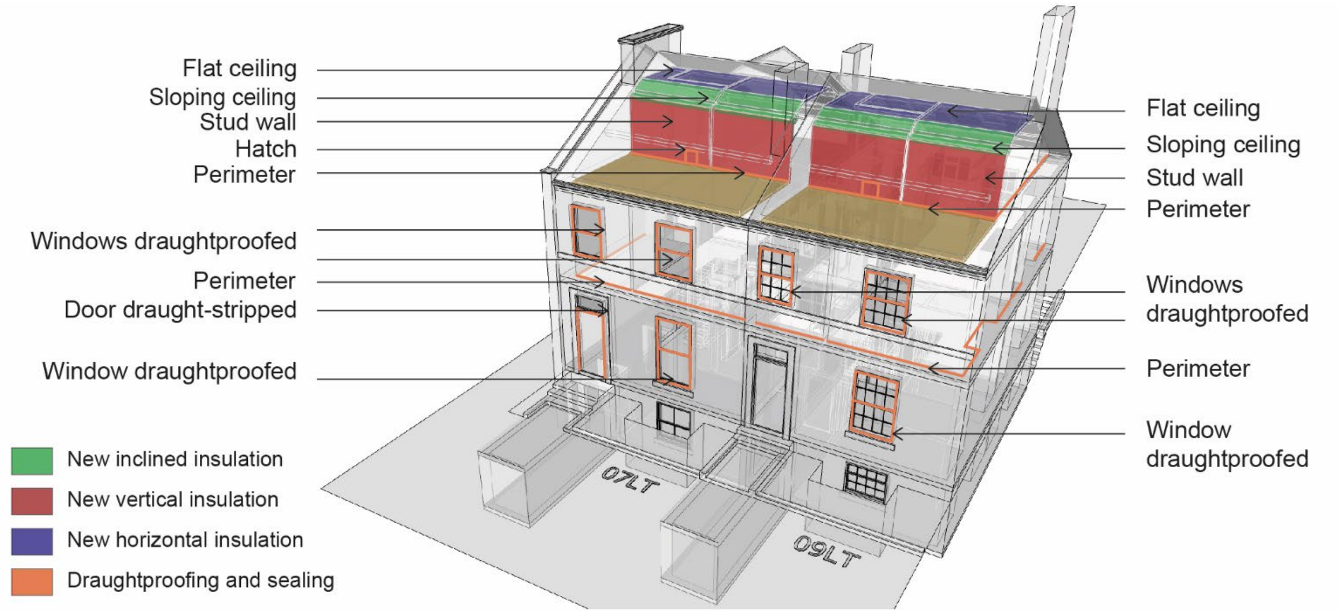

Figure 1-7 Stage 2: Insulation and draughtproofing added – front and rear (07LT.R.A and 09LT.R.A)

Case study and retrofit summary

07LT and 09LT provided an opportunity to investigate the impact of a room-in-roof retrofit on energy savings, and assess the incidental impacts on airtightness and overheating.

The retrofit allowed for assessment of the impact of airtightness improvements in solid walled terraced homes, including refurbishing single glazed sash windows.

2 Fieldwork and modelling methods

Building performance evaluation (BPE) tests and modelling activities were undertaken on 07LT and 09LT at each retrofit stage in accordance with the methodologies listed in the DEEP Methods 2.01 Report. This section outlines the specific implementation of these methods including any variations and additions.

2.1 Environmental and internal conditions data collection

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

2.2 Measured survey

A detailed survey of the buildings was undertaken and a digital version of the houses was developed using SketchUp. This model was used to calculate dimensions for each element and to draw up the plans shown in Figure 1-3. Plans, sections and elevations were directly exported as .dxf (drawing exchange format) files to generate the geometry for use in DSM. The construction makeup of the existing building was also assessed, where access could be gained to observe the material construction.

2.3 Airtightness and thermography

Blower door tests were successfully undertaken at all baseline and retrofit stages. The results were used to identify airtightness changes related to the retrofits and to approximate annual average heat losses attributable to background ventilation (HTC_v). Qualitative thermography under depressurisation was undertaken, and additional thermography of specific details under normal conditions were used to identify changes between each retrofit stage. Pulse air tests and CO_2 tracer gas tests were used during the testing programme to compare with the blower door tests results.

2.4 Heat flux density measurement and U-values

36 Hukseflux HFP01 heat flux plates (HFPs) were installed on various elements in 07LT, and 41 were installed in 09LT. These were used to measure the U-values of fabric elements, quantify improvements in U-values achieved by the fabric upgrades and quantify party wall heat loss experienced during the coheating test. The HFP locations are listed in Table 2-2 and, for context, visualised in Figure 2-1 and Figure 2-2. Thermography was undertaken to identify the most representative HFP location for each fabric element and, where possible, multiple locations for each element were measured.

Heat flux data from individual HFPs, along with internal and external temperature recordings, were used to generate in-situ U-values for each element. Where more than one HFP was located on a single element, an average of the values was used to obtain a single U-value for the element. Where HFPs were placed on inhomogeneous elements, weighting was applied based upon the proportion of each across the element measured.

The in-situ U-values were used to calibrate energy and thermal models, to estimate the heat loss due to the plane elements of the building fabric (HTC_f), and to compare with the whole house HTC and disaggregation techniques. It is important to realise that the in-situ U-values were based on a very limited set of measurements, excluding non-repeating and point thermal bridges, so are not necessarily representative of the performance of the element in practice. This has implications for the results obtained using the disaggregated approach and, more importantly, the results of the modelling where in-situ measurements were used as input data.

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

While the BRE calculator has the capacity to calculate the U-value of windows, in these case studies the necessary manufacturer details of the existing windows were not available due to the age of the dwellings. These included the glazing U-value, the frame U-value and internal construction to estimate the linear Ψ-value. The U-values for the windows had to be assumed and this is therefore an area of uncertainty in the energy model inputs.

Table 2-1 HFP locations (07LT)

HFP	Element	Room
AH01	Dormer ceiling	Bedroom 3
AH02	Dormer cheek	Bedroom 3
AH03	Rear sloped ceiling	Bedroom 3
AH04	Knee wall	Bedroom 3
AH05	Party wall	Bedroom 3
AH06	Party wall	Bedroom 3
AH07	Flat ceiling	Bedroom 3
AH08	Loft hatch	Bedroom 3
AH09	Stud wall	Bedroom 3
AH10	Front sloped ceiling	Bedroom 3
AH11	Stud wall	Corridor (room-in-roof)
AH12	Dormer window	Bathroom
AH13	Gable wall	Bathroom

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HFP	Element	Room
AH14	Gable wall	Landing
AH15	Gable wall	Bathroom
AH16	Rear sloped ceiling	Bathroom
A1	Front external wall	Living room
A2	Gable wall	Corridor (ground floor)
A3	Party wall	Living room
A4	Chimney breast	Living room
A5	Floor	Living room
B1	Gable wall	Corridor (ground floor)
B2	Rear external wall	Dining room
B3	Party wall	Dining room
B4	Chimney breast	Dining room
B5	Floor	Dining room
T1	Window	Bedroom 2
T2	Rear external wall	Bedroom 2
T3	Party wall	Bedroom 2
T4	Chimney breast	Bedroom 2
T5	Ceiling	Bedroom 2
N1	Front external wall	Bedroom 1
N2	Chimney breast	Bedroom 1
N3	Party wall	Bedroom 1
N4	Gable wall	Corridor (first floor)
N5	Ceiling	Bedroom 1

Table 2-2 HFP locations (09LT)

HFP	Element	Room
L1	Rear external wall	Dining room
L2	Chimney B	Dining room
L3	Chimney B	Dining room
L4	Party wall to 11LT	Dining room
L5	Floor	Dining room
I1	Party wall to 07LT	Living room
I2	Party wall to 07LT	Living room
I3	Floor	Living room
I4	Chimney	Living room
I5	Party wall to 11LT	Living room
J1	Ceiling	Bedroom 2
J2	Rear window	Bedroom 2
J3	Rear external wall	Bedroom 2
J4	Party wall to 11LT	Bedroom 2
J5	Chimney B	Bedroom 2
G1	Ceiling	Bedroom 1
G2	Front external wall	Bedroom 1
G3	Party wall to 11LT	Bedroom 1
G4	Chimney B	Bedroom 1
G5	Party wall to 07LT	Corridor (first floor)
AC1	Small knee wall	Bedroom 3
AC2	Small knee wall	Bedroom 3
AC3	Rear sloped ceiling	Bedroom 3
AC4	Rear sloped ceiling	Bedroom 3
AC5	Rear sloped ceiling	Bedroom 3
AC6	Ceiling	Bedroom 3
AC7	Ceiling	Bedroom 3

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HFP	Element	Room
AC8	Party wall to 11LT	Bedroom 3
AC9	Party wall to 11LT	Bedroom 3
AC10	Big knee wall	Corridor (room-in-roof)
AC11	Big knee wall	Corridor (room-in-roof)
AC12	Party wall to 07LT	Corridor (room-in-roof)
AC13	Ceiling	Bedroom 4
AC14	Sloped ceiling	Bedroom 4
AC15	Small knee wall	Bedroom 4
AC16	Small knee wall	Bedroom 4
O1	Small knee wall (by AC1)	Bedroom 3
O2	Sloped ceiling (by AC3)	Bedroom 3
O3	Sloped ceiling	Bedroom 3
O4	Ceiling	Bedroom 3
O5	Big knee wall	Bedroom 3

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

Similarly, where areas of thermal bridging were expected, such as near corners, heat flux density measurements were taken to provide context to the whole fabric heat loss and inform the weighted average calculations.

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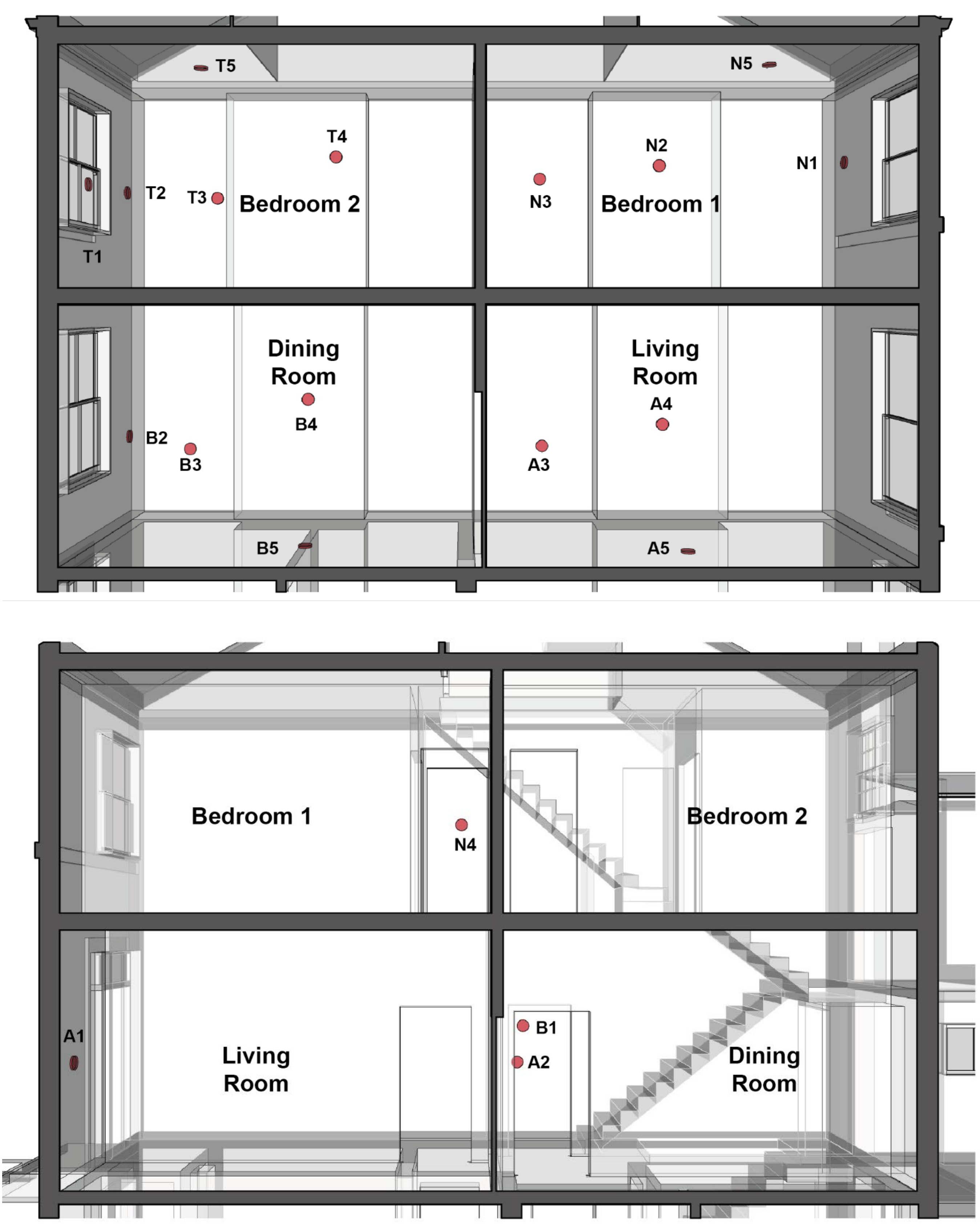


Figure 2-1 Heat flux plate locations for 07LT at ground and first floor level

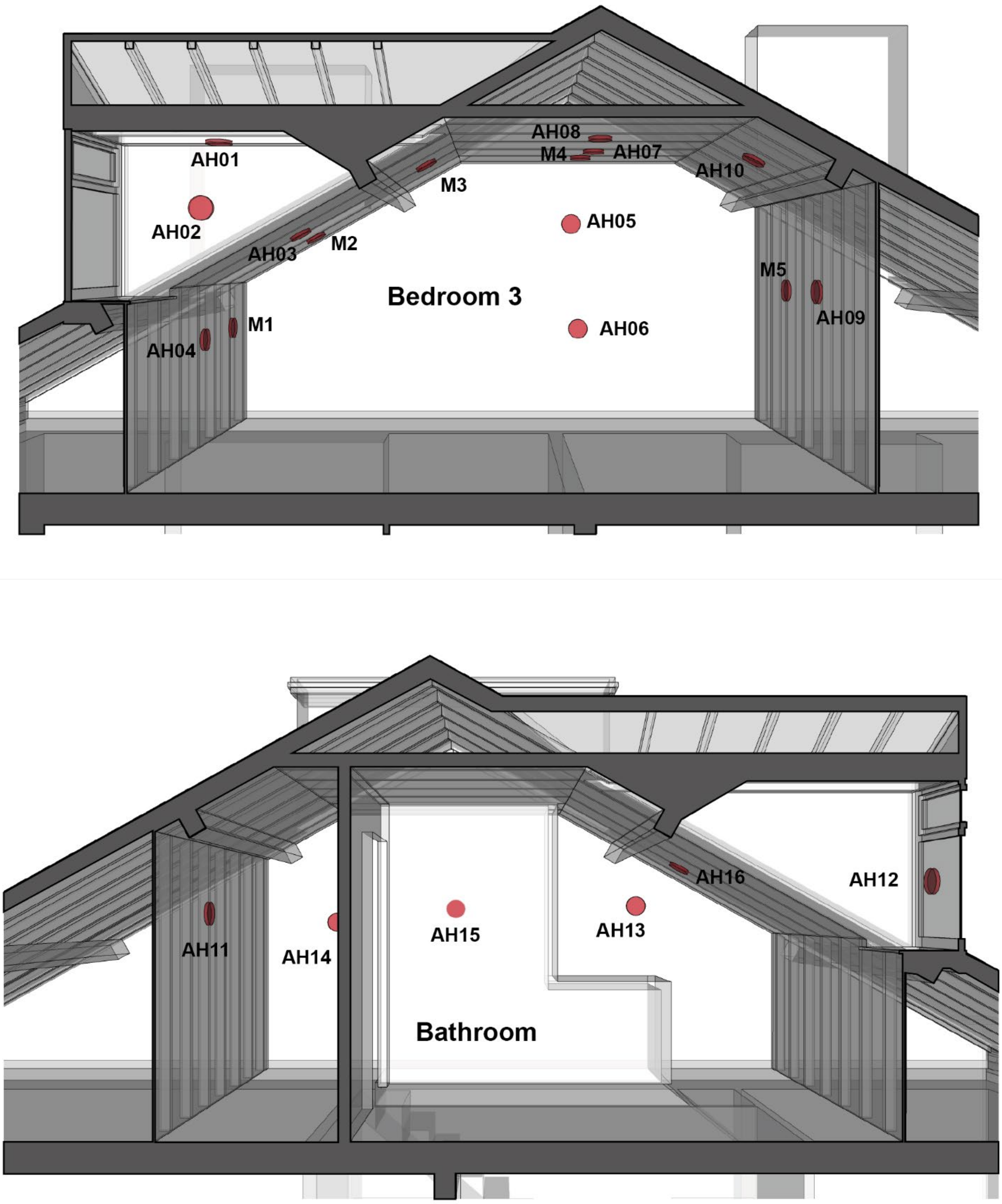


Figure 2-2 Heat flux plate locations for 07LT across the room-in-roof

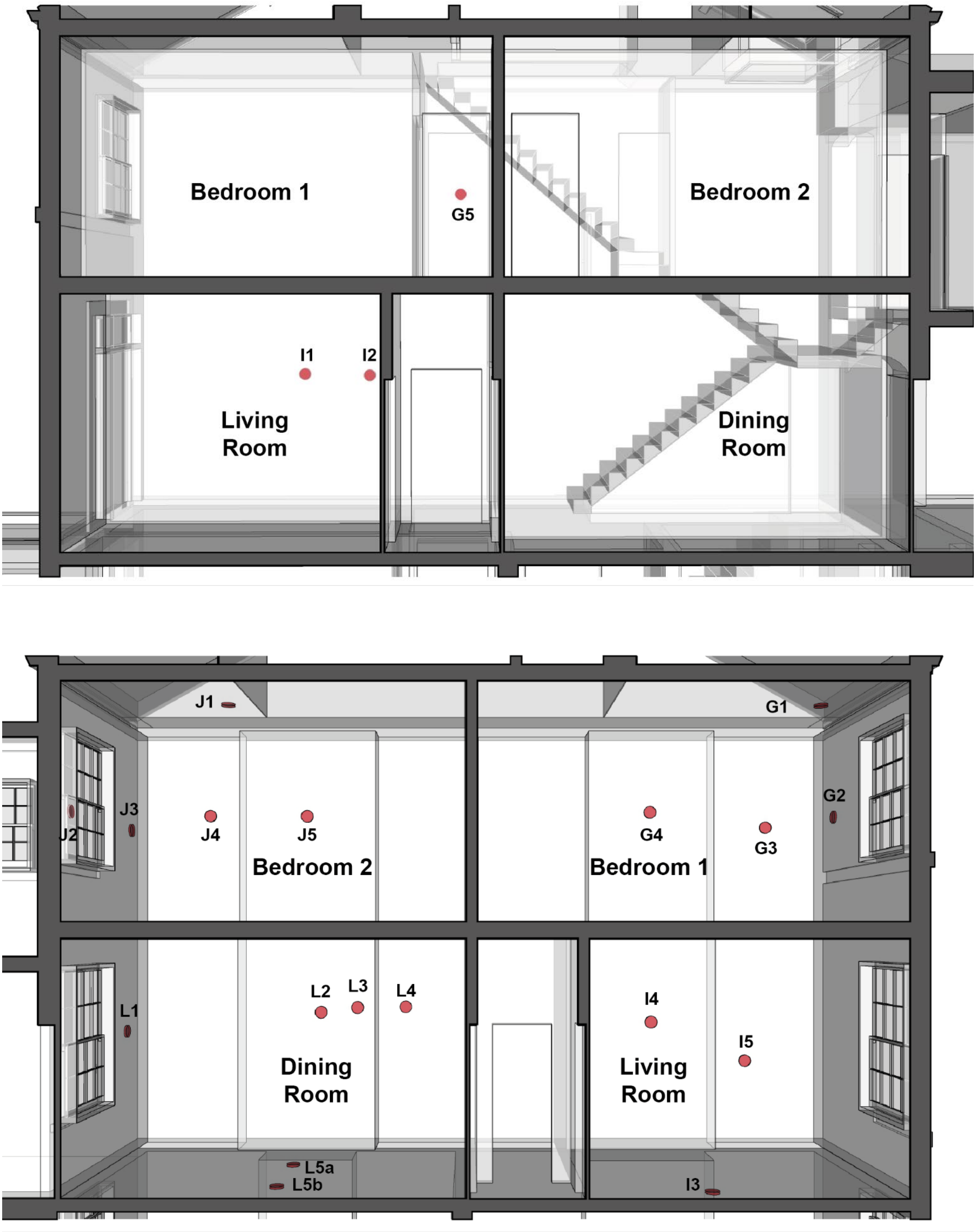
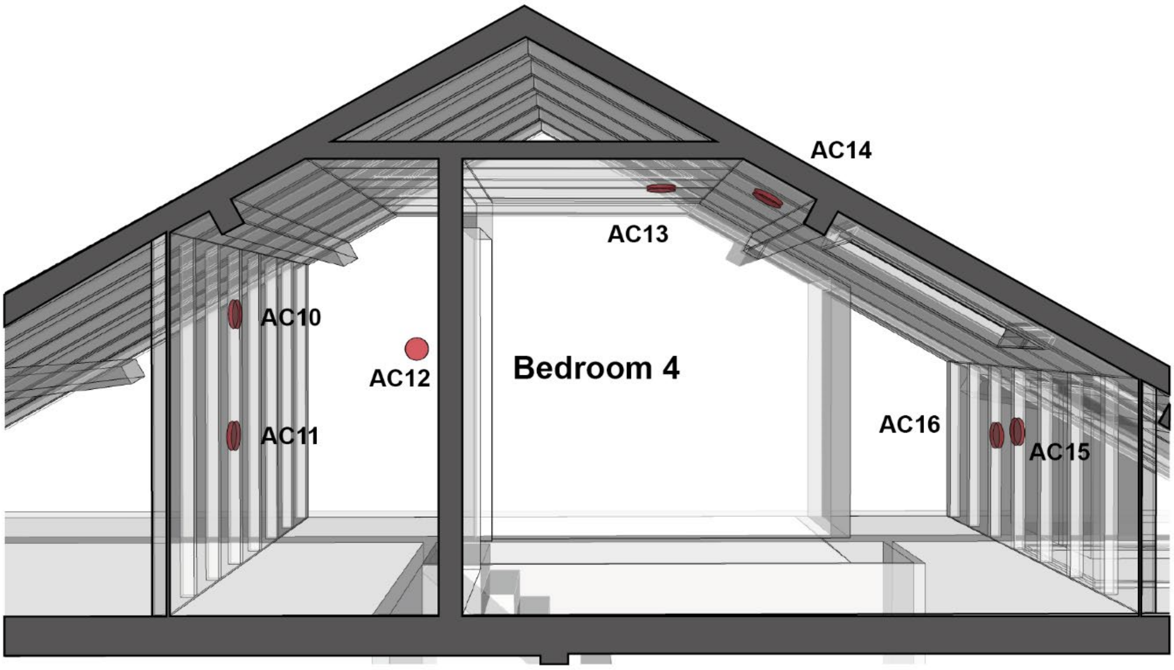


Figure 2-3 Heat flux plate locations for 09LT at ground and first floor level



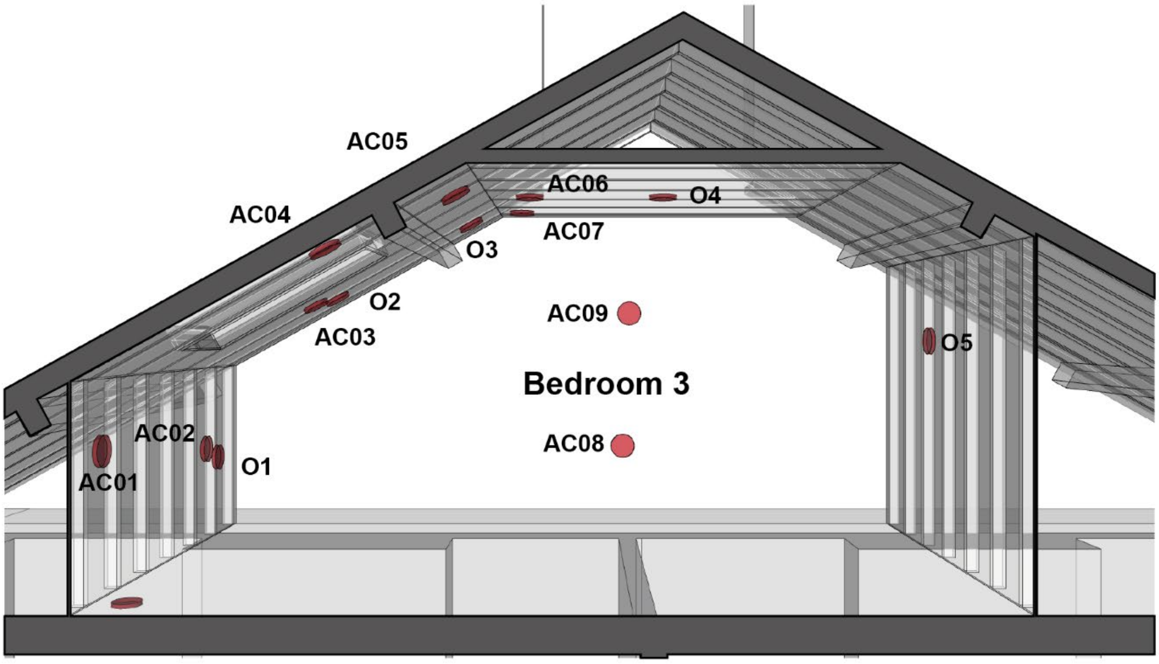


Figure 2-4 Heat flux plate locations for 09LT across the room-in-roof

2.5 Whole house heat transfer coefficient (HTC)

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

2.6 Whole building energy modelling

The modelling methodologies undertaken are explained in detail in the DEEP Methods 2.01 Report. DEEP first uses the steady-state energy model, BREDEM, which generates EPCs for existing homes via RdSAP software. Using RdSAP means that EPC assessors interact with BREDEM using standard conventions and input defaults. DEEP compares how these restrictions affect the HTCs that BRDEM predicts. These are compared with the HTCs predicted by DSM (using DesignBuilder software version 7.0.0.088 [3]) at each retrofit stage. Table 2-3 describes the approach taken to understanding how the predictions change as the default inputs are overridden.

Table 2-3 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 models predict annual energy demand, annual heating cost, carbon dioxide emissions, SAP score and EPC band. The success of the retrofits against these criteria can therefore be evaluated and, along with the retrofit install costs, simple payback periods for each retrofit can be calculated. By learning about the variability of the models and how they compare to measured data in real cases, recommendations can be made for improvements to both the models and the ways they are used. Improving the understanding of modelling uncertainty may lead to more informed retrofit decision making at the 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 tests.
[5] Derived from the BRE calculator.
[6] Derived from HFP measurements.

Case study method summary

A deep dive into the 07LT and 09LT retrofit case study was undertaken, involving coheating tests, blower door tests, and 36 and 41 heat flux density measurements on fabric elements, respectively, taken before and after each retrofit.

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

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

3 Results

This chapter firstly presents the results of the in-situ field trials; airtightness tests, U-values and the whole house heat loss as measured by the coheating test. It then describes how modelled predictions compare with the measured data and how successful five different calibration steps are at improving predicted heat loss, including assessing thermal bridging. The model outputs are discussed in terms of their implications for EPCs, space heating, CO_2 emissions, fuel bills and paybacks. Finally, the potential surface condensation risks posed in the house at each retrofit stage are discussed.

3.1 Airtightness improvements

Airtightness testing was undertaken as described in the DEEP Methods 2.01 Report. Tests were undertaken on both houses at four stages: in 'as found' condition, following the room-in-roof retrofit, following additional airtightness sealing, and following repairs carried out on the single-glazed sash windows. In all the blower door tests, the fans were located in the front doorways of the houses, with the rear extensions of the houses closed off and not included in the airtightness measurements to match the coheating test zoning.

Co-pressurisation tests were undertaken at each stage following the standard blower door tests, where both houses were simultaneously pressurised to approximately 50 Pa and readings taken when the internal/external pressure differentials of the two houses were isobaric to within 1.0 Pa of each other. This removed drivers for air movement between the two test houses, providing an indication of how much of the measured air leakage was inter-dwelling exchange, rather than air exchange with the external environment.

As shown in Figure 3-1, in their original condition both test houses displayed levels of air permeability fairly typical for houses of this age and construction. 07LT had a mean air permeability of 12.32 $m^3/(h\cdot m^2)$ @ 50Pa, and 09LT had 12.30 $m^3/(h\cdot m^2)$ @ 50Pa. With the volumes of the houses being >450 m^3, this suggests that there was a considerable amount of uncontrolled air movement through the properties, well above the limiting value for new build homes, though less than assumed in the RdSAP EPC model.

The amount of benefit that draughtproofing is predicted to have in the EPC models is approximately 3 $m^3/(h\cdot m^2)$ @ 50Pa, yet this retrofit had almost no impact on the measured infiltration in either home. The modelled predictions and measurements, however, may not be comparable, since the EPC draughtproofing assumptions are not intended to relate to the refurbishment of single glazed timber sash windows, which were among the actual measures taken.

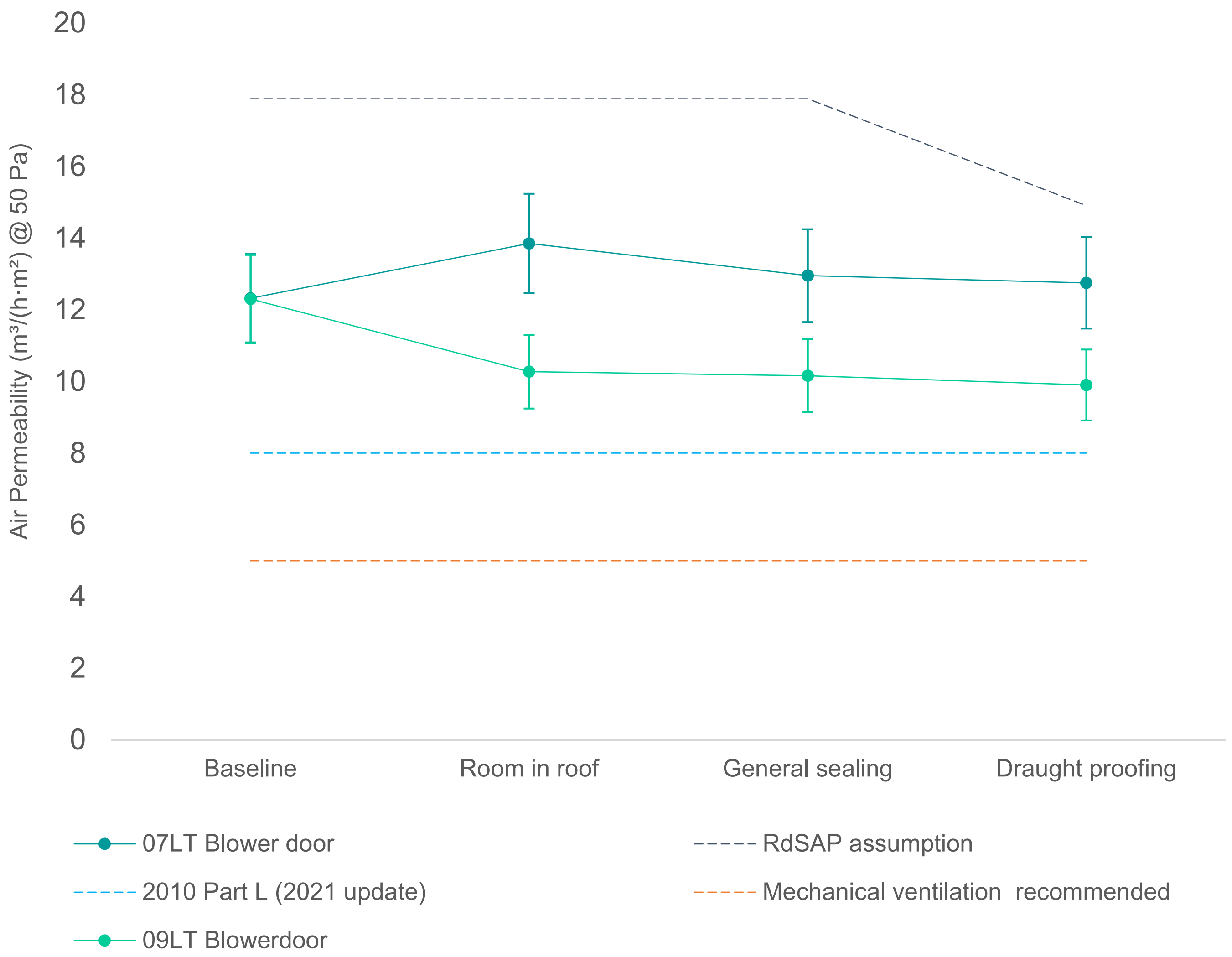


Figure 3-1 Airtightness of case studies

Air leakage paths were detected all around both houses, including both direct air leakage to outside and indirect leakage through interconnected voids within the houses. Some indirect leakage paths were long and complex, with the internal points of air leakage some distance from where it escaped the building envelope. The most significant direct air leakage was detected around doors, windows, fireplaces and access hatches, as illustrated in Figure 3-2 to Figure 3-7.

Leakage at the front doors was not included in the blower door tests as the fans were positioned here for the tests, but even when closed daylight was visible between the doors and frames. The rear annexes were closed off for the pressure tests, but both these doors and the cellar doors were only internal doors. Even though they provided the boundary of the airtightness barrier for the tests, they were not designed to be as airtight as external doors. The windows also performed poorly, particularly the single glazed sash windows throughout the ground and first floors of both houses.

Air leakage was detected around the frames of all windows and doors, with severe air leakage commonplace around the sashes and particularly between the sash meeting rails. Some fireplaces had been blocked up and fitted with vents, and these performed reasonably well. However, the remaining open fireplaces and those which had just been boarded over allowed considerable amounts of airflow through and around them. The hatches to the eaves voids and lofts were not draught-stripped and all allowed air movement around them.

Figure 3-2 Air leakage at the front door of 07LT (moving into the floor void above) and around the first floor door to the rear annex and window above

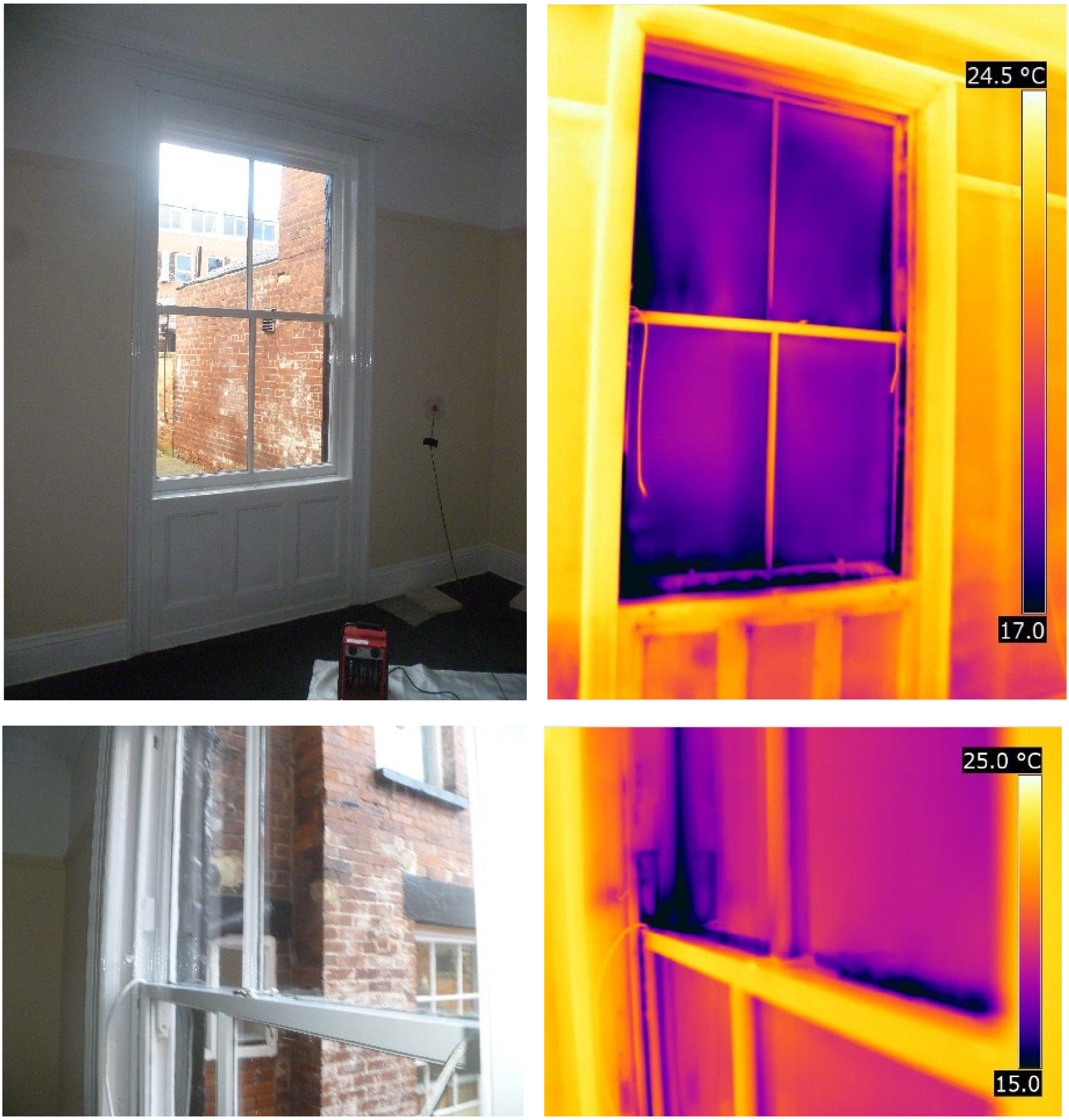


Figure 3-3 Significant air leakage at the single glazed sash windows around, and at the meeting rails between the sashes

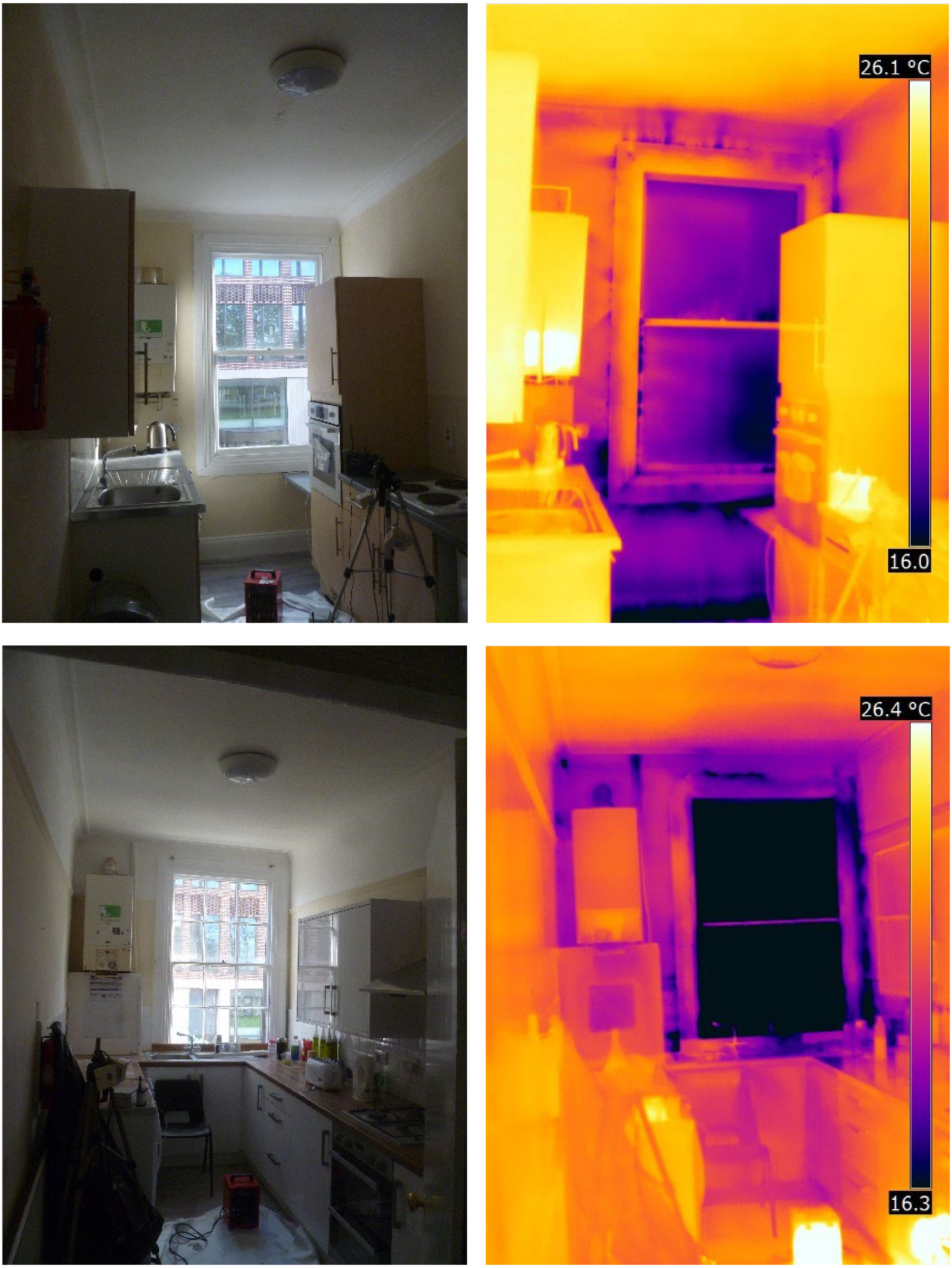


Figure 3-4 Significant air leakage around the kitchen windows in 07LT (top) and 09LT (bottom)

Figure 3-5 Significant air leakage around the window frames in 07LT Bedroom 1 (top) and 09LT Bedroom 2 (bottom)

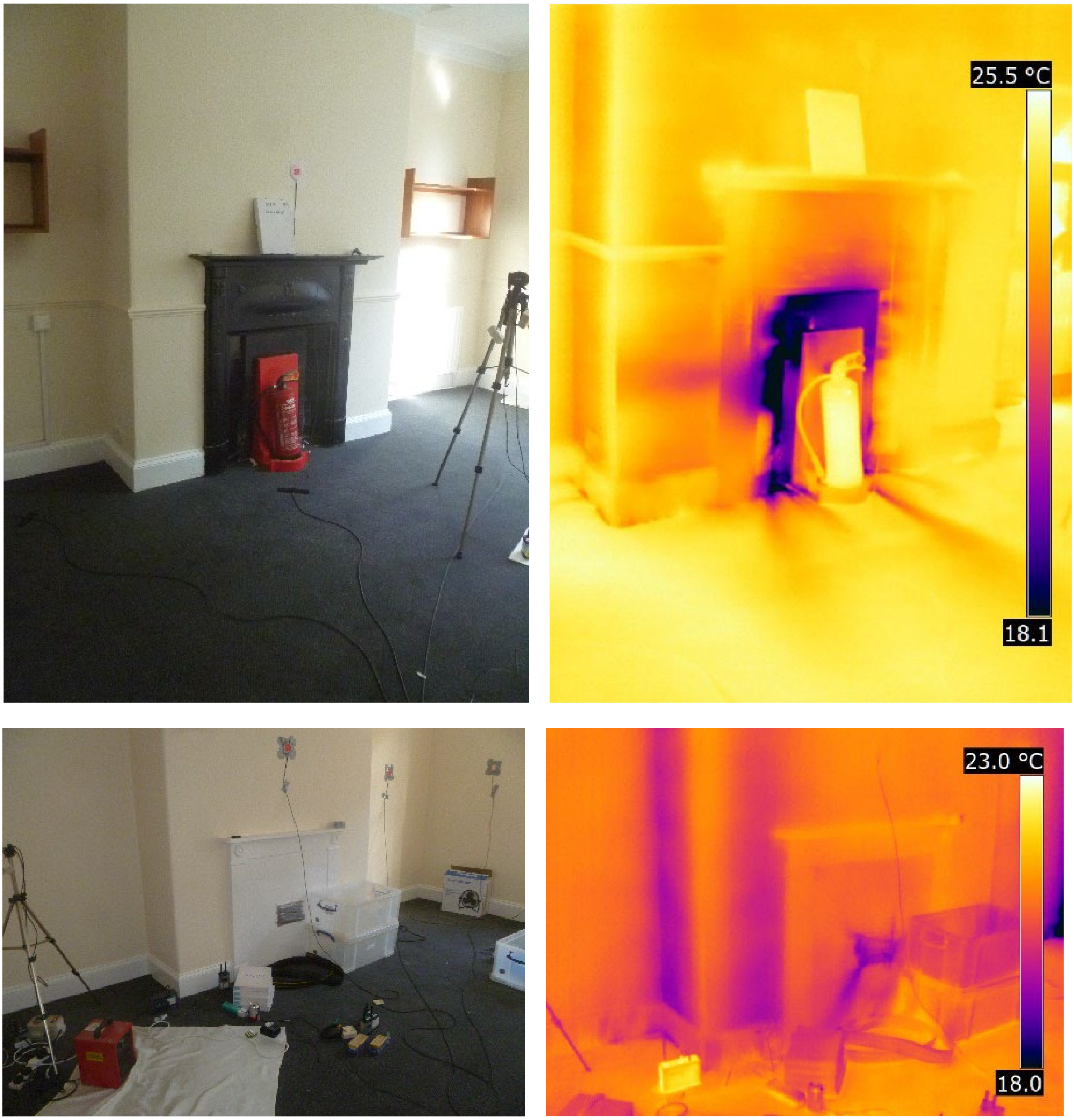


Figure 3-6 Contrasting airtight performance of the fireplaces in Bedroom 1 of 07LT (open) and Bedroom 1 of 09LT (sealed and vented)

Figure 3-7 Air leakage around all loft and eaves void access hatches

2.11 DEEP 07 & 09LT

Under depressurisation, cooler air was observed being drawn up from the cellars through and around the ground floor in both properties. This was observed around all ground floor room perimeters and in some areas through gaps between the floorboards (Figure 3-8).

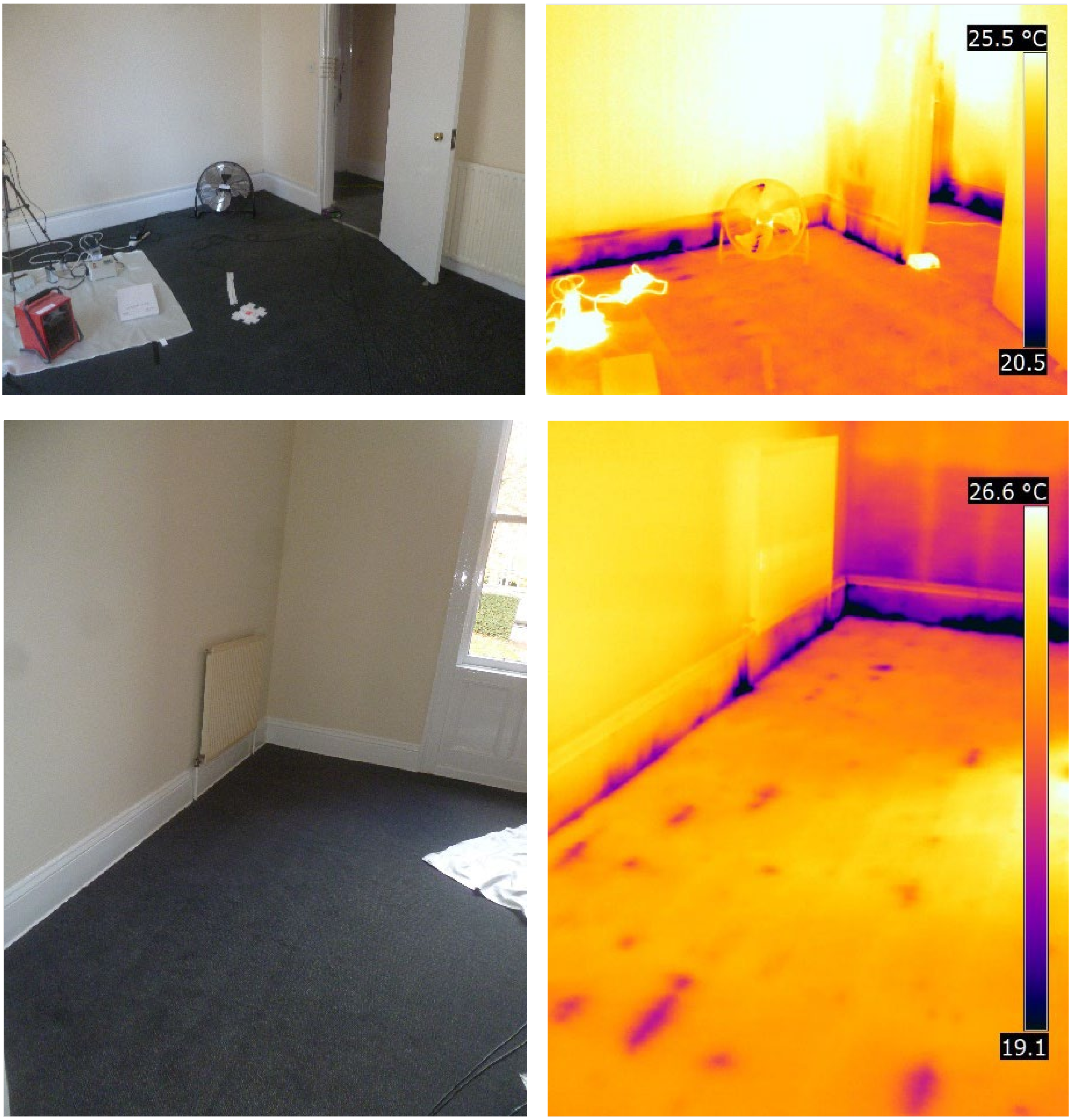


Figure 3-8 Air leakage at the ground floor room perimeters in 09LT (top) and 07LT (bottom) with cold spots on the carpet where air was drawn up from the cellar through gaps between the floorboards

The emerging air was noticeably cooler at the junctions of the ground floor with the front and rear external walls. Figure 3-9 illustrates this, with air emerging at the floor perimeter as cold as the air entering around the window and air coming through areas of uncarpeted floor, suggesting an equally short and direct leakage path.

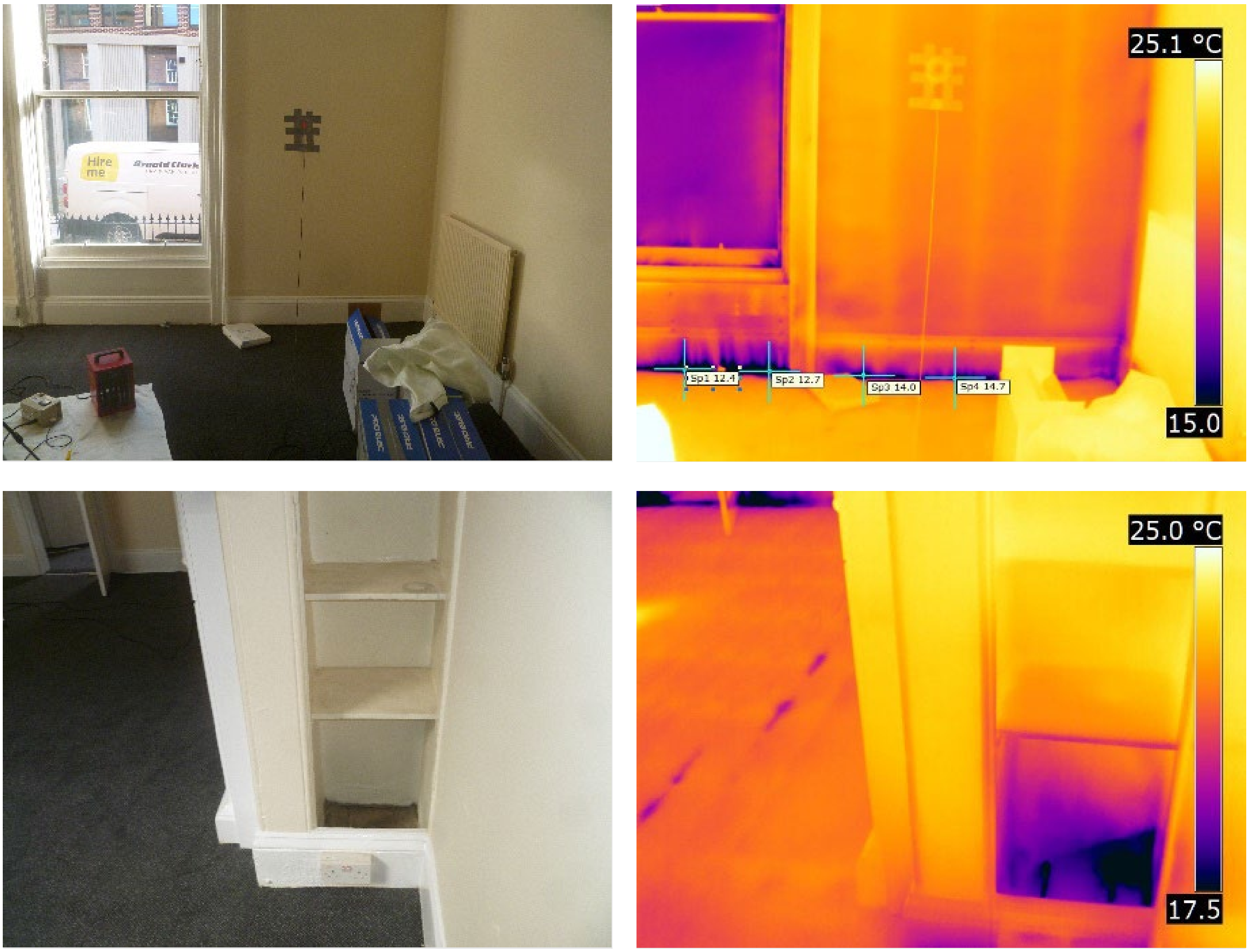


Figure 3-9 Emerging air at the ground floor, coolest at the room perimeter junctions with the external walls and areas of uncarpeted floor

Many additional, less-direct air leakage pathways were detected around both houses, where the air emerging under depressurisation was some distance from the point of entry into the habitable space through the external envelope. Figure 3-10 shows air emerging around the perimeters of both the first and second intermediate floors in 07LT under depressurisation. It cannot be deduced from these where the emerging air was entering the house, but with no nearby openings or penetrations the air must have been travelling through interconnected voids within the dwelling.

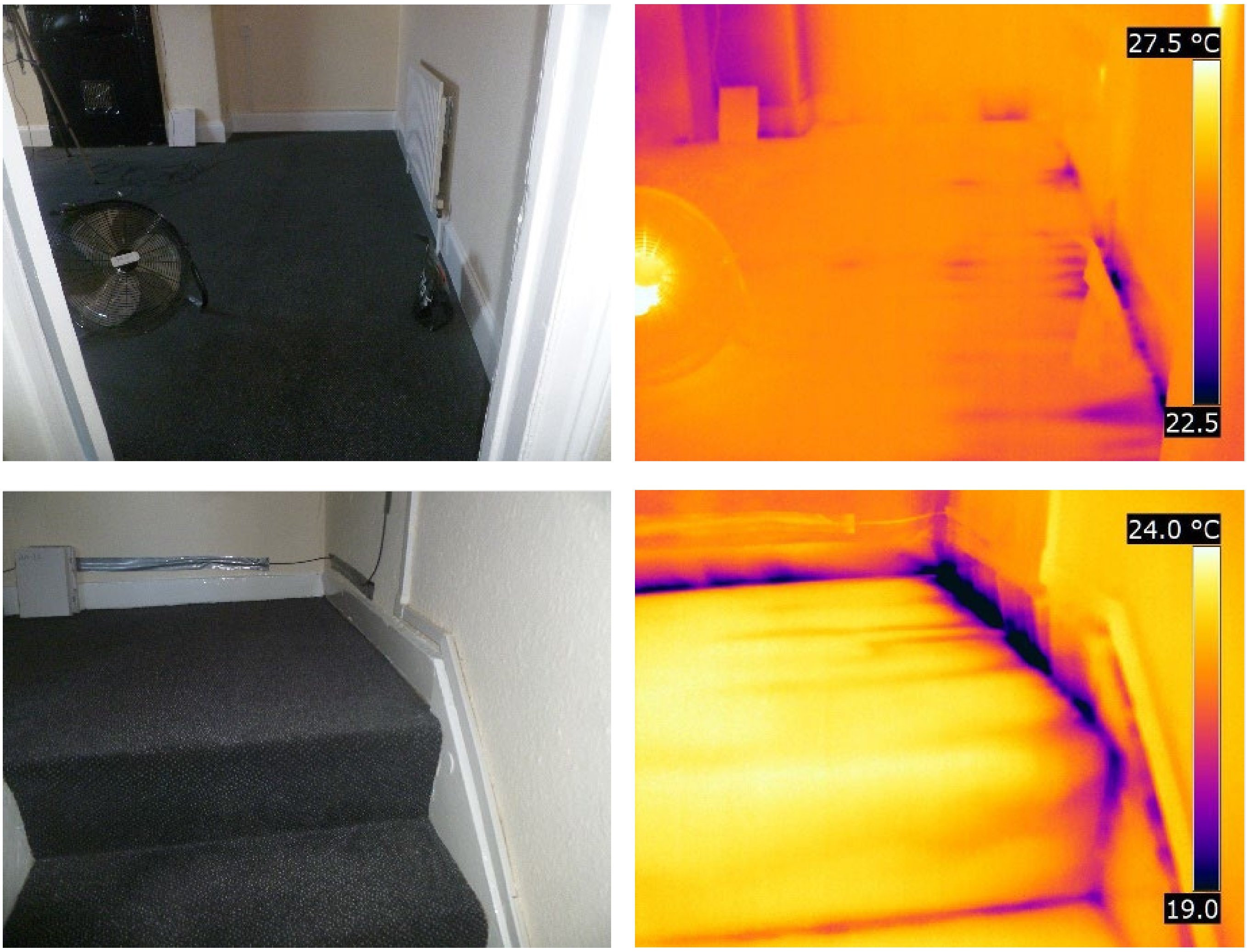


Figure 3-10 Infiltration around intermediate floor and stair perimeters

2.11 DEEP 07 & 09LT

Figure 3-11 shows the ceiling of the first floor Bedroom 2 in 07LT, where cold air can be seen circulating in the eaves void directly above but not in the area of ceiling directly below the bathroom.

Figure 3-11 Signs of air movement in the ceilings beneath the eaves voids in 07LT (top) and 09LT (bottom)

Following the room-in-roof retrofits, the mean air permeability in 09LT reduced slightly from 12.30 to 10.27 m^3/(h·m^2) @ 50Pa (a reduction of 17 %), but 07LT saw an increase from 12.32 to 13.85 m^3/(h·m^2) @ 50Pa (an increase of 12 %). The slight reduction in air permeability observed in 09LT matched expectations, as no airtightness improvements were instigated elsewhere in the house and the majority of air leakage paths detected were on the other two floors.

The increase in air leakage in 07LT following the room-in-roof retrofit was partly due to some deterioration in temporary sealing made elsewhere in the property (Figure 3-12), but also delays due to additional repair work in the roof meant that testing had to be conducted before the room-in-roof retrofit had been fully completed with some final finishing work still to be done. Time pressure on the testing regime resulted in the pressurisation testing of 07LT being undertaken when the thermal barrier had been completed but not all final finishing, such as fastening and draught-stripping the loft and eaves void access hatches (Figure 3-13 and Figure 3-14).

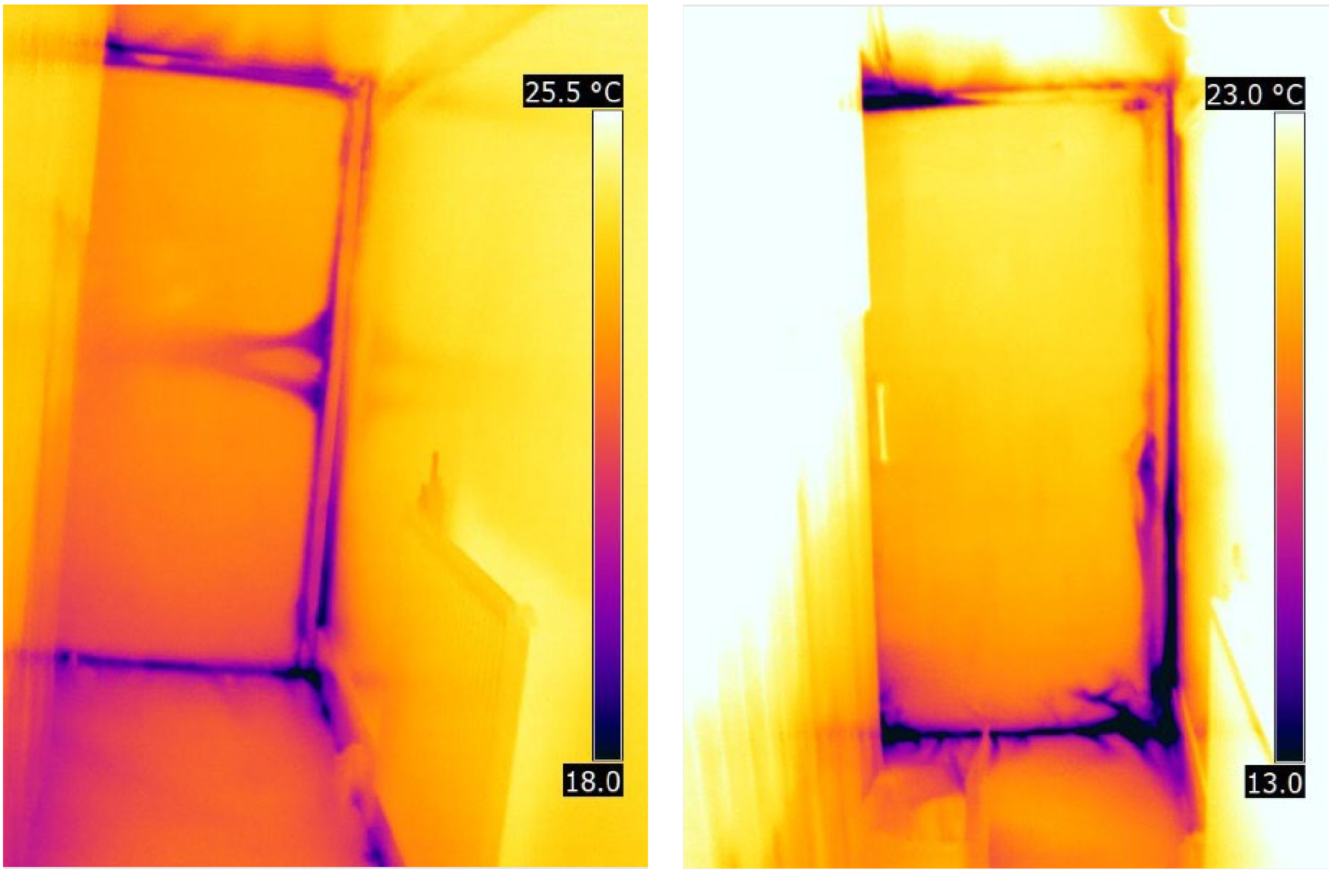


Figure 3-12 Air leakage at the door to the rear annex in 07LT in the original condition (left) and following the room-in-roof retrofit (right), showing the increase in airflow signified by the cooler emerging air post-retrofit

Figure 3-13 The new loft hatches, not yet draught-stripped, in 07LT at the time of the post room-in-roof retrofit pressure test

Figure 3-14 The new eaves void access hatches in 07LT, not yet fastened and draught-stripped, at the time of the post room-in-roof retrofit pressure test

2.11 DEEP 07 & 09LT

Following both room-in-roof retrofits, additional indirect air leakage into the existing internal partition wall voids which had not been previously detected was revealed. Figure 3-15 and Figure 3-16 show cold air being drawn from the roof and eaves voids under depressurisation into the second floor partition wall voids in each home. This was made obvious by the increased temperature differential between the living space and loft/eaves voids. What remains unclear is how much the improved thermal performance of the refurbished roofs contributed to the increased temperature differential and how much was due to cooler external temperatures at the times of the tests. The post-retrofit tests were undertaken with external temperatures just above 5 °C, whereas the pre-retrofit tests were conducted with external temperatures approaching 10 °C.

Figure 3-15 Indirect air leakage into the second floor partition wall voids in 07LT

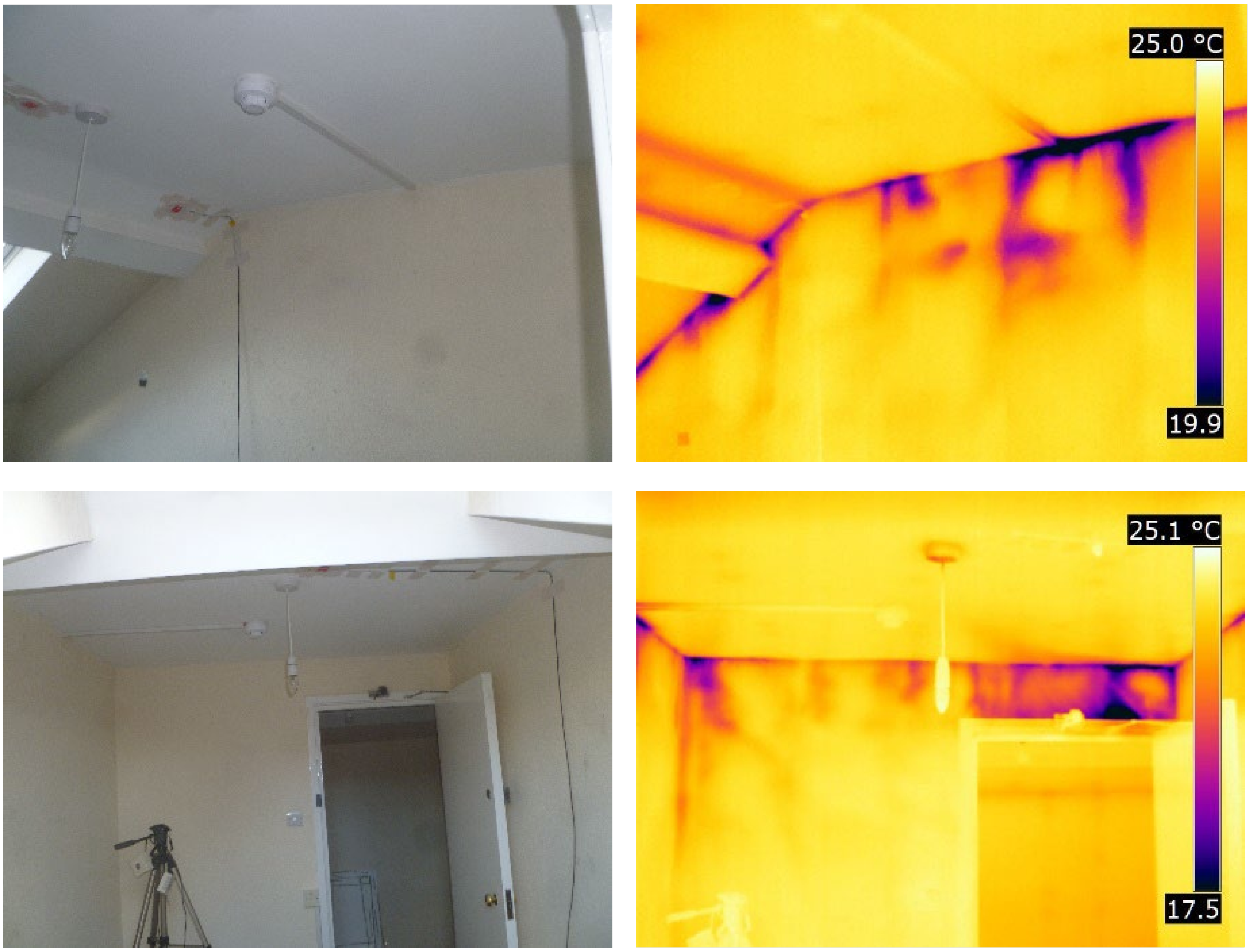


Figure 3-16 Indirect air leakage into the second floor partition wall voids in 09LT

Additional airtightness retrofit measures were undertaken following the room-in-roof retrofits. These saw only small improvements in the mean air permeability of both properties, with 07LT decreasing from 13.85 to 12.95 $m^3/(h{\cdot}m^2)$ @ 50Pa and 09LT dropping from 11.08 to 10.16 $m^3/(h{\cdot}m^2)$ @ 50Pa.

These airtightness measures appeared to address mainly direct infiltration by sealing visible and easily accessible gaps around penetrations, openings and floor perimeters with expanding foam and mastic, without tackling the more complex indirect air leakage through interconnected voids throughout the homes. Figure 3-17 and Figure 3-18 illustrate the types of measures undertaken.

2.11 DEEP 07 & 09LT

Figure 3-17 Additional sealing in the kitchen of 07LT

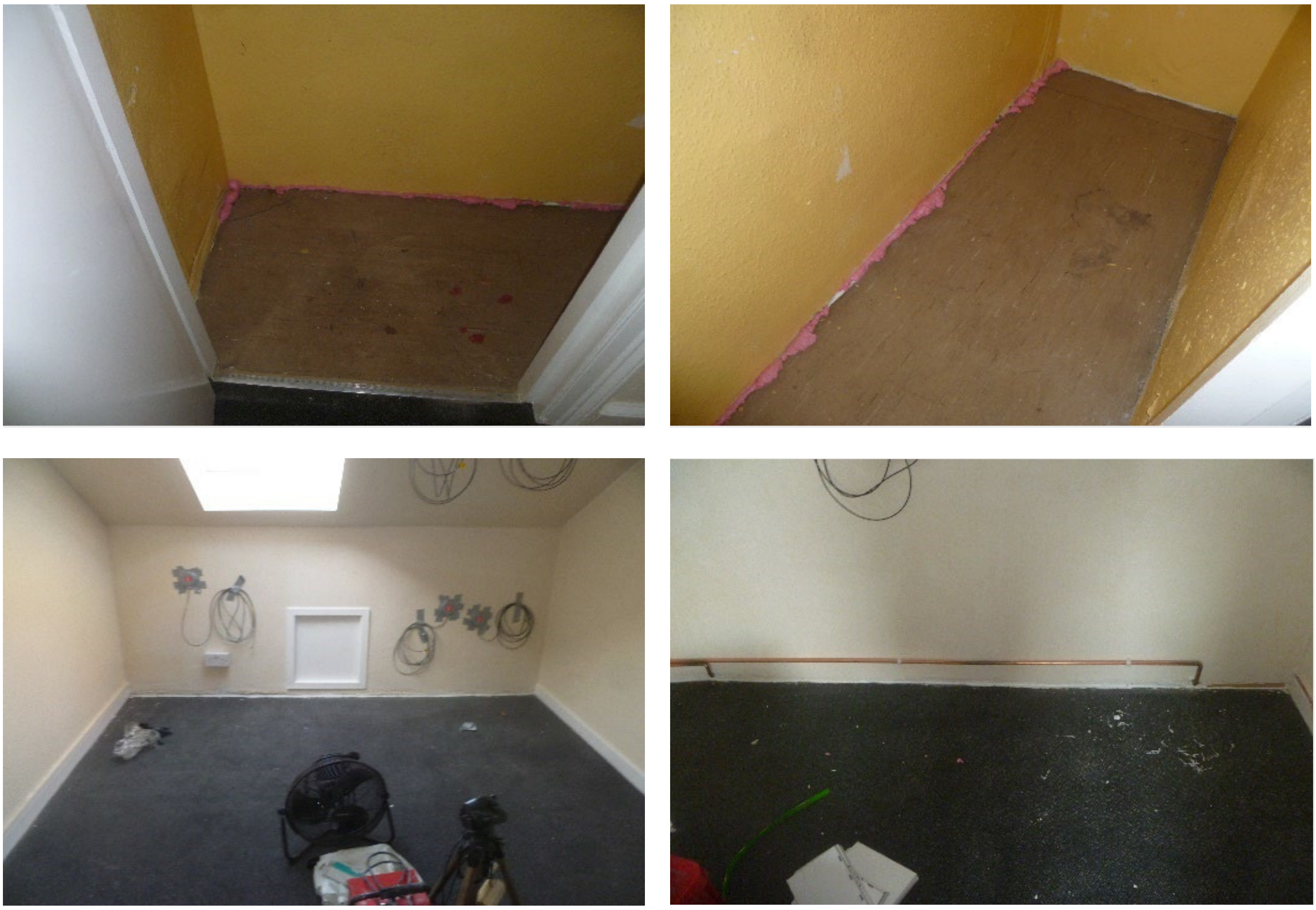


Figure 3-18 Additional sealing around room perimeters on both intermediate floors in 09LT

2.11 DEEP 07 & 09LT

Following the airtightness measures described above, the single glazed sash windows on the ground and first floors of both properties were refurbished and draught-stripped. However, these saw only small improvements in the mean air permeability of both properties, with 07LT decreasing from 12.95 to 12.75 $m^3/(h{\cdot}m^2)$ @ 50Pa and 09LT dropping from 10.16 to 9.90 $m^3/(h{\cdot}m^2)$ @ 50Pa.

In 07LT, the window refurbishment included repairing damaged sash rails, replacing beading around each of the upper and lower sashes, replacing damaged or missing locks and backplates, and the addition of draught-stripping brushes around the lower sashes and between the sash meeting rails (Figure 3-19 and Figure 3-20). A small reduction in mean air permeability was seen under both dwelling depressurisation (0.23 $m^3/(h{\cdot}m^2)$ @ 50Pa) and pressurisation (0.17 $m^3/(h{\cdot}m^2)$ @ 50Pa).

Figure 3-19 Individual sashes and beading removed, sashes repaired and beading replaced

Figure 3-20 Damaged window locks replaced and new beading fitted in 07LT

2.11 DEEP 07 & 09LT

In 09LT, not only were the same measures undertaken as 07LT, but the sash weights, cords and pulleys were overhauled to make the windows fully operable (Figure 3-21).

Figure 3-21 Kitchen window in 09LT removed and mechanism repaired

The reduction in mean air permeability was due to a decrease in the result under pressurisation (0.62 $m^3/(h \cdot m^2)$ @ 50 Pa), with only a negligible change under depressurisation. Leakage detection under depressurisation showed that the brushes installed at the meeting rails reduced air leakage between the sashes but failed to prevent significant air leakage at either end of the meeting rails (Figure 3-22). The new beading was, however, reasonably effective at reducing airflow around the lower sashes.

Figure 3-22 Front room in 07LT showing reduced air leakage at meeting rails and lower sash

Air leakage around the upper sashes and through the sash weight boxes on both sides of the windows was still detected after the window repairs (Figure 3-23). This shows that the repair of timber sash windows may not always have airtightness as a priority, instead prioritising functionality and maintenance. The new brushes and beading appeared to reduce air leakage around and between the sashes, but air movement around the pulleys and ropes into the sash weight boxes showed no similar reduction.

These are only a single pair of case studies, so the lack of success in eradicating air leakage around timber sash windows may not be representative and more testing is needed of the effectiveness of refurbishing timber sash windows to understand how beneficial it can be in improving the airtightness of homes.

Figure 3-23 Air leakage remaining around the upper sashes in 09LT

3.1.1 Co-pressurisation

Co-pressurisation blower door tests were undertaken alongside standard blower door tests on a number of occasions when there was time in the testing schedule, as shown in Table 3-1. The co-pressurisation tests involved installing blower doors in each house simultaneously and capturing readings only when the elevated pressures in each house, relative to external, matched to within 1.0 Pa. This removed drivers of air movement through the party wall between 07LT and 09LT as the properties were effectively isobaric (but not the party wall between 09LT and its other neighbouring property) and provided an indication of how much of the measured air leakage from each property was due to inter-dwelling exchange with the neighbouring test house rather than with the external environment.

Table 3-1 Co pressurisation results for case study homes

	Pressurisation $m^3/(h \cdot m^2)$ @ 50Pa	Co-pressurisation $m^3/(h \cdot m^2)$ @ 50Pa	Difference $m^3/(h \cdot m^2)$ @ 50Pa	% Difference
07LT.B Baseline	12.88	-	-	-
07LT.R Room-in-roof	14.61	11.87	2.74	18.8
07LT.R.A General sealing	13.24	12.02	1.22	9.2
07LT.R.A.A Window sealing	13.07	-	-	-
09LT.B Baseline	13.17	11.66	1.51	11.5
09LT.R Room-in-roof	11.77	-	-	-
09LT.A General sealing	10.35	-	-	-
09LT.R.A.A Window sealing	9.77	8.89	0.88	9.0

The co-pressurisation test saw 09LT's air permeability results under pressurisation reduce from 13.17 to 11.66 $m^3/(h \cdot m^2)$ @ 50Pa in the baseline condition, a fall of 1.51 $m^3/(h \cdot m^2)$ @ 50Pa or 11.5 % from its original test value. Following the window retrofit, a similar reduction from 9.77 to 8.89 $m^3/(h \cdot m^2)$ @ 50Pa was measured, a fall of 0.88 $m^3/(h \cdot m^2)$ @ 50Pa or 9.0 %.

In 07LT, the air permeability results under co-pressurisation with 09LT reduced from 14.61 to 11.87 $m^3/(h \cdot m^2)$ @ 50 Pa following the room-in-roof retrofit, a fall of 2.74 $m^3/(h \cdot m^2)$ @ 50Pa or 18.8 %. Following the additional airtightness measures a reduction from 13.24 to 12.02 $m^3/(h \cdot m^2)$ @ 50Pa was measured, a fall of 1.22 $m^3/(h \cdot m^2)$ @ 50Pa or 9.2 %.

The reductions in air permeability observed from the co-pressurisation of the two houses varied from 18.8 % to 9.0 %, which falls into the range observed throughout the project for dwellings with solid party walls. The measured air permeability was used to calculate ventilation rates and ventilation heat losses for SAP and EPCs. If a significant proportion of the measured air permeability using the fan pressurisation method is inter-dwelling air exchange (rather than assumed internal-external air exchange) attached dwellings might have to be considered differently from detached dwellings in future ventilation heat loss calculations.

3.1.2 Alternative infiltration measurements: Low pressure Pulse tests and CO_2 decay tests

Low pressure Pulse tests
Pulse tests were undertaken at various stages, at the same visits as blower door tests. However, for most of the test period the large volumes and low levels of airtightness proved beyond the capabilities of the Pulse system with just one 40 litre receiver and a single 60 litre expansion tank, as 3 x 40 litre air receivers/tanks are required for such properties[7]. Uploading the failed Pulse test outputs to the BTS Pulse portal for reprocessing resulted in valid test results with warnings about test conditions. TM 23 AP_{50} conversions of the updated test results are shown alongside blower door results in Figure 3-1.

Using the conversion from TM23: 2022, the post-retrofit Pulse test air permeability result for 07LT matched well with the blower door test. The Pulse test AP_4 value of 2.51 $m^3/(h \cdot m^2)$ @ 4 Pa converts to AP_{50} of 12.30 $m^3/(h \cdot m^2)$ @ 50 Pa compared to a blower door result of 13.07 $m^3/(h \cdot m^2)$ @ 50 Pa for pressurisation only. This corresponds to a -6 % difference in AP_{50} results. The Pulse test results for 09LT did not correlate to the blower door test results quite as closely, but still showed a good relationship, with a variation ranging from +14.2 % to -11.7 %. Pre- and post-retrofit AP_4 values of 3.12 and 1.71 $m^3/(h \cdot m^2)$ @ 4 Pa convert to AP_{50} values of 15.04 and 8.63 $m^3/(h \cdot m^2)$ @ 50 Pa, whereas the comparable blower door results of 13.17 and 9.77 $m^3/(h \cdot m^2)$ @ 50 Pa were obtained under pressurisation at the same stages.

CO_2 tracer gas decay
Simple CO_2 decay analysis was not possible using the standard CO_2 release, dispersal and distribution techniques used throughout the rest of this project. Due to the large volumes (>450 m^3) and low levels of airtightness of both test houses, the decay rates were too short and too variable for reliable analysis using the available equipment.

Airtightness improvement summary

Both homes had high infiltration rates linked to multiple direct and indirect air leakage pathways. Since air leakage occurred at the room-in-roof, the addition of insulation marginally reduced air leakage in 09LT. However, owing to cracks in the plaster and new seals to access hatches being incomplete, infiltration worsened in 07LT. This suggests some retrofits, if not completed with airtightness in mind, can make homes less airtight.

The general sealing to penetrations and floors did not achieve any measurable reduction in airtightness, and any improvement was within the error of the test method. Due to the number and complexity of interlinked air leakage pathways, the general sealing appears to have redirected rather than eliminated air leakage. This implies that efforts to improve airtightness which do not involve creating an entirely new continuous airtight barrier may be unlikely to achieve significant savings in homes similar to the case studies.

The window refurbishment improved the ability of the windows to open and close smoothly. Surprisingly, however, it had no measurable impact on airtightness, indicating that draught-stripping timber sash windows may not always achieve improvements.

As found in other DEEP case studies, between 9 % and 19 % of the air leakage reported by blower door tests may, in fact, be inter-dwelling air exchange.

[7] https://www.Pulseairtest.com/sizing-guide.html

3.2 U-value improvements

Three methods were adopted for 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 are undertaken using an approved methodology. This approach is the most specialist and costly 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 differences between them. The report considers the implications of the method selected for the accuracy of the energy and heat loss predictions, the contribution of fabric elements to the HTC, and the predicted benefit achieved by retrofits. A summary of the pre- and post-retrofit U-value measurements are discussed, followed by a discussion of the implications with respect to the heat loss in both homes.

A summary of the pre- and post-retrofit U-values for each of the fabric elements that were not altered in the retrofit is presented in Figure 3-24, while Figure 3-25 shows the U-values that were improved during the room-in-roof retrofit. Where no measured heat flux took place, the calculated and default U-values only are shown.

The measured U-value for the suspended floor was higher than calculated and the model default, whereas the measured U-value for the external walls was similar to the calculated value but higher than the model default. The measured U-value of the gable wall was considerably higher than calculated and lower than the model default. The window U-values were only representative of the centre pane U-values and did not include heat loss from the frame.

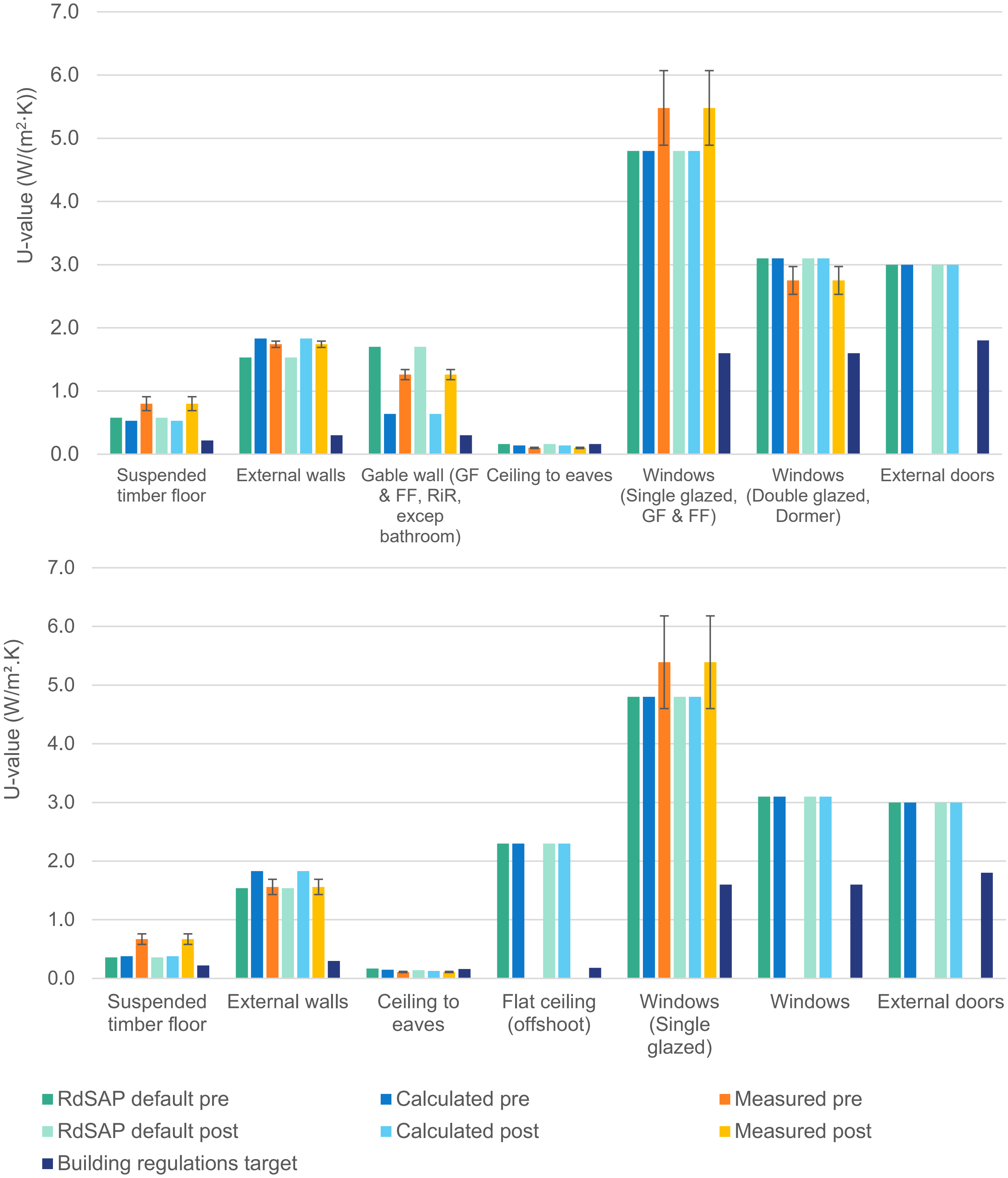


Figure 3-24 07LT (top) and 09LT (bottom) pre- and post-retrofit fabric U-values for elements that were not insulated (W/(m²·K))

Substantial reductions in U-values were achieved for those elements that were insulated in the room-in-roof in both homes. In 07LT, all the uninsulated U-values were already lower than assumed in RdSAP, and often lower than the calculated predictions owing to the pre-existing insulation on some fabric elements. This means the absolute reduction achieved was smaller than predicted, even though the post-retrofit U-values were similar to the predictions. In 09LT, the baseline flat ceiling had a much higher U-value than predicted, indicating the incumbent loft insulation was underperforming, though this was resolved by the retrofit.

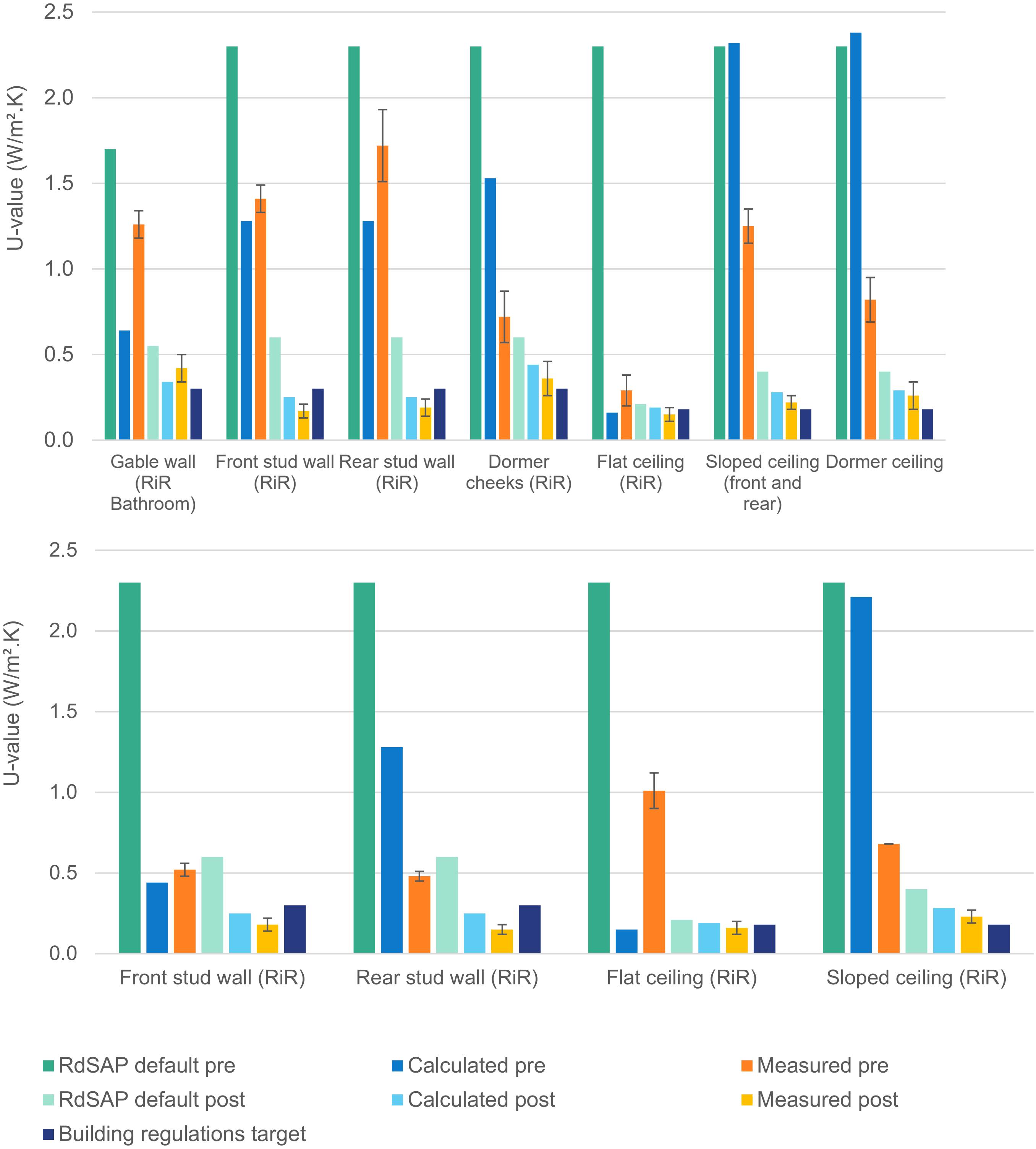


Figure 3-25 07LT (top) and 09LT (bottom) pre- and post-retrofit fabric U-values for room-in-roof retrofit (W/(m²·K)

3.2.1 U-values summary

The pre- and post-retrofit U-values of the elements that were insulated are listed in Table 3-2. This confirms that uninsulated room-in-roof fabric can have high heat losses and that substantial reductions can be achieved by room-in-roof retrofits. The reductions in the U-values varied between (48 ± 10) % and (89 ± 22) %.

The measured post-retrofit U-values were almost always lower than predicted by RdSAP or the BRE calculator. However, the measured U-value reduction was often smaller than predicted, due to the baseline RdSAP and calculated U-values being higher than measured.

Table 3-2 RdSAP default, calculated and measured U-values (W/(m²·K))

	Pre-retrofit			Post-retrofit U-value and % improvement		
	RdSAP default	Calculated	Measured	RdSAP default	Calculated	Measured
07LT						
Gable wall (RiR bathroom)	1.70	0.64	1.26 ± 0.08	0.55 (68%)	0.34 (47%)	0.42 ± 0.08 (67 ± 11) %
Front stud wall (RiR)	2.30	1.28	1.41 ± 0.08	0.60 (74%)	0.25 (80%)	0.17 ± 0.04 (88 ± 9) %
Rear stud wall (RiR)	2.30	1.28	1.72 ± 0.21	0.60 (74%)	0.25 (80%)	0.19 ± 0.05 (89 ± 22)
Dormer cheeks (RiR)	2.30	1.53	0.72 ± 0.15	0.60 (74%)	0.44 (71%)	0.36 ± 0.10 (50 ± 18) %
Flat ceiling (RiR)	2.30	0.16	0.29 ± 0.09	0.21 (91%)	0.19 (-19%)	0.15 ± 0.04 (48 ± 10) %
Sloped ceiling (front and rear)	2.30	2.32	1.25 ± 0.10	0.40 (83%)	0.28 (88%)	0.22 ± 0.04 (82 ± 11) %
Dormer ceiling	2.30	2.38	0.82 ± 0.13	0.40 (83%)	0.29 (88%)	0.26 ± 0.08 (68 ± 15) %
09LT						
Front stud wall (RiR)	2.30	0.44	0.52 ± 0.04	0.60 (74%)	0.25 (43%)	0.18 ± 0.04 (65 ± 6) %
Rear stud wall (RiR)	2.30	1.28	0.48 ± 0.03	0.60 (74%)	0.25 (80%)	0.15 ± 0.03 (69 ± 4) %
Flat ceiling (RiR)	2.30	0.15	1.01 ± 0.11	0.21 (91%)	0.19 (-27%)	0.16 ± 0.04 (84 ± 12) %
Sloped ceiling (RiR)	2.30	2.21	0.68 ± 0.00	0.40 (83%)	0.28 (87%)	0.23 ± 0.04 (66 ± 4) %

The findings suggest that any use of the RdSAP default U-values for uninsulated rooms-in-roof is likely to result in inaccurate heat loss prediction for these homes pre-retrofit. This is confirmed by Table 3-3, which shows a significant prediction gap for almost every room-in-roof element.

Table 3-3 also identifies an as-built performance gap for some elements, where the measured values did not achieve the savings predicted by the calculated values. However, in some instances, greater savings were measured than predicted (i.e., a negative performance gap). The discrepancy between the calculated and measured performance may, in some instances, occur due to errors in the assumed construction details used to calculate the U-values, rather than the under- or over-performance of the insulation material.

Table 3-3 Summary of measured U-value reductions and gaps in performance (numbers in red show a statistically significant gap)

Element	RdSAP default predicted reduction	Calculated predicted reduction	Measured reduction	RdSAP defaults prediction gap	As-built performance gap
07LT					
Gable wall (RiR bathroom)	1.15	0.30	0.84 ± 0.11	0.31± 0.11	-0.54± 0.11
Front stud wall (RiR)	1.70	1.03	1.24 ± 0.09	0.46 ± 0.09	-0.21 ± 0.09
Rear stud wall (RiR)	1.70	1.03	1.53 ± 0.22	0.17 ± 0.22	-0.50 ± 0.22
Dormer cheeks (RiR)	1.70	1.09	0.36 ± 0.18	1.34 ± 0.18	0.73 ± 0.18
Flat ceiling (RiR)	2.09	-0.03	0.14 ± 0.10	1.95 ± 0.10	-0.17 ± 0.10
Sloped ceiling (front and rear)	1.90	2.04	1.03 ± 0.11	0.87 ± 0.11	1.01 ± 0.11
Dormer ceiling	1.90	2.09	0.56 ± 0.15	1.34 ± 0.15	1.53 ± 0.15
09LT					
Front stud wall (RiR)	1.70	0.19	0.34 ± 0.06	1.36 ± 0.06	-0.15 ± 0.06
Rear stud wall (RiR)	1.70	1.03	0.33 ± 0.04	1.37 ± 0.04	0.70 ± 0.04
Flat ceiling (RiR)	2.09	-0.04	0.85 ± 0.12	1.24 ± 0.12	-0.89 ± 0.12
Sloped ceiling (RiR)	1.90	1.93	0.45 ± 0.04	1.45 ± 0.04	1.48 ± 0.04

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

Plane element fabric heat loss is the primary cause of heat loss in most homes, so improving U-values is an essential part of any retrofit. The individual U-value measurements for 07LT and 09LT were area weighted to calculate the heat loss via the main building elements. Table 3-4 shows that the total fabric heat loss was reduced by around 52 W/K (14 %) in 07LT and 25 W/K (10 %) in 09LT, the difference being due to 07LT having a gable wall.

As shown in Table 3-4, external walls were responsible for almost half the fabric heat loss in 07LT. In 09LT, walls were only responsible for a third of the home's fabric heat losses, as it is a mid-terrace. Windows (single glazed) and external doors were the largest fabric heat loss mechanism in 09LT, being slightly more important than the walls. Interestingly, in 07LT, windows and doors were only half as important as walls. This result has some uncertainty associated with it since the window U-values were based on centre pane measurements and did not include the frame heat loss. However, the results still highlight the importance of single glazing and the wall to window area ratio in determining optimal retrofit pathways.

Pre-retrofit, the ground floors were the least important for fabric heat loss, followed by the room-in-roof areas. The absolute heat loss through the room-in-roof was greater in 07LT, again due to there being a gable wall in this area. Post-retrofit, the rooms-in-roof became the elements with the least heat loss, being responsible for only (5 ± 0.5) % and (8 ± 1) % of the heat loss in 07LT and 09LT, respectively.

Table 3-4 Contribution of individual elements to fabric heat loss in 07LT and 09LT

Element	Pre-retrofit (W / K)	*Proportion of heat loss*	Post-retrofit (W / K)	*Proportion of heat loss*
07LT				
Room-in-roof	66 ± 3	*(18 ± 1) %*	15 ± 2	*(5 ± 0.5) %*
Ground floor	48 ± 7	*(13 ± 2) %*	48 ± 7	*(15 ± 2) %*
Doors and windows	84 ± 8	*(22 ± 2) %*	84 ± 8	*(26 ± 2) %*
Walls	178 ± 10	*(47 ± 2) %*	177 ± 8	*(55 ± 2) %*
Total	**375 ± 28**	-	**324 ± 25**	-
09LT				
Room-in-roof	42 ± 2	*(18 ± 1) %*	18 ± 1	*(8 ± 1) %*
Ground floor	40 ± 5	*(17 ± 2) %*	40 ± 5	*(19 ± 3) %*
Doors and windows	83 ± 10	*(35 ± 4) %*	83 ± 10	*(39 ± 5) %*
Walls	74 ± 1	*(31 ± 0.3) %*	74 ± 1	*(35 ± 0.3) %*
Total	**238 ± 18**	-	**214 ± 17**	-

Figure 3-26 shows the relative importance of each heat loss element according to the predicted and measured U-values. As shown, the general trends agree, i.e., walls were the most significant heat loss element in 07LT, while the windows and room-in-roof were proportionally more significant in 09LT. The predicted window and door heat losses were lower than the measured heat loss, though this may be expected as the single glazing measurements were based on centre pane values. Measured and predicted heat losses show a significant reduction in fabric heat loss following the room-in-roof retrofit.

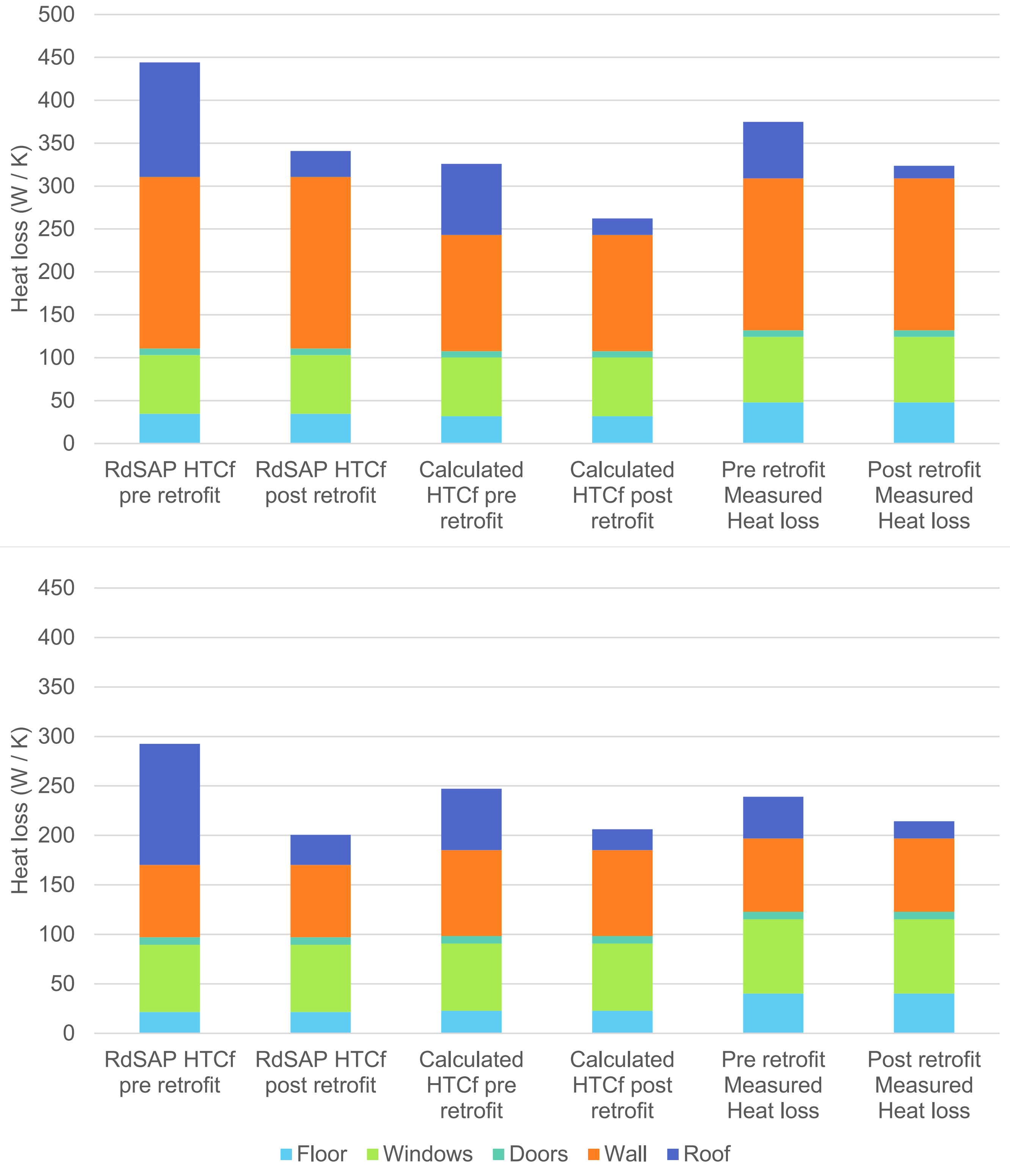


Figure 3-26 Heat loss of fabric elements pre- and post-retrofit in 07LT (top) and 09LT (bottom)

U-value improvement summary

The in-situ U-value measurements suggest that the retrofits undertaken in 07LT and 09LT achieved a significant reduction in both homes of around 14 % and 10 % of total fabric heat losses, respectively. The absolute reduction in heat loss was twice as large in 07LT (52 W/K) as the reduction in 09LT (25 W/K) because it is an end-terrace with a gable wall, while 09LT is a mid-terrace.

The heat lost via the existing external glazing and doors based on HFP measurements was significant in both homes, responsible for between (83 ± 10) W/K and (84 ± 8) W/K. There is some uncertainty over these values, since the single glazing window U-values are based on only centre pane heat flux density measurements, though these were found to be broadly in line with the RdSAP and calculated U-values.

The assumed RdSAP U-values of 2.3 $W/(m^2 \cdot K)$ for all room-in-roof elements were shown to be substantial overestimates, causing a significant modelling gap, i.e., over-predicting the heat loss of the uninsulated rooms-in-roof, and over-predicting the savings achieved by insulation. The calculated U-values were variously shown to be higher or lower than the measured values, though this may reflect errors associated with the assumed construction of the room-in-roof fabric.

3.3 Whole house heat loss (HTC) improvement

The total measured heat loss for the dwellings at the baseline and post-retrofit stages are shown in Table 3-5.

Table 3-5 Test house HTC

Retrofit stage	HTC (W/K)	HTC uncertainty	HTC reduction (W/K)	Percentage reduction
07LT.B Baseline	352	12 (3%)	-	-
07LT.R.A Room-in-roof, general and window sealing	310	34 (11%)	42 ± 36	(12 ± 10) %
09LT.B Baseline	228	14 (6%)	-	-
09LT.R.A Room-in-roof, general and window sealing	218	6 (3%)	10 ± 15	(4 ± 7) %

As shown, 07LT had more heat loss than 09LT due to it being an end-terrace and having a gable wall, which gives it a much larger heat loss area. This means that the potential to achieve savings from the room-in-roof retrofit was greater than observed.

The savings in 07LT are statistically significant whereas the savings measured in 09LT are within the uncertainty of the test. Since only marginal reductions in infiltration were measured in 07LT and no airtightness improvements were achieved in 09LT, the savings can predominantly be attributed to the room-in-roof insulation.

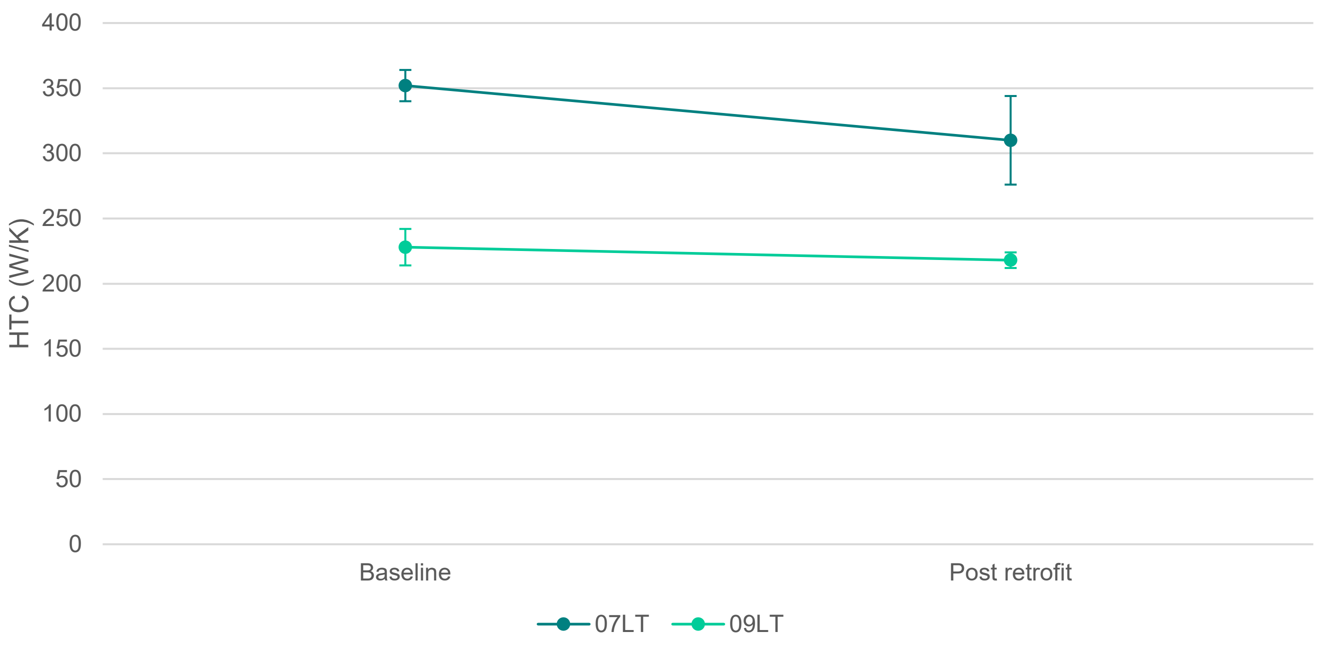


Figure 3-27 Coheating HTC

The retrofit involved the removal of existing knee walls and ceilings. To take the additional weight of the wood fibre boards, additional bracing support was needed which added unanticipated costs and time to the programme. The wood fibre board was mechanically fixed to existing gable walls and timbers, and care was taken to continue the insulation layer around the purlins, as shown in Figure 3-28.

Figure 3-28 Wood fibre board installation

The installation of the wood fibre board necessarily reduced the head hight available in the room-in-roof. As shown in in Figure 3-29, the increase in additional insulation on the ceiling did not cause any overlap on the window frames, which could have caused additional design challenges. However, the extra fabric thickness did mean that standard access hatches could not be installed, and bespoke joinery work was needed.

Figure 3-29 Reduction in ceiling height caused by the addition of wood fibre insulation

2.11 DEEP 07 & 09LT

In addition to the retrofit achieving heat loss savings, the fabric achieved more consistent and higher surface temperatures. Room-in-roof geometry is complex, often leading to discontinuities in insulation layers, as found in these homes prior to the retrofit (Figure 3-30). These areas can cause cold spots which maybe at elevated risk of surface condensation.

Figure 3-30 Discontinuities around complex geometries in room-in-roof pre-retrofit causing cold bridging resolved post-retrofit

3.3.1 Aggregated and disaggregated HTC

The aggregate whole house HTC was measured using the coheating test, but can be disaggregated into three individual components:

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

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

HTC_b (non-repeating thermal bridging heat losses), 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.

According to Equation 1, the heat loss saving achieved from airtightness improvements in 09LT was approximately 14 W/K (6 % of whole house HTC), while in 07LT infiltration heat loss increased marginally post-retrofit by 4 W/K (1 % of HTC).

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

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

Any attempt to disaggregate the whole house HTC into fabric and background ventilation heat loss using the n/20 rule should be treated with caution. This is demonstrated in a recent publication, where the rule of thumb is shown to be inappropriate for a sample set of 21 buildings [4]. Investigation using a larger sample set would be required to identify an alternative rule of thumb for a range of UK archetypes.

The measured HTC from the coheating test and the HTC calculated from summing the disaggregated HTC_v, HTC_f and HTC_b are presented in Figure 3-31. As can be seen, the disaggregated method consistently predicts a higher HTC than measured by the coheating test.

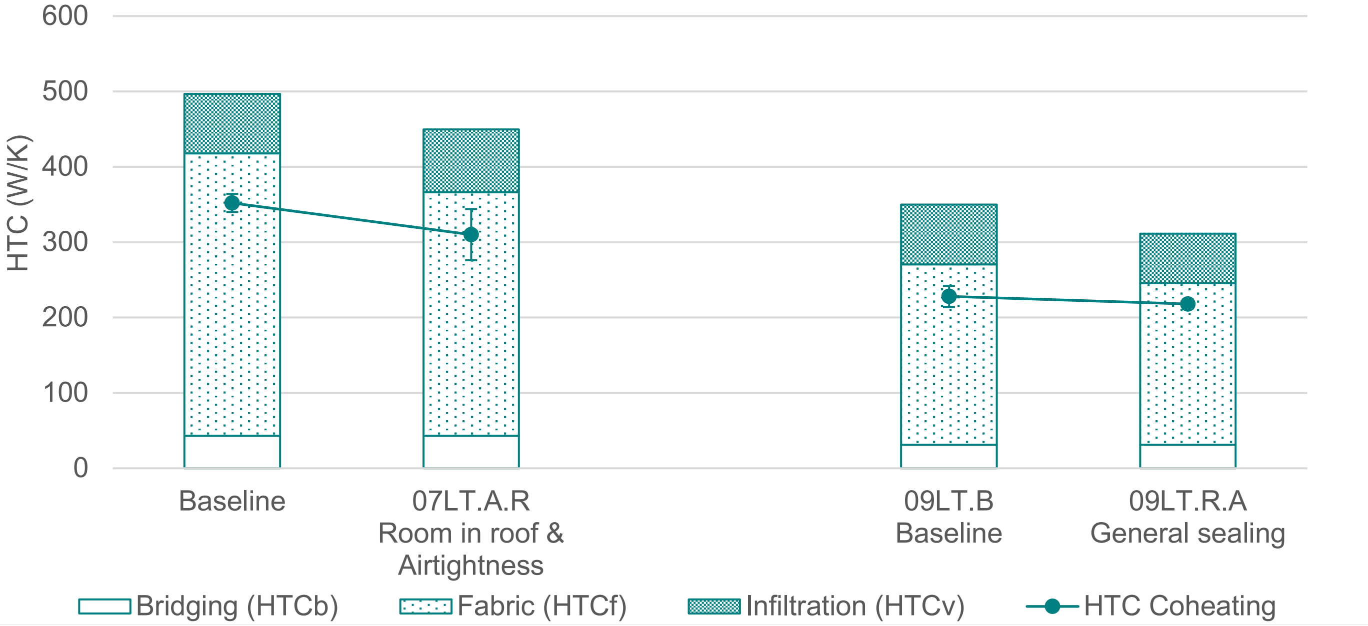


Figure 3-31 Aggregated vs. disaggregated measured HTC

The reduction in fabric HTC is shown to have been 52 W/K (15 % of HTC) and 25 W/K (11 % of HTC) in 07LT and 09LT, respectively, meaning the combined disaggregated HTC reductions of fabric and infiltration were 47 W/K (14 % of HTC) and 39 W/K (17 % HTC), respectively. This compares to the aggregated measured coheating reductions of (12 ± 10) % and (4 ± 7) %.

The HTC_b shown here is taken from the EPC prediction, which is why there is no change post-retrofit. Insulating building fabric tends to increase the severity of thermal bridges. However, when these rooms-in-roof were insulated, many of the discontinuities causing thermal bridges in the home were eliminated. Thus, without detailed thermal bridging calculations of each junction in the home, it is difficult to estimate what impact the retrofits had on the thermal bridging heat loss.

The disaggregated approach shows that the homes had higher HTCs of between 93 W/k and 145 W/K more than the aggregated coheating HTC. Despite this, the HTC reductions in 07LT measured by the coheating test (42 W/K) and the disaggregated method (47 W/K) were similar. However, in 09LT, where there was a significant difference in airtightness though less reduction in fabric heat loss, the methods did not agree on the reduction achieved by the retrofit; 10 W/K and 39 W/K for the aggregated and disaggregated HTC, respectively. This suggests that the fabric heat loss measurements are more robust and there is more uncertainty in the disaggregated approach to calculating infiltration heat losses. It is not known why these differences are observed, though the reasons could be:

- The n/20 rule is an average annual approximation which may not be appropriate for different building types or for different levels of wind exposure, geography or topography.
- The HFP placements may not have been representative or comprehensive of the whole element heat loss.
- Systematic uncertainty in the coheating test cannot be perfectly accounted for, e.g., party wall heat exchange, solar gains, and wind. In addition, only quasi steady-state conditions are possible.
- The default U-values for the pre-retrofit external windows were assumed because specific performance details were not known.

Table 3-6 shows the relative heat losses in both homes pre- and post-retrofit. The table suggests the room-in-roof retrofit had a relatively minor impact on the whole house HTC.

Table 3-6 Whole house heat loss via disaggregated methods

Retrofit stage	HTC_f (W/K)	HTC_v W/K	HTC_b W/K
07LT.B Baseline	375 (76%)	79 (16%)	43 (9%)
07LT.R.A Room-in-roof, general and window sealing	324 (72%)	83 (18%)	43 (10%)
09LT.B Baseline	239 (68%)	80 (23%)	31 (9%)
09LT.R.A Room-in-roof, general and window sealing	214 (69%)	66 (21%)	31 (10%)

3.3.2 QUB and coheating test HTC results

An alternative method of measuring the HTC, QUB, was undertaken in the houses at both retrofit stages to compare against the coheating test. The QUB method is described in full in the DEEP Methods 2.0 Report. In total, 14 QUB tests were performed, 7 on each house. These were done to investigate the reliability and accuracy of the QUB test.

For both houses, three tests were done at the baseline stage in November 2021 and four were done following the completion of the retrofit measures in April 2022 (Figure 3-32). Each test had a 10 hour duration. When completing the tests, attempts were made to ensure a compliant α value (heat loss / heat gain ratio), which can impact the accuracy of measurements. This was done through use of additional temperature and time-controlled heaters. A reference HTC is needed to compute α. For 07LT and 09LT, a provisional result of the coheating test was used. This resulted in all but four tests having a compliant α value. The α calculation was repeated when the coheating results were finalised which resulted 5 tests with α values outside the recommended range. However, all attempted tests are included in the analysis, as the duration of the tests was 10 hours and the impact of the α value is known to be reduced in tests of over 8-hour duration.

The individual QUB HTC measurements are shown against the upper and lower uncertainty boundaries of the corresponding coheating measurements. Despite the houses being mid- and end-terrace properties with party walls, raw coheating and QUB measurements (no adjustment for party wall losses) are used in these comparisons.

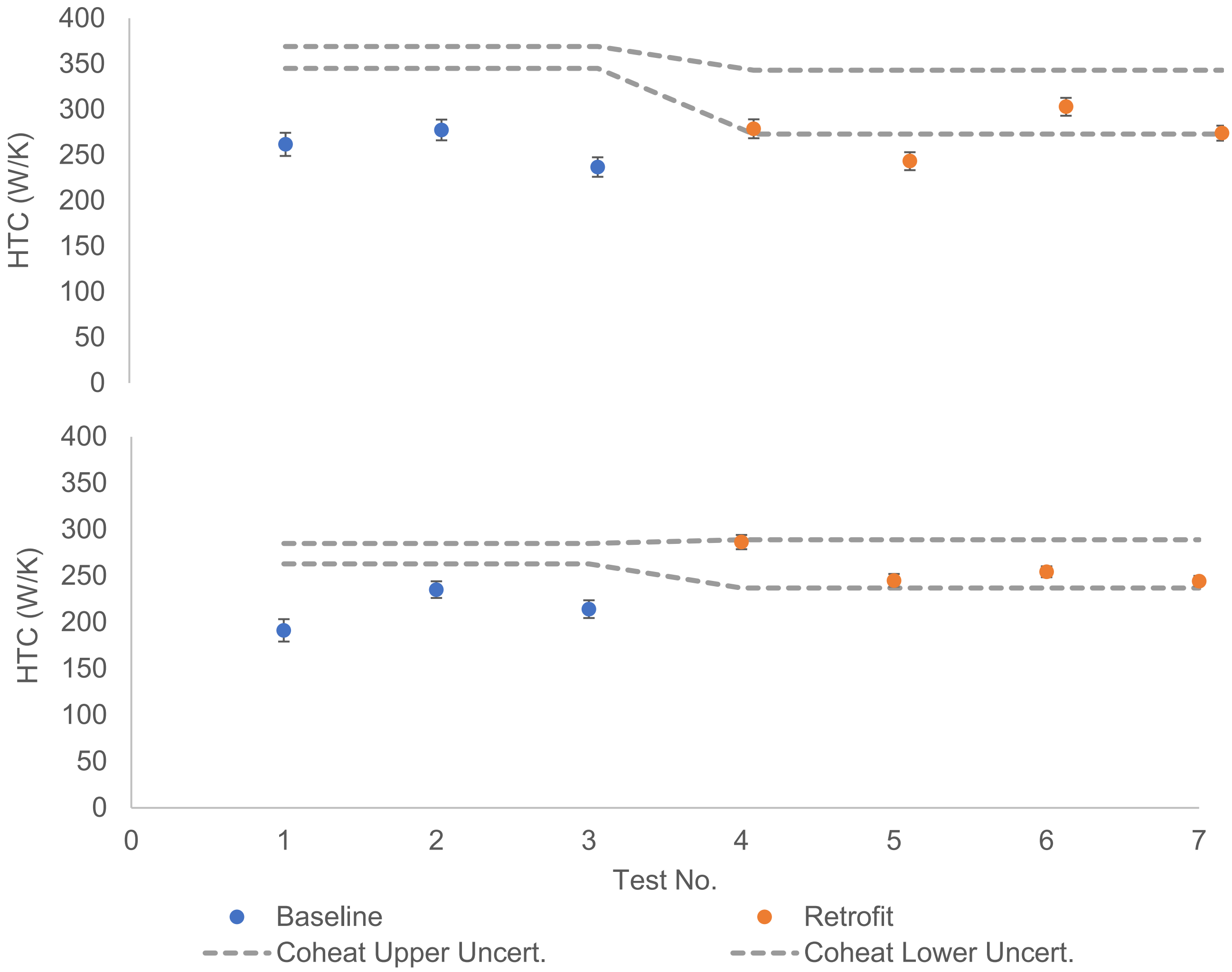


Figure 3-32 Comparison of individual QUB HTC and coheating measurements for 07LT (top) and 09LT (bottom)

For both houses, the results from the retrofitted stage show closer agreement than the baseline. None of the baseline QUB tests had overlapping confidence intervals with coheating. Comparatively, six of the seven (85%) QUB tests completed in the retrofit stage overlapped with the coheating measurement. The impact of the retrofit on the dispersion of the results is inconclusive. From baseline to retrofit, the range relative to the mean improved from 20 % to 17 % for 09LT, and from 16 % to 22 % for 07LT.

The overall uncertainty weighted average QUB measurements are compared against coheating in Figure 3-33. When evaluating the uncertainty weighted average for the QUB measurements, the agreement between the two techniques improved with the completion of the retrofit works. The relative difference for the baseline and retrofit stages improved from 28 % to 11 % for 07LT, and 21 % to 3 % for 09LT.

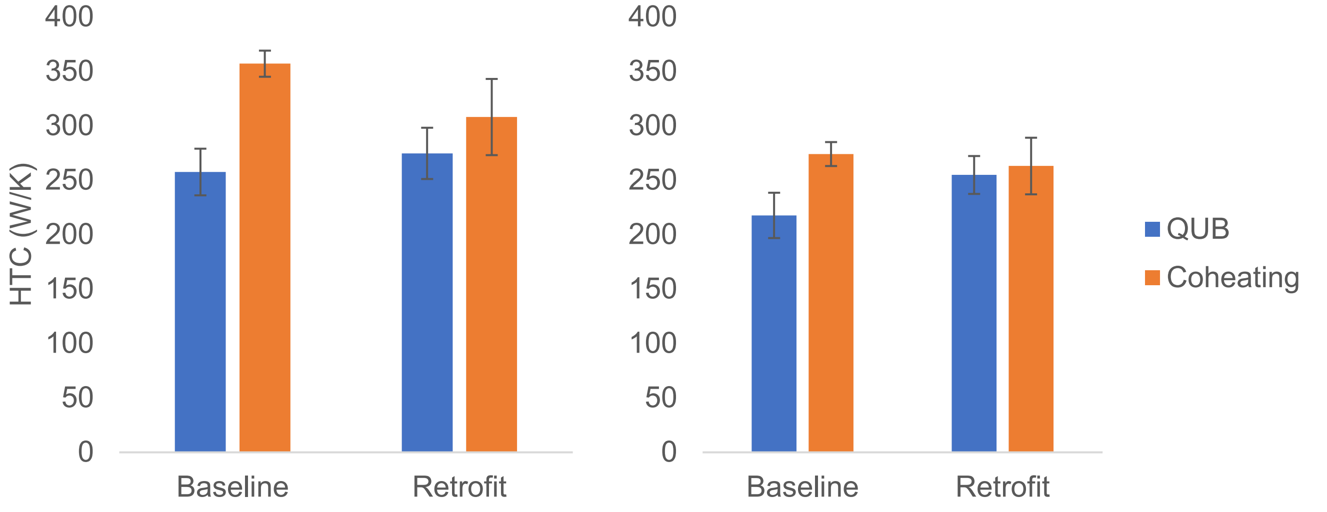


Figure 3-33 Average QUB HTC measurement vs. coheating measurement for 07LT (left) and 09LT (right)

The patterns observed in the results are reflective of existing research which shows better agreement between QUB and coheating tests in higher performing (lower heat loss) buildings [5, 6]. However, as the retrofit works led to only modest reductions in overall heat loss no significant improvement in the QUB measurements was detected.

There are factors relating to the building characteristics and test conditions that could impact the results of the measurements. The presence of party walls on both houses introduces heat transfer that does not follow the internal–external temperature difference. Correcting the QUB measurements for party wall losses has not been included in the analysis as there is currently not a validated way of doing so.

Unique to these houses, there are three unconditioned spaces outside the thermal envelope for HTC measurements, the basement, a ground floor kitchen and a first floor room (storage space in 07LT and a bathroom in 09LT). As with the party walls, these spaces introduce losses that do not follow the internal–external temperature difference and may have contributed to the difference between the QUB and coheating results. The temperature in these spaces was monitored which allows their impact on both the QUB and coheating tests to be estimated. Equation 2 determines the heat loss from the internal space to the conditioned space, H_u (W/K) [7].

Equation 2 Heat transfer to unconditioned spaces

$$H_u = \frac{T_i - T_u}{T_i - T_e} * H_{iu}$$

T_i, T_u and T_e are the temperature of the internal space, unconditioned space and external environment (K).

H_{iu} is the direct heat transfer from the internal space to the unconditioned space (W/K). This was calculated through summation of the U-values of the building fabric multiplied by the applicable area. The measured U-values of the floor and external walls were used along with an assumed value of 1.4 W/(m^2.K) for the doors facing the unconditioned space. As the spaces were sealed, no infiltration was assumed.

By subtracting H_u from the raw HTC measurement, the losses to the unconditioned space were disaggregated. The results of this disaggregation and the impact on agreement between the two measurement techniques are presented in Table 3-7.

Table 3-7 Comparison of QUB and coheating HTC measurements with losses to unconditioned spaces disaggregated

House Retrofit stage	Coheating HTC (losses to unconditioned spaces disaggregated) (W/K)	Average QUB HTC (losses to unconditioned spaces disaggregated) (W/K)	Percentage difference (unconditioned spaces disaggregated)	Percentage difference (raw results)	Percentage difference improvement
07LT Baseline*	316	237	25%	28%	+ 3%
07LT Retrofit	215	233	8%	11%	+ 3%
09LT Baseline*	225	205	9%	21%	+ 12%
09LT Retrofit	197	220	12%	3%	- 9%
*For baseline stages only temperature in the basement was measured, losses to the unconditioned spaces on the ground and first floor are not accounted for.					

The agreement between the two measurement techniques improved for three of the four testing configurations. This suggests that the presence of the unconditioned spaces and the differing temperature gradients introduced impact the performance measurements. This should be considered in future comparative studies between measurement techniques, and more robust methods to control or account for unconditioned spaces should be developed, which could include the measurement of the heat flux density of unconditioned space.

The difference in HTC measurement between techniques increased following the retrofit of 09LT. The cause of this could be party wall heat transfer or the impact of environmental conditions such as wind or precipitation.

Whole house heat loss improvement summary

According to the coheating test, the retrofits in 07LT achieved significant reductions in heat loss of 42 ± 36 W/K (12 ± 10) %. However in 09LT the reduction was not significant at 10 ± 15 W/K (4 ± 7) %. This indicates that there is potential for room-in-roof retrofits to reduce whole house heat losses in solid walled homes where rooms-in-roof have large heat loss areas (e.g., gable walls), but the savings may be less certain where rooms-in-roof have less external heat loss area (e.g., mid-terrace homes). Room-in-roof retrofits can be effective in eliminating discontinuities in existing fabric isolation where complex room geometry has caused existing insulation to have been erratically installed.

07LT achieved greater reduction in fabric heat loss, largely because it is an end-terrace and thus has more heat loss area that could be insulated as part of the retrofit. In contrast, 09LT achieved significant airtightness improvements, estimated to be equivalent to 14 W/K, where 07LT achieved none.

The disaggregated approach substantially overestimated HTC compared to the coheating test between 93 W/K and 145 W/K. Thus, although disaggregated methods can be useful in highlighting heat loss hotspots, they have high levels of uncertainty, which makes summing their individual contributions to attain a whole house value problematic. The aggregated heat loss assessment provided by the coheating test may be less susceptible to these errors, though it has its own inherent uncertainties related to variables such as accounting for solar radiation and party wall heat losses, which are not perfectly accounted for. There is also the potential for variable quasi steady-state conditions to occur.

Similarly, the QUB measurements may have been affected by sub-optimal test conditions, including the presence of large party walls and unconditioned spaces, which may have caused a discrepancy between the QUB and coheating measurements. However, post-retrofit QUB was more in line with the coheating tests in both houses.

3.4 Measured vs. modelled retrofit performance

3.4.1 Measured vs. modelled HTC calibration step 1

In this step, the default input values for airtightness and U-values are used. The measured HTC values from the coheating test pre- and post-retrofit are plotted against the HTC values predicted by the uncalibrated models using default RdSAP input data in Figure 3-34.

- All the models predict significantly higher HTC and HTC reductions than the coheating tests, since the RdSAP default U-values for rooms-in-roof are substantially higher than usually measured.
- The RdSAP default input room-in-roof simplified assumptions mean that EPCs predict the highest HTC savings of 17 % and 22 % for 07LT and 09LT, respectively, whereas the coheating test measured only (12 ± 10) % and (4 ± 7) % reductions.
- Additionally, the room-in-roof simplification in EPCs does not consider there to be party walls in the room-in-roof, meaning that RdSAP has higher HTC predictions than BREDEM (where the actual geometry is used) especially in 09LT, which is a mid-terrace.
- Consistent with other DEEP case studies, the DSM model predicts much lower HTC values than the steady-state models.

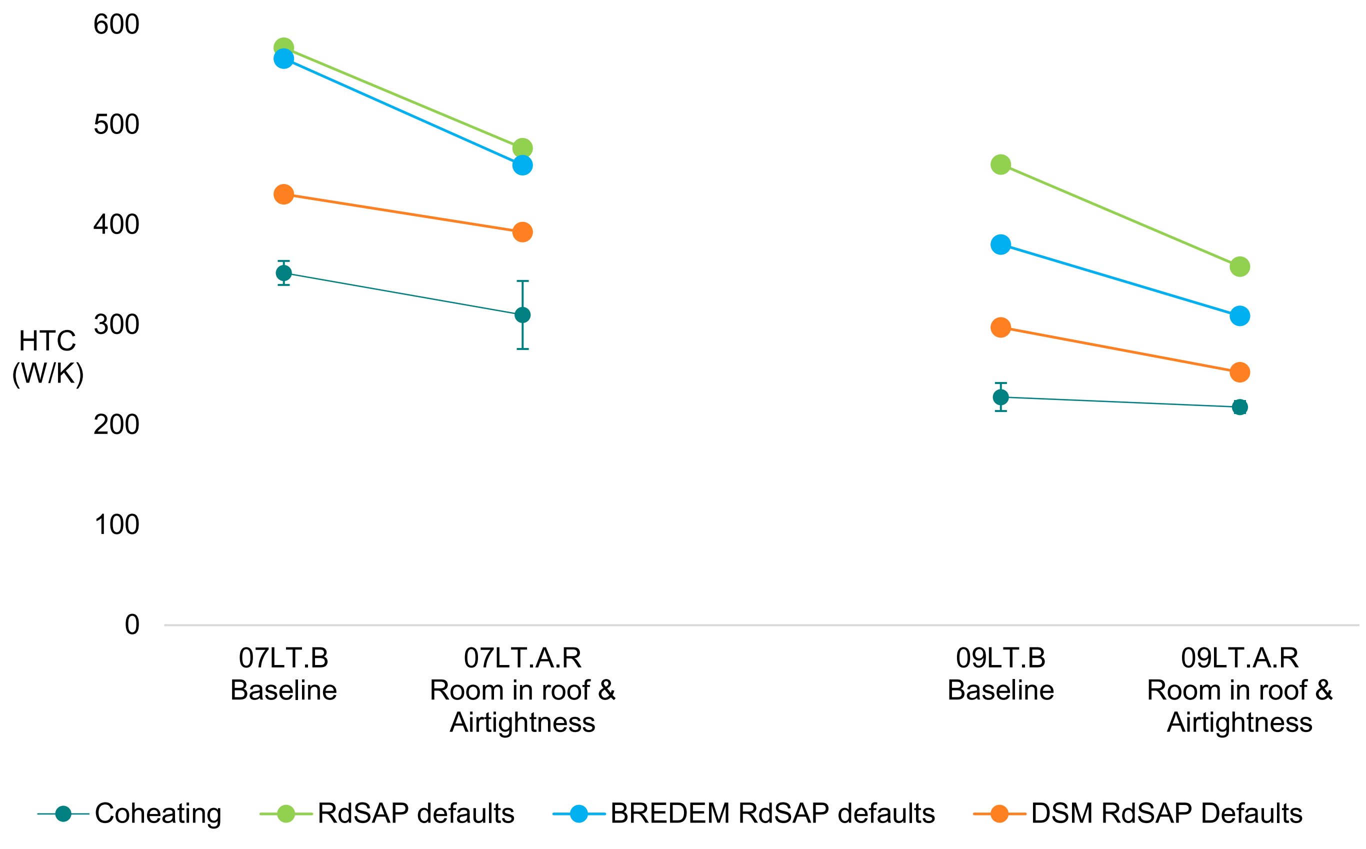


Figure 3-34 Measured vs. modelled HTC calibration step 1: Default data

3.4.2 Measured vs. modelled HTC calibration step 2: Measured infiltration

In this calibration step, the models use the average annual infiltration rates derived from the blower door test, as these data are most likely to be acquired in practice. The impact of this compared to the previous calibration stage is shown in Figure 3-35.

- RdSAP is not shown since it is not possible to alter the infiltration rate in the software.
- Adding the measured infiltration rates results in the models predicting lower HTC since the homes were more airtight than the RdSAP defaults predicted. This brings the predictions more in line with the measured values.
- A smaller benefit resulting from the retrofit is observed in 07LT since the measured airtightness of the home marginally increased after the retrofit.

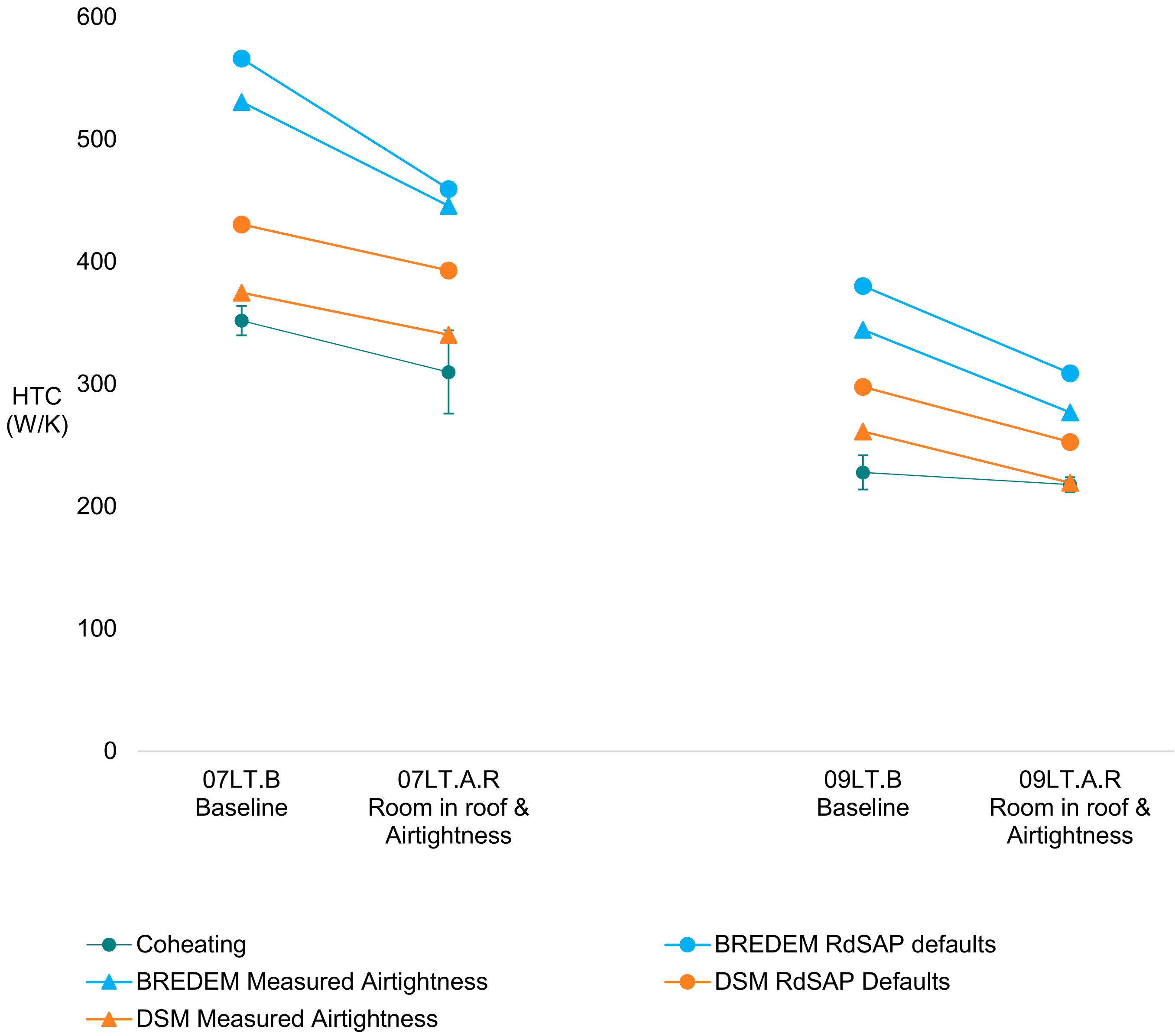


Figure 3-35 Measured vs. modelled HTC calibration step 2: Measured infiltration

3.4.3 Measured vs. modelled HTC calibration step 3: Calculated U-values

In this step, the models included U-values defined using the BRE calculator, based on detailed surveys. Such surveys often require 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 3-36.

- RdSAP is not shown since it is not possible to include calculated U-values in the software.
- The introduction of the measured U-values brings about a significant reduction in the HTC predicted for 07LT since the RdSAP default U-values for the room-in-roof are significantly higher than they were calculated to be according to the BRE U-value calculator.
- There is no change in 09LT pre-retrofit because there is less room-in-roof fabric heat loss area. A slight increase in the post-retrofit 09LT is observed because the post-retrofit calculated U-values are in line with the RdSAP defaults and because there is a slight increase in the window U-values compared to the RdSAP defaults.
- Adding the calculated U-values brings the HTC predictions generally closer to the coheating test results and specifically, post-retrofit, the DSM predictions are within the error of the coheating test measurements.

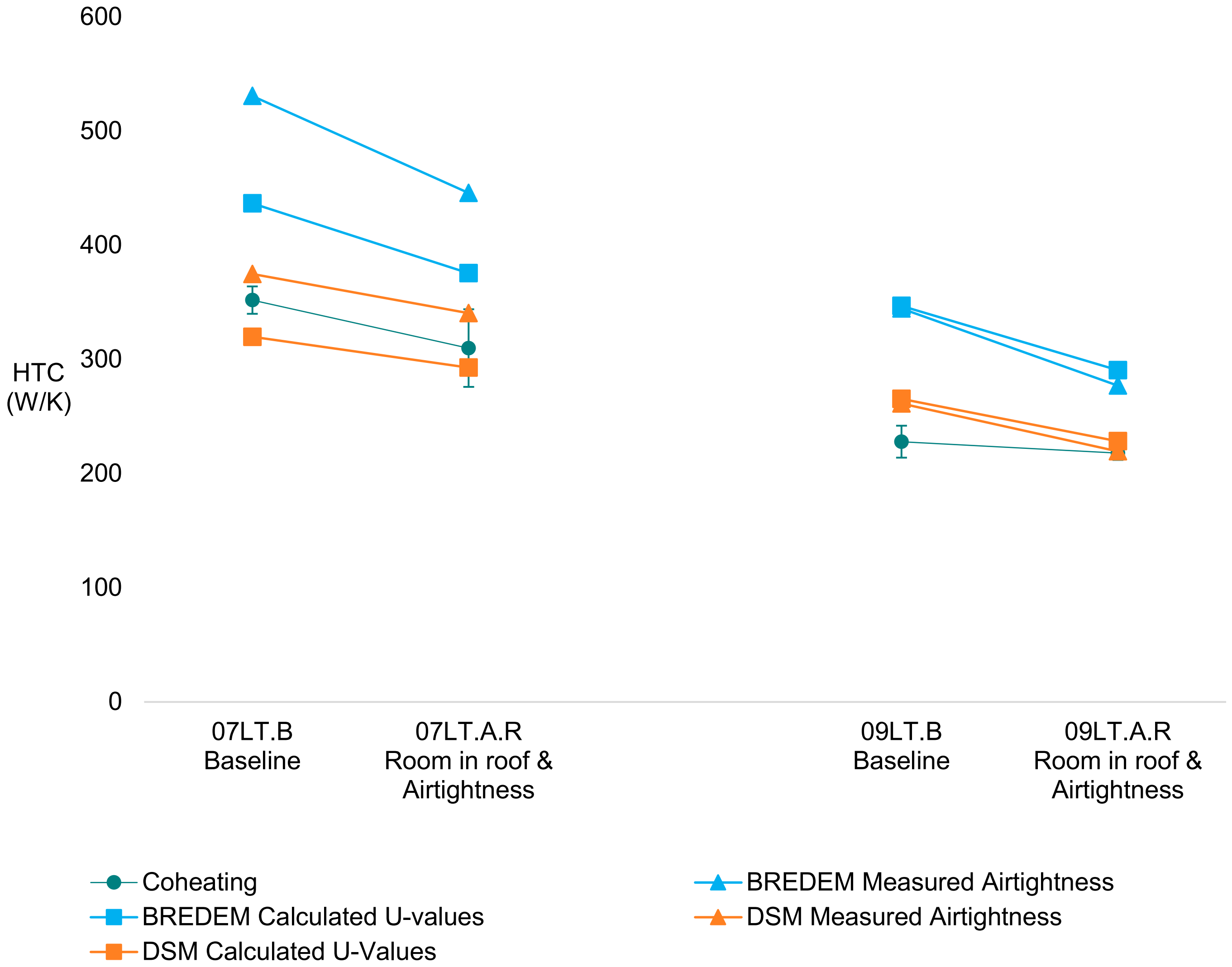


Figure 3-36 HTC calibration step 3: Calculated U-values

3.4.4 Measured vs Modelled HTC calibration step 4: Measured U-values

In this step, the models use the measured U-values which require resource intensive in-situ testing. The impact of this compared to the previous calibration stage is shown in Figure 3-37.

- The measured U-values for external walls were in some instances higher than they were calculated to be in the homes, e.g., the gable wall, some stud walls and the flat ceiling, however, in some instances they were lower, e.g., the dormer wall and ceiling and slope ceilings. The net impact of including the measured U-values was to increase the BREDEM and DSM HTC in 07LT, though almost no change occurred in 09LT.
- Including the measured U-values in the RdSAP model substantially reduced the HTC in both homes, compared to the RdSAP default prediction used in the EPC. This default prediction incorporates the unrealistic room-in-roof simplification of U-values and geometry. Thus, adding in measured data could bring the HTC prediction more in line with the other models and the coheating test, though it still predicts higher heat loss than the other approaches.
- The addition of the measured U-values means the DSM predictions are within the uncertainty measurement of the cheating test pre and post-retrofit for 07LT, though in 09LT this only occurs for the post-retrofit HTC.

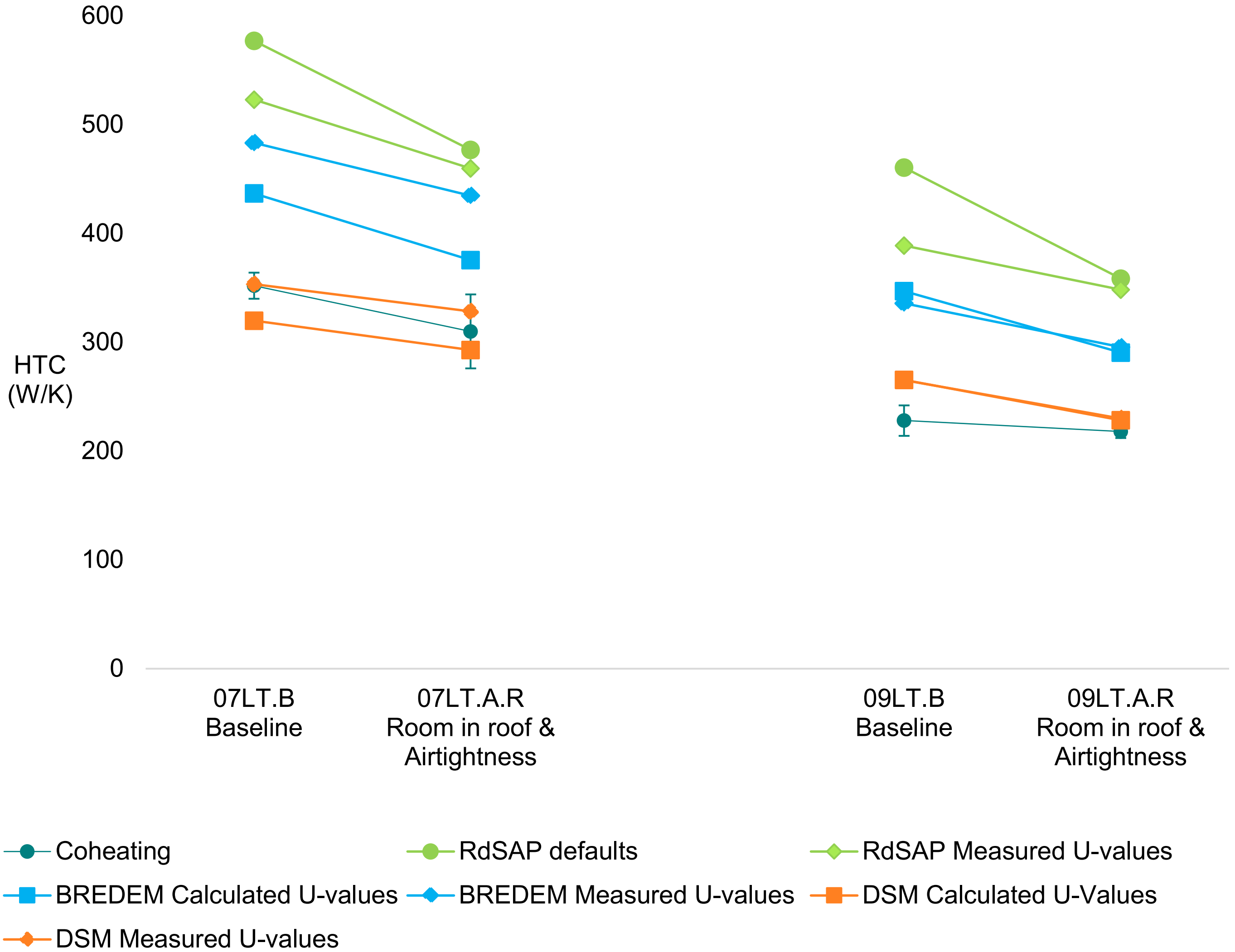


Figure 3-37 HTC Calibration step 4: Measured U-values

Measured vs. modelled HTC summary

The room-in-roof retrofit coupled with the airtightness improvements made substantial reductions in the heat loss of the case study homes. The models which use the default assumptions predict HTC savings of between 9 % and 15 % in 07LT, and 15 % and 25 % in 09LT.

When the default input data were updated, the benefits were predicted to be lower, between 7 % and 12 % for 07LT, and 10 % and 12 % for 09LT. These are more comparable with the coheating HTC reductions of (12 ± 10) % and (4 ± 7) % for 07LT and 09LT, respectively.

As found in other DEEP case studies, the RdSAP simplification of the room-in-roof geometry and default U-values cause EPCs to make substantial overestimations of heat losses from the homes, and overpredictions of the benefits of room-in-roof retrofits.

When using default inputs, steady-state models tend to predict higher HTCs than DSM, which in turn predicts higher HTC than the coheating tests. When airtightness and U-value defaults are updated with measured or calculated values, DSM predictions can be within the uncertainty values of the coheating tests.

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, energy models can predict the impact of retrofits on these metrics.

All the models share matching occupancy profiles and internal heat gain inputs as defined in the RdSAP conventions. These are described in detail in the DEEP Methods 2.01 Report. Matching occupancy profiles were used to provide a comparison between the modelling approaches, based on 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 the results to 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. The RdSAP age-band default data underestimated the baseline EPC scores, and thus overestimated the retrofit savings.

3.5.1 Potential reasons for differences in annual model outputs

Fundamental differences between the steady-state and DSM models led to discrepancies in the predicted heat loss and energy calculations for the DEEP case studies. The differences between the models are discussed in the DEEP Methods 2.01 Report, and 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 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 differs 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 in 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 lead to lower heat loss, and this is more pronounced in dwellings with a greater area of south facing plane elements. The reverse can occur during the darker winter months, although the thermal mass of constructions retains some heat after sundown.

Geometry
DSM models exclude areas and volumes of 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 BREDEM inputs in the same way as internal gains. The weather file used in the DSM was selected due to the close similarity between the monthly average external temperature values (CIBSE Test Reference Year file for Leeds) as discussed in the DEEP Methods 2.01 Report.

Differences specific to 07LT and 09LT
For the baseline scenarios, using measured infiltration rates and U-values, BREDEM predicts a space heating demand that is 8,176 kWh/year higher than DSM for 07LT, and 4,300 kWh for 09LT. In the majority of the other DEEP case studies, the HTC value 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 on the thermal transmittance, area of construction 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 for 07LT is 16,474 kWh, compared to the DSM estimate of 15,236 kWh, meaning that BREDEM predicts a demand which is higher by 1,237 kWh. For 09LT, the normalised demand is 11,656 kWh in BREDEM, compared to 12,020 kWh in DSM, meaning BREDEM is 364 kWh lower. The BREDEM calculations can be further normalised using the DSM volume of conditioned space (30.21 m^3 less in 07LT and 56.79 m^3 less in 09LT). Following this final adjustment, the BREDEM estimate for 07LT is 157 kWh higher than the DSM output, and 1,775 kWh lower for 09LT.

In keeping with other DEEP case study terraced dwellings, the orientation of both buildings has some impact on the model outputs. The large gable wall in 07LT is orientated towards the south-south-east, and the front of both houses face west-south-west. These are simplified in RdSAP, meaning that the front of the houses face directly west in this instance. This results in the DSM model for 07LT including 681 kWh more solar gain than the BREDEM model. It also means that the large gable wall is subject to higher surface temperatures at times, which reduces heat transfer in the model. However, this wall has a second skin built after the demolition of the original neighbours, which reduces this effect when compared to a standard solid wall construction. The RdSAP model for 09LT includes slightly higher solar gains than the DSM version. This is due to the large neighbouring dwelling of 11LT being a whole storey higher than 09LT, reducing gain through the second floor glazing and at the rear on all floors.

3.5.2 Impact of retrofits on EPC bands

Several policy mechanisms set EPC targets, and the Government has set an ambition that all homes, where practically possible, should achieve 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 3-38. The space heating demand predicted by DSM is the only output that differs in the comparative EPC calculations.

- Pre-retrofit, the homes were both considered to be in band D according to the RdSAP model used for EPCs. However, 07LT was a low D while 09LT, which is a mid-terrace and so has less heat loss area, was a mid D.
- Pre-retrofit only the BREDEM default model predicted 07LT to be a band E, and only the BREDEM with airtightness and U-value inputs updated with measured data predicted 09LT to be a band C.
- Post-retrofit no models predicted 07LT to improve to a band C, since the heat loss in the home was dominated by the uninsulated solid wall on the ground and first floors which were not improved by the retrofit.
- Post-retrofit the steady-state models predicted that 09LT could achieve EPC band C, since they already predicted the home to be a mid to high band C. The DSM, however, did not consider the retrofits able to raise either of the houses to a band C.

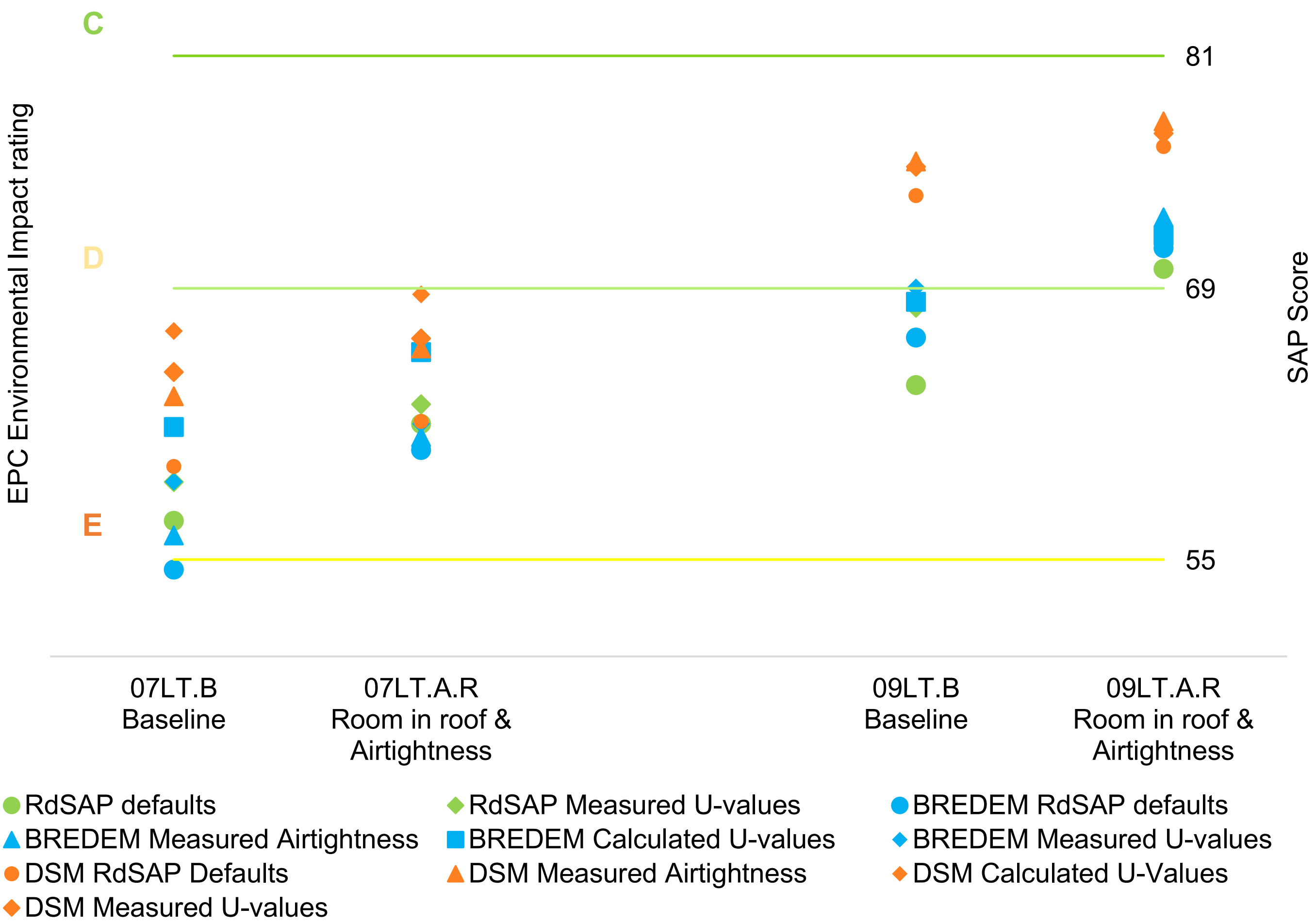


Figure 3-38 Predicted impact of retrofits on EPC band

3.5.3 Impact of retrofits on annual space heating

The Social Housing Decarbonisation Fund (SHDF) Wave 1 evaluates retrofit success by setting a target of 90 kWh per m² for annual space heating retrofits [9]. The predicted annual space heating demand attributable to the retrofit undertaken in the case study dwellings is shown in Figure 3-39.

- The choice of model and data used has a significant impact on the overall space heating requirement in the homes, the baseline requirement in 07LT ranges from 99 kWh/m²/yr using DSM with calculated U-values to 179 kWh/m²/yr using BREDEM with measured infiltration (180 % higher).
- 09LT is predicted to have substantially lower space heating requirements than 07LT since it is a mid-terrace and has less heat loss area and proportionally more party wall.
- The reduction in space heating from the room-in-roof retrofit in 07LT ranges from 7 % to 17 %, while the reduction in space heating from the room-in-roof and airtightness retrofits in 09LT ranges from 11 % to 22 %.
- In both homes the DSM predicts smaller reductions than steady-state models and the greatest reductions are predicted when RdSAP default inputs are used.
- No models predict the SHDF target can be achieved in 07LT, though 09LT is shown to achieve the SHDF target post-retrofit using the DSM model in all scenarios, as well as in BREDEM when infiltration inputs are updated with measured data. Neither RdSAP models predicts the target can be achieved.

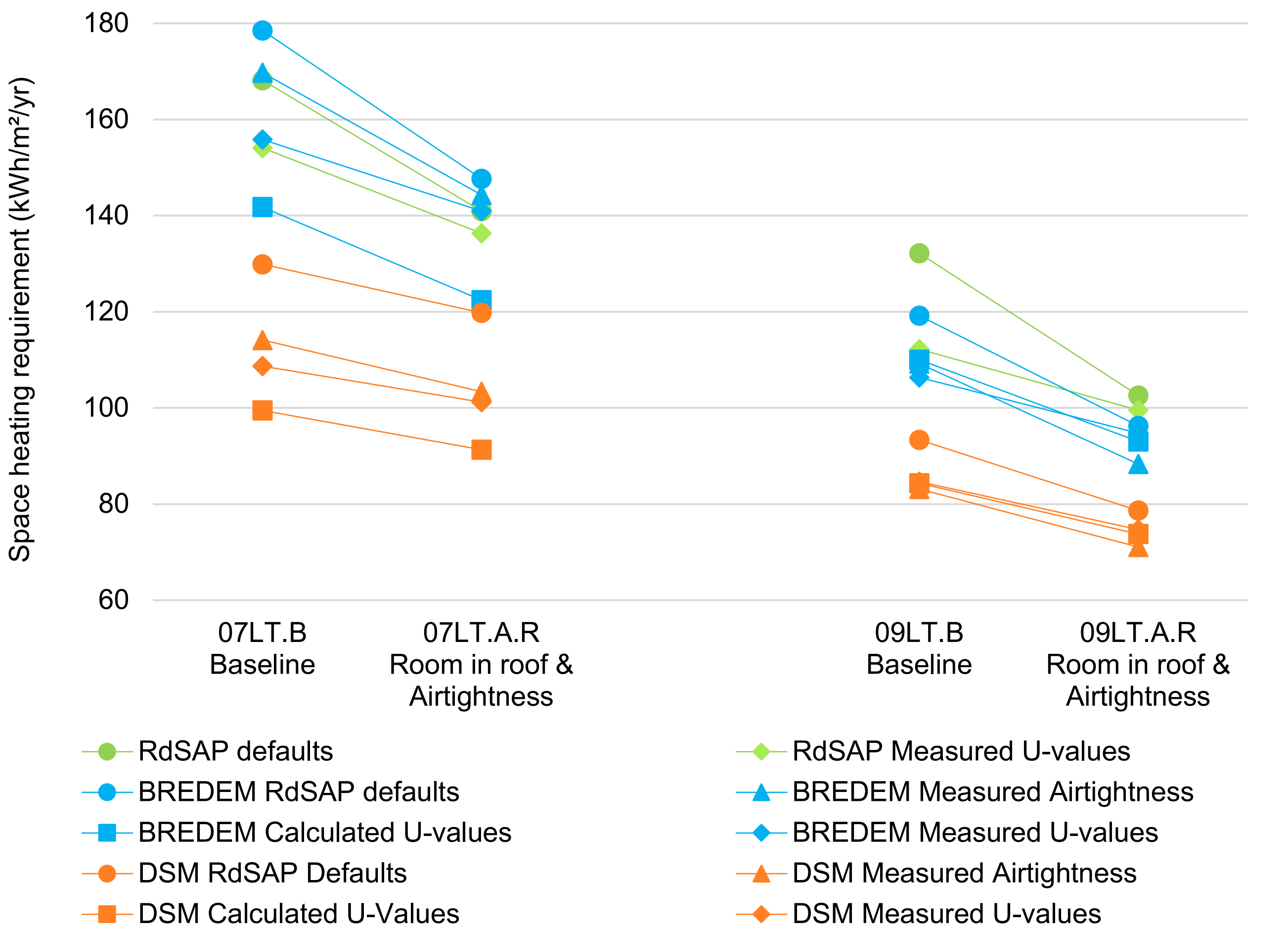


Figure 3-39 Predicted reduction in annual space heating demand

3.5.4 Impact of retrofits on CO_2 emissions

Heating homes is responsible for around 15% of the UK's CO_2 emissions [10]. The predicted reduction in CO_2 emissions achieved by the case study retrofits is shown in Figure 3-40, based on fuel carbon emissions factors in RdSAP.

- The retrofits are predicted to achieve a reduction in annual CO_2 emissions ranging from around 6 % to 15 % in 07LT and 9 % to 19 % in 09LT.
- In both homes, the DSM predicts lower savings than the steady-state models.
- The largest savings are predicted when default RdSAP inputs are used, since the simplification of the room-in-roof means that the pre-retrofit U-values are much higher than calculated or measured. The savings are therefore greater when the room-in-roof is insulated.

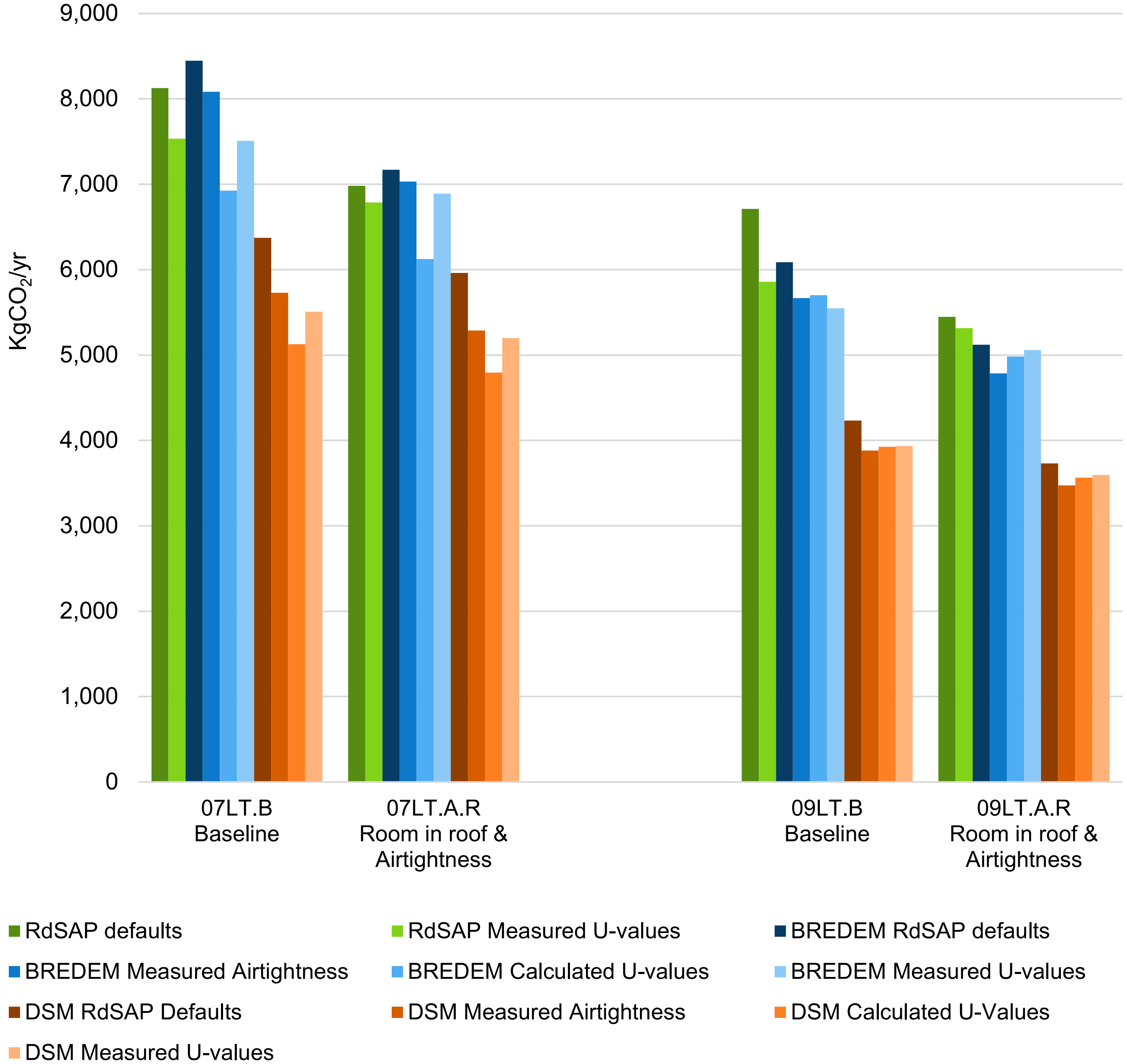


Figure 3-40 Annual CO_2 emission savings achieved by each individual retrofit

Predicting EPC band, space heating and carbon reductions summary

The homes had different starting SAP scores. Since 09LT is a mid-terrace, it had a higher score. However, both were judged to be EPC band D in the base case. Because of this, the retrofits in 09LT were successful in bringing the home up to EPC band C, but this was not the case for 07LT.

As with other DEEP case studies, DSM predicts lower space heating savings than the steady-state models, since the specific impacts of hourly weather, useful solar gains, geometry and orientation are all considered.

The reduction in CO_2 emissions achieved in the homes was between 6 % and 19 % depending on which model and inputs were used. Again, DSM predicts lower savings due to assuming lower space heating demand.

The space heating reductions were slightly higher, between 7 % and 22 %, since the CO_2 emissions in the home were influenced by how water heating, lighting and power were provided, which were not changed by the retrofits. Despite the reduction, the EPC predicts that neither retrofit would be capable of achieving the SHDF annual space heating targets of 90 kWh/m²/yr. However, if the default input values were updated with measured infiltration and U-values, this target may be achieved in 09LT.

3.6 Overheating risk of retrofitting

As part of the overall DEEP project, Loughborough University carried out parametric analysis of overheating scenarios, using a 10-year weather data file. The overheating analysis in this section is complementary to this work and uses the overheating assessment method from CIBSE TM59, which is cited in the PAS2035 guidance [11].

Two metrics are used to assess whether a dwelling could overheat. Criteria A of TM59 is taken from another CIBSE publication, TM52: The limits of thermal comfort: avoiding overheating in European buildings [12]. The two assessment criteria are defined as follows:

A. For living rooms, kitchens, and bedrooms: the number of hours during which 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 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 was 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 DSY files available for the 14 UK regional locations, which use actual weather data that simulate various heatwave intensities. DSY1 represents a moderately warm summer; DSY2 represents a short, intense warm spell; and DSY3 represents a longer, less intense warm spell [13]. 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 of the windows that has the strongest influence on overheating risk, and these are illustrated in Figure 3-41.

There is very little difference between the window opening areas in both houses, and between pre- and post-retrofit stages. The main differences are at the rear and in the room-in-roof areas. The two dwellings have differently shaped extensions at the rear, which means 07LT has an additional window opening on the first-floor landing. There are opening skylights in the room-in-roof bedrooms in 09LT, whereas 07LT has a small dormer construction at the rear of the room-in-roof, although the openable areas of the windows in both properties are very similar overall.

Figure 3-41 Percentage of opening area for openable windows

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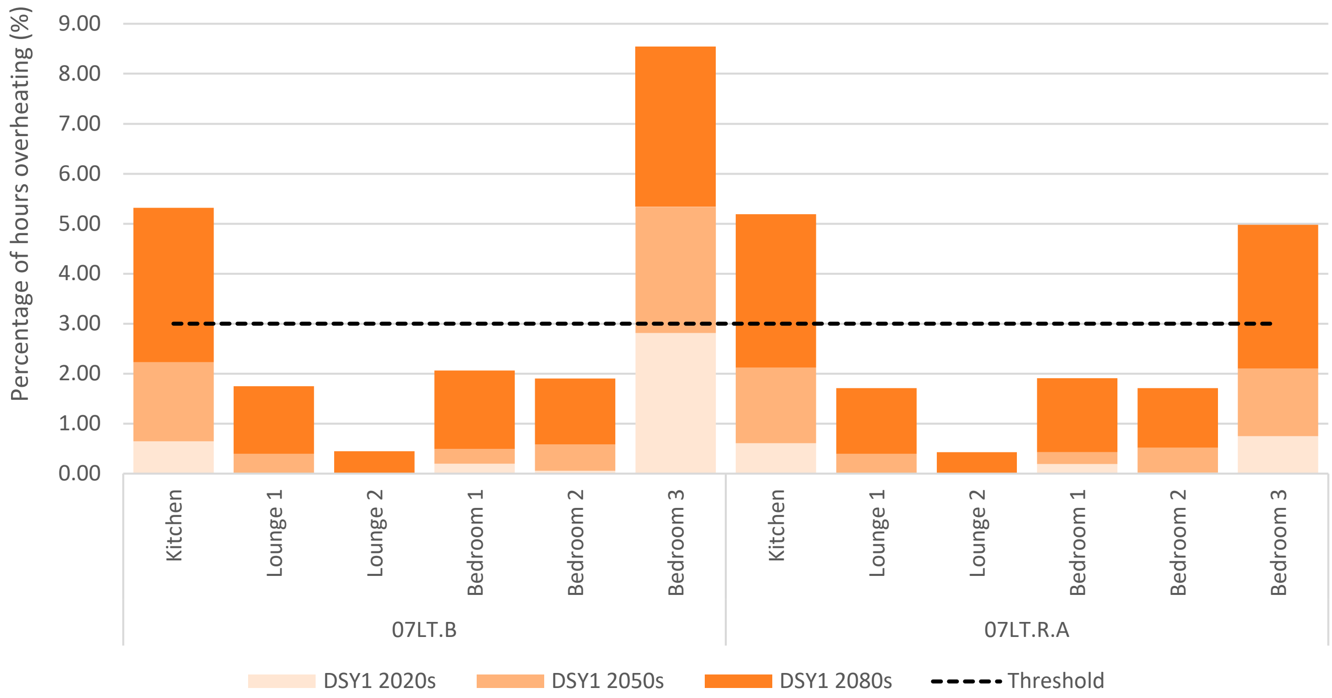
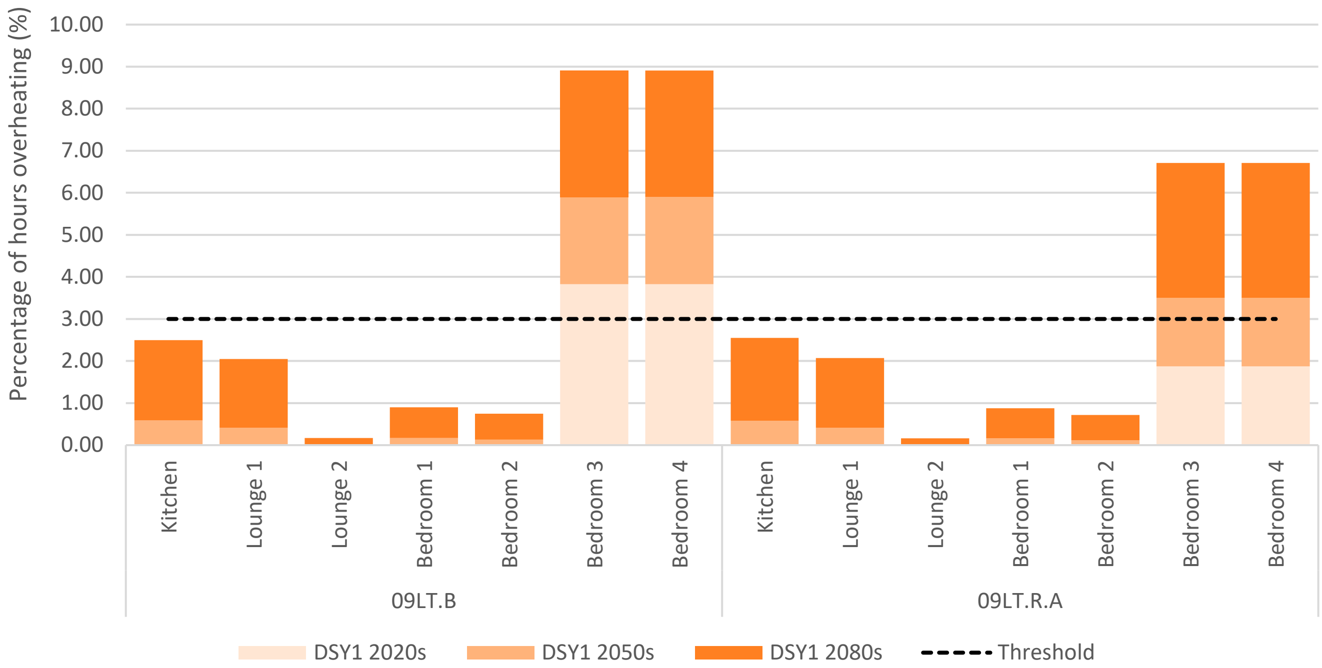
As shown in Figure 3-42, most rooms were not at risk of overheating pre- or post-retrofit. The only rooms at risk were the kitchen and Bedroom 3 in 07LT, and Bedrooms 3 and 4 in 09LT. All three of these bedrooms are located in the room-in-roof and, accordingly, the room-in-roof retrofit substantially reduced the overheating severity in the bedrooms. This was achieved because the insulation limits the amount of solar radiation entering the room-in-roof through the opaque elements during the summer months. The overheating risk in the kitchen, which is not located in the room-in-roof, is unaffected by the retrofit.



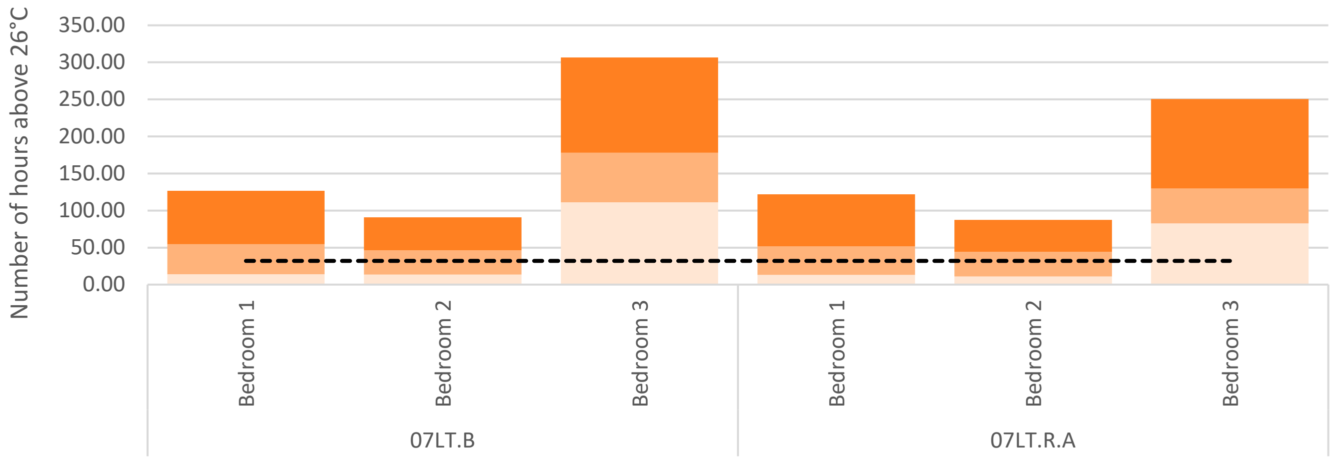
07LT Criteria A



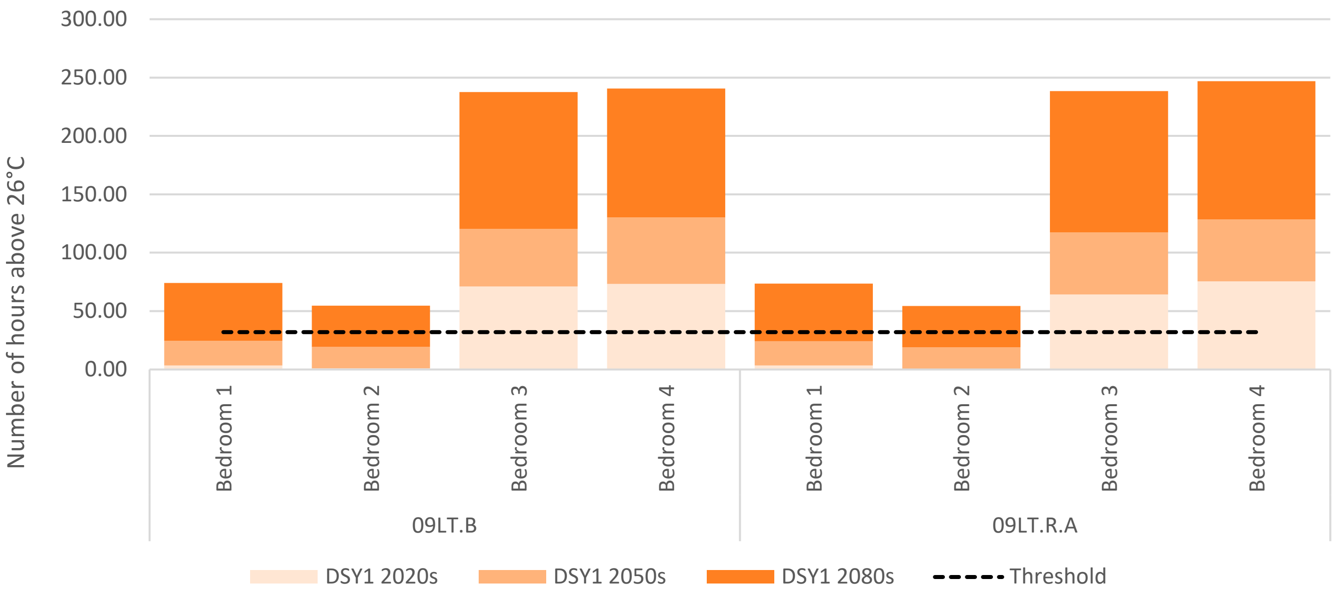
09LT Criteria A

Figure 3-42 Modelled overheating under TM59 Criteria A

Despite this reduction in overheating risk according to Criteria A, there is no similar benefit according to Criteria B, as shown in Figure 3-43, although it does slightly improve for 07LT. Thus, while the retrofit reduced the general overheating risk in the bedrooms, the number of extreme overheating periods over 26 °C remained similar to the baseline.



07LT Criteria B



09LT Criteria B

Figure 3-43 Modelled overheating under TM59 Criteria B

Overheating risk of retrofit summary

Insulating the room-in-roof reduced the amount of solar radiation entering the case study homes during the summer months which resulted in reduced overheating risk being predicted post-retrofit. However, the upstairs bedrooms were still expected to overheat beyond recommended thresholds to allow for comfortable sleeping conditions, and so the installation of insulation alone was not sufficient. Additional strategies to maximise purge ventilation or further inhibit solar gains would be needed to remove the risk completely.

3.7 Retrofit costs and payback

This section looks at the costs of undertaking the retrofits. However, this is only a single case study, and 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 the retrofit. It is also important to note that the cost data presented here may not be representative of the national retrofit market. Since retrofits tend to be highly 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 relate to only one house type and a limited range of retrofit specifications. Additionally, the costs are expected to be higher than benchmarks, as the project does not benefit from any of the economies of scale of neighbourhood schemes.

Costs associated with decorating are outside the scope of this project. These costs have been found to represent around 14 % of the cost of IWI [14], though it is recognised that they may be different for the retrofits in these case studies.

The costs of the 07LT and 09LT retrofits are outlined in Table 3-8 and Table 3-9. The total retrofit costs were £35,166 and £36,736, respectively, though 34 % and 32 % of these costs were to undertake enabling works not directly linked to the retrofit including:

- The roof was found to have pre-existing leaks in two locations which had to be repaired requiring scaffolding to be installed at significant cost.
- When the ceilings were removed, black soot fell from the previously untouched roof space causing several days of delay to undertake cleaning of the rooms prior to work commencing. If this were an occupied home this would have caused significant damage and disruption to the rest of the house since the soot escaped to the first floor in addition to the room-in-roof.
- When the roof timbers were exposed, they were deemed inadequate and so were reinforced to ensure they could take the weight of the additional wood fibre insulation.
- A radiator and piping on the knee walls needed to be removed to allow the insulation to be installed, then relocated to the load bearing party walls.
- The additional thickness added to the ceiling and walls meant that bespoke loft and knee wall access hatches had to be made by a joiner since no suitable product could be sourced.
- When the insulation boards were delivered, supply issues meant that only multiple boards of different thicknesses could be sourced. This meant the boards' tongue and groove edges were not all compatible, requiring additional labour to make the board edges flush so they would butt up against each other to ensure a continuous insulation layer.
- The breathable plaster supplied required additional drying time and additional layers that needed to be installed, meaning substantially more time for plastering compared to a gypsum plaster finish.

These issues meant that an additional £23,700 was spent across the two homes, a cost that the householders would need to fund, and which was unpredictable at the start of the project. Such costs are not necessarily factored into policy cost projections for retrofit funding. However, there were no additional costs associated with the airtightness or window repair.

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Table 3-8 Cost of retrofits

Retrofit	i) Retrofit activity	Retrofit costs	ii) Additional enabling work required	Enabling work costs
07LT				
07LT Room in roof	Removal of existing wall coverings and ceilings, installation of Woodfibre insulation and plaster.	£ 21,500	Roof repairs, scaffolding, cleaning, plastering delays, extra skips, strengthening roof timbers, plumbing, bespoke loft hatches, decoration, additional delivery costs, additional installation time due to incorrect insulation boards delivered	£ 12,100
07LT General sealing	Sealing around penetrations in external walls and floor perimeters	£ 446	n/a	-
07LT Window draught proofing	Addition of draught proofing strips and refurbishment of timber sash windows	£ 1,120	n/a	-
09LT				
09LT Room in roof	Removal of existing wall coverings and ceilings, installation of Woodfibre insulation and plaster.	£ 21,500	Roof repairs, cleaning, additional scaffolding, plastering delays, extra skips, strengthening roof timbers, plumbing, bespoke loft hatches, decoration, additional delivery costs, additional installation time due to incorrect insulation boards delivered	£11,600
09LT General sealing	Sealing around penetrations in external walls and floor perimeters	£ 446	n/a	-
09LT Window draught proofing	Complete rebuilding of window opening mechanisms, repairs to timbers sash windows including draught proofing strips	£ 3,190	n/a	-

Table 3-9 Breakdown of cost of retrofits

Retrofit	Cost	Proportion of total cost	Treated area (m²)	Cost per area (£/m²)	Benchmark (£/m²) [15]
07LT					
07LT Room-in-roof	£33,600	96 %	88	£331	-
07LT General sealing	£ 446	1%	60	£7	-
07LT Window draughtproofing	£ 1,120	3%	5 windows	£224 per window	£300 - £1,000 per window
Total 07L.R.A	**£ 35,166**				
09LT					
09LT Room-in-roof	£ 33,100	90%	79	£363	-
09LT General sealing	£ 446	1%	60	£7	-
09LT Window draughtproofing	£ 3,190	9%	5 windows	£638 per window	£300 - £1,000 per window
Total 09L.R.A	**£ 36,736**				

Overwhelmingly, the room-in-roof retrofits dominated the overall costs, but there is no reliable benchmark data to explain the average costs of this sort of home improvement. The costs were high largely because pre-existing failings in the building fabric (roof leaks) were not discovered until the retrofit started.

Additionally, since the roofs had not previously been disturbed, the mess caused from over one hundred years of soot build up was not inconsiderable, and as such the retrofit was particularly intrusive for the entire home. Another disruptive consideration was the need to remove all the old materials through the house via the main staircase, as well as bringing all the new materials up to the room-in-roof, which caused significant additional mess. This retrofit may not therefore be appropriate for homes which are occupied.

The difference in cost between the windows represents the relative efforts needed to repair the windows, i.e., the windows in 09LT underwent extensive repairs, while those in 07LT were repaired with a lighter touch. This difference, however, did not manifest in any measurable difference in airtightness performance.

3.7.1 Predicted fuel bill savings

The impact of the retrofits on household dual fuel bills is shown using SAP fuel prices of 3p per kWh for gas and 13p per kWh for electricity. These values are substantially out-of-date at the time of writing. The impact of this on paybacks and fuel bill savings are discussed in the DEEP Report 2, DEEP Case Studies Summary. The indicative annual fuel bills are shown in Figure 3-44.

- The fuel bills in 07LT and 09LT are predicted to reduce between 5 % and 14 %, and 7 % and 17 %, respectively.
- The DSM model predicts substantially lower fuel bills and therefore fuel bill reductions than the steady-state models.
- EPC models when the default RdSAP values are used, predict the largest savings because the default U-values for uninsulated rooms-in-roof are unrealistically high.

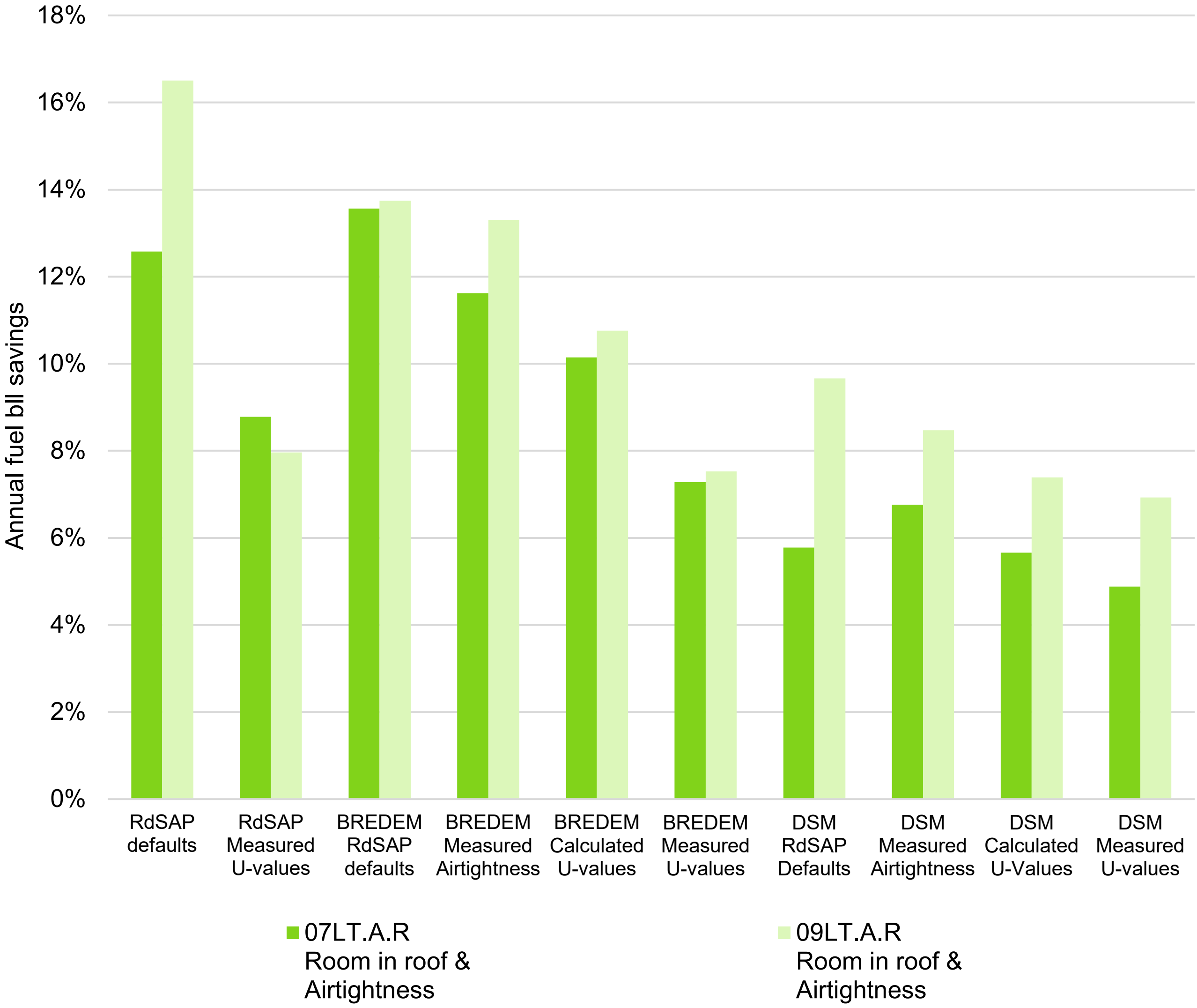

Figure 3-44 Predicted annual fuel bill savings achieved by the retrofits

3.7.2 Predicting simple payback of retrofits

The simple payback time, (i.e., not considering fuel price inflation or discount rates) calculated from the retrofit costs and annual fuel bill savings estimates for the case study are shown in Figure 3-45. Recent fuel and retrofit price increases will significantly affect payback rates.

- Payback rates vary depending on which model and input data are used, but range between 150 and 670 years.
- Payback rates are substantially higher for these case studies since the additional enabling works (repairing the roof, strengthening roof timbers, extensive cleaning etc.) were substantial. It is not known if these would be incurred by similar retrofits in other homes.
- DSM predicts lower fuel bills and savings, and thus DSM payback times are generally longer.
- RdSAP and models using RdSAP inputs have the lowest payback rates, since they predict that the savings from the room-in-roof retrofits would be higher than measured in these case studies.

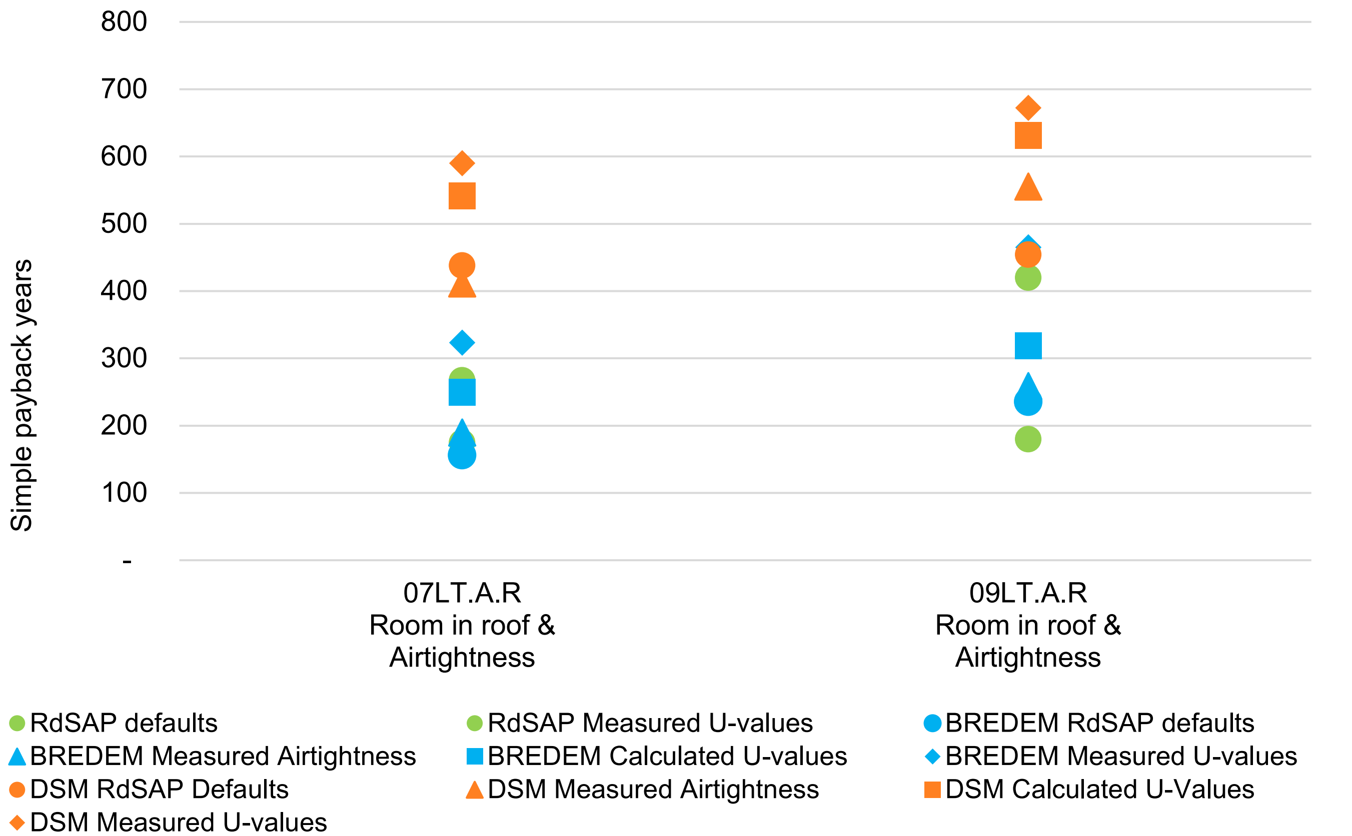

Figure 3-45 Simple retrofit paybacks

Retrofit costs summary

The models using RdSAP inputs predict the retrofits would collectively save up to 17 % of the homes' annual fuel bills. However, when default inputs are replaced with measured values the savings may only be a third of this amount, suggesting any predictions based on EPC outputs may be exaggerated.

The additional works experienced in these case studies (around a third of the total installation costs) were unexpected, but may be representative for some historic homes in the UK. These excessive enabling costs mean that, regardless of which model and assumptions are used, the retrofits would not have payback times of less than 150 years.

4 Conclusions

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

Complex air leakage

The homes were found to be relatively airtight (around 12 $m^3/(h\cdot m^2)$ @ 50 Pa) compared to the EPC model default inputs (around 18 $m^3/(h\cdot m^2)$ @ 50 Pa). Yet, since the homes are large, the absolute amount of background ventilation heat loss was still proportionally large, constituting between 16 % and 23 % of the heat loss. It is not known if the n/20 rule adequately predicts this heat loss, and this may be one of the reasons why the closing-the-loop analysis comparing the aggregated whole house heat loss (coheating test) and disaggregated approaches is not in good agreement.

Uncertain success for airtightness improvements

The homes underwent general sealing around floor perimeters on the first floor and in the room-in-roof to reduce the background ventilation heat loss. Similarly, they had sealing around the accessible penetrations to the outside (e.g., pipes and vents in external walls). However, while these measures were successful in inhibiting air leakage pathways, the success of these measures on the whole house was negligible. This is because many of the air leakage pathways were complex and interconnected, so the sealing redirected rather than eliminated air pathways to the outside. The implication is that, in homes with complex air leakage, it is unlikely that the simple sealing of accessible air leakage pathways would be effective, and that more intrusive and disruptive airtightness works to provide a continuous primary air barrier throughout the house would be needed. It is not possible to know if a home has complex air leakage pathways without undertaking air leakage detection.

Inter-dwelling air exchange

As observed in many DEEP case study homes, air leakage was complicated by the presence of inter-dwelling air exchange. In 07LT and 09LT, this ranged from 9 % to 18 % of the infiltration rate measured by the blower door. A significant proportion of this was observed to take place via the room-in-roof and was eliminated following the room-in-roof retrofit. More generally, inter-dwelling air exchange may result in an overestimation of the amount of background ventilation heat loss. This may be another reason why the n/20 rule of thumb resulted in the disaggregated approach to measuring the heat transfer coefficient (HTC) predicting higher heat loss than the coheating tests.

Timber sash window refurbishments

The sash windows in the homes had damaged timber, inadequate seals causing air leakage, and faulty opening mechanisms. The repairs and refurbishment, however, did not achieve significant improvements in airtightness, and so substantial air leakage was still observed between the windows and the timber frames and at the sash weight boxes. There may be potential to achieve heat loss reductions by refurbishing timber sash windows in homes, but it is important to combine refurbishment work with air leakage detection to ensure the savings are achieved.

Room-in-roof RdSAP simplifications
The measured U-values in the room-in-roof elements in the homes ranged from (0.29 ± 0.09) to (1.72 ± 0.21) W/(m^2·K). Yet the simplification of the room-in-roof inputs in RdSAP assume that all elements have a U-value of 2.3 W/(m^2·K). Additionally, the RdSAP assumptions do not account for there being two party walls, as is the case for 09LT. This means that when insulation is applied to the room-in-roof, EPC tends to predict larger savings than are achieved in practice. Addressing these simplified inputs for rooms-in-roof is likely to improve EPC accuracy.

Importance of gable wall heat loss in end-terrace homes
The two case study homes were in many respects nearly identical, with the main exception being their building form. 07LT is an end-terrace while 09LT is a mid-terrace. The implication is that the end-terrace, because it has a gable wall and therefore a large heat loss area, has substantially higher (124 W/K) heat losses, i.e., 09LT's HTC was only two thirds that of 07LT. The significance of this is that end-terrace homes have higher space heating demands and lower EPC ratings than their neighbours, and therefore could be specifically targeted for support.

EPC band ranges
Both homes were awarded the same EPC band D pre-retrofit. Both received the same retrofit and improved their SAP scores by a similar margin, yet 07LT was still considered band D post-retrofit, while 09LT was considered band C. The reason is that the EPC band ranges are relatively broad. 07LT had considerably more heat loss than 09LT so was assessed as a low band D pre-retrofit, while 09LT was a higher band D. Landlords and householders may expect all homes in the same band to have relatively similar performance levels, and that similar retrofits would yield the same improvement in homes with the same starting EPC bands. As shown in these case studies, two neighbouring homes with the same EPC, which have the same retrofit, can have different outcomes. EPC band ranges may therefore need reconsidering to improve the transparency and understanding of the rating system.

Room-in-roof retrofit performance
The room-in-roof retrofit in 09LT (mid-terrace) was predicted to bring the home up to EPC band C. However, when the RdSAP defaults were updated with the measured inputs, the home did not achieve band C. This means that homes may be judged to align with Government ambitions for band C, while not being particularly energy efficient. In 07LT (end-terrace), the retrofit alone did not reduce the heat loss in the home enough to achieve EPC band C according to any of the models or input values. This means that, for end-terrace homes, additional retrofits are likely to be needed to achieve Government EPC targets.

Room-in-roof retrofit disruption
These case study homes had roofs which had been undisturbed for decades, perhaps more than a hundred years. Work in these areas to allow for insulation to be installed revealed and disturbed excessive amounts of black soot, which permeated the whole house and required extensive cleaning before the retrofit could be installed. Additionally, the intrusiveness of the movement of labour and materials up and down the central staircases means it is unlikely that room-in-roof retrofits would be compatible with occupied homes.

Enabling costs of retrofits

Around a third of the retrofit costs (over £11,000 and £12,000 in 07LT and 09LT, respectively) were not directly related to the retrofit itself. They related to the cost of repairing roof leaks, strengthening roof timbers, additional cleaning and decoration caused by black soot, extra scaffolding, plumbing to move radiators, and additional plastering layers required by the breathable insulation system. This has implications for budgets set by individual householders and national retrofit schemes. The potential for retrofits to trigger enabling works that relate to general building maintenance is relatively unpredictable. Furthermore, these costs may not be identified by retrofit surveys and are not well understood on a national scale.

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