Department for Energy Security & Net Zero

LEEDS BECKETT UNIVERSITY
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DEEP Report 2.09

Case Study 27BG

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Executive summary

27BG is one of fourteen solid walled DEEP case study homes. In this home building performance tests were undertaken to investigate the success and risk of retrofitting suspended timber floors and how the results compare to predictions.

The case study provides useful insights into the success and challenges of retrofitting suspended timber floors, though more data are needed in order to make broader generalisations for the housing stock. The findings should be interpreted in the context of the house typology and testing conditions. The house is relatively unusual as it is a back-to-back mid-terrace home with a basement (over 50 % of the home's envelope area is party walls) which made party wall heat loss an area of uncertainty.

In this case study, although the retrofit achieved a 56 % reduction in U-values, no reduction in the home's heat transfer coefficient (HTC) was observed by coheating tests, for either the XPS or mineral wool suspended timber floor retrofits. This may be because the house had a small floor area, meaning the 4 W/K improvement predicted by the U-value reduction was too small to identify, relative to the uncertainty of the test.

Energy models were performed to further explore the potential heat loss reductions that may be achieved. The energy performance certificate (EPC) for this house suggests the retrofits may reduce HTC by up to 5 %, although when the default inputs for U-values are entered this falls to 3 %. This saving is not sufficient to materially affect the EPC score or change the home's EPC band under any of the steady-state or dynamic energy model scenarios. For instance, replacing the EPC default data in the models with measured infiltration rates from blower door tests and U-values derived from heat flux measurements altered the predicted HTC by more than double the amount that the floor retrofit was predicted to achieve.

Other benefits of insulating floors include the reduction of draughts and improvements in floor surface temperatures, both of which may improve the thermal comfort of occupants. The investigations in this case study identified improved floor surface temperatures post-retrofit, however there was no measurable improvement in airtightness. This may be because the retrofits were installed without an air barrier membrane, which highlights the importance of including this in floor retrofit specifications. More data from different types of floor retrofits are required to understand the potential comfort benefits of floor insulation and the detailed design and construction factors required to achieve them.

It is worth noting that, even when uninsulated, this home still achieved an EPC rating of C, due to being a back-to-back mid-terrace house and therefore only having one wall exposed to the outside, meaning heat losses were relatively low. This is called the *penguin effect*, in reference to the huddling of penguins in severe weather, and also affects blocks of high- and low-rise flats. The penguin effect could have significance for retrofit policy. A similar back-to-back home on the same street but an end of terrace was assessed to have an EPC band E rating.

1 Introduction to 27BG

Case study 27BG is a two-bed 1890 solid walled dwelling with a room-in-roof. It is a back-to-back style terrace home resulting in a very large area of party wall. Two comparable suspended timber ground floor retrofits were undertaken. In the first, XPS boards were installed between the timber joists. This was then removed and replaced with mineral wool of equivalent performance. The case study provided the opportunity to evaluate retrofits in house types with large areas of party walls, explore the risks and performance of suspended floor retrofits in this type of house and compare two common ground floor retrofit approaches.

1.1 DEEP field trial objectives

27BG is one of fifteen DEEP case studies, which, collectively, investigate 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 consequence	More retrofit scenarios need modelling to confirm condensation, underperformance, air quality and comfort risks.
Cumulative impact	Piecemeal retrofits are common, clarity is needed on impact of 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 yet this measure represents only 0.5 % of ECO measures. Greater clarity is required on potential energy savings and costs in various house types.
Airtightness retrofit	Infiltration can undermine retrofits, balancing airtightness and indoor air quality is an important issue. Greater understanding is likely to enable increased energy savings and reduce under-ventilation risk.
Neighbour risk	We investigate whether whole house or staged retrofits affect condensation risks 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 committee, and expert QA panel, objectives have been refined and the seven discreet research questions listed below have been developed, and are used to discuss the findings.

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 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 coheating test?*

Data collected from case study 27BG contribute to the formation of a body of evidence that addresses these questions.

1.3 Case study house information

27BG, shown in Figure 1-1, is a two-bedroom property in Leeds, West Yorkshire, built around 1890. It is a mid-terrace back-to-back (i.e., neighbours to the sides and rear), made of solid nine-inch brick, so it has only one external wall (front). It also has a chimney stack, a room-in-roof, a half-basement and a suspended timber ground floor. Entry is directly into the Living Room, with the Kitchen also on the ground floor. Stairs up to the middle floor (comprising Bedroom 1 and Bathroom) are at the rear of the Living Room. Stairs down to the basement, which spans part of the ground floor, are accessed through the Kitchen. Bedroom 2 is in the roof. While the Living Room and Bedroom 1 have chimney breasts, they are both sealed.

This is a typical construction for the local area, though not nationally. No estimates of back-to-back homes in the UK exist, though some findings from this case study are relevant to solid walled terraced homes of similar construction, where solid-wall insulation is not practical or desirable, and where suspended floor retrofits represent one of the remaining retrofit strategies. There are over five and a half million pre-1918 homes in England and Wales [1] and two-bed terraced houses make up around 9 % of these homes [2]. Additionally, the case study provides insight into the impacts of retrofits in properties where the external surface is dominated by party walls, including blocks of solid walled flats.

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Figure 1-1 Case study house

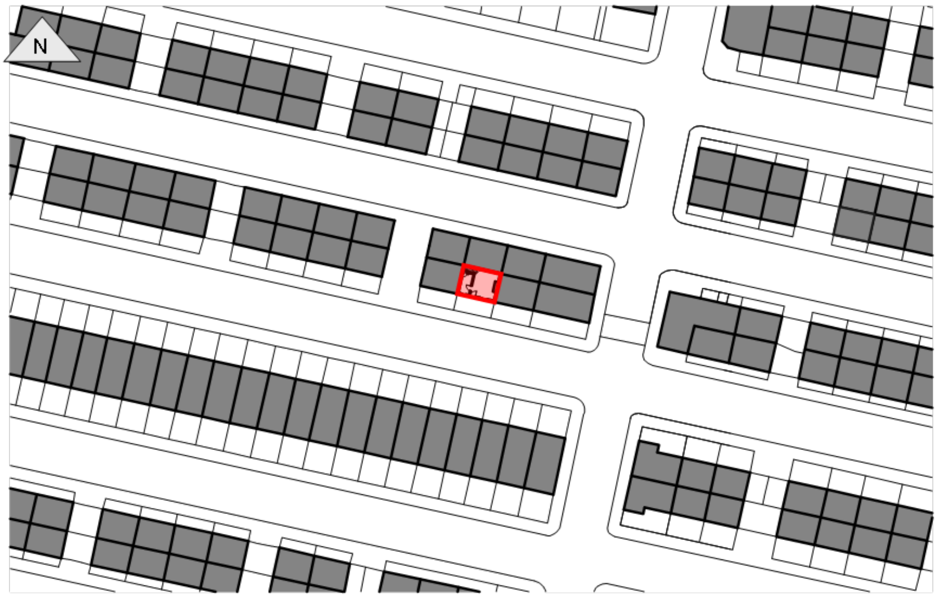

Figure 1-2 Case study house site location plan

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The floor plans, elevation and sections for the dwelling are given in Figure 1-3 and Figure 1-4.

Figure 1-3 House floor plans

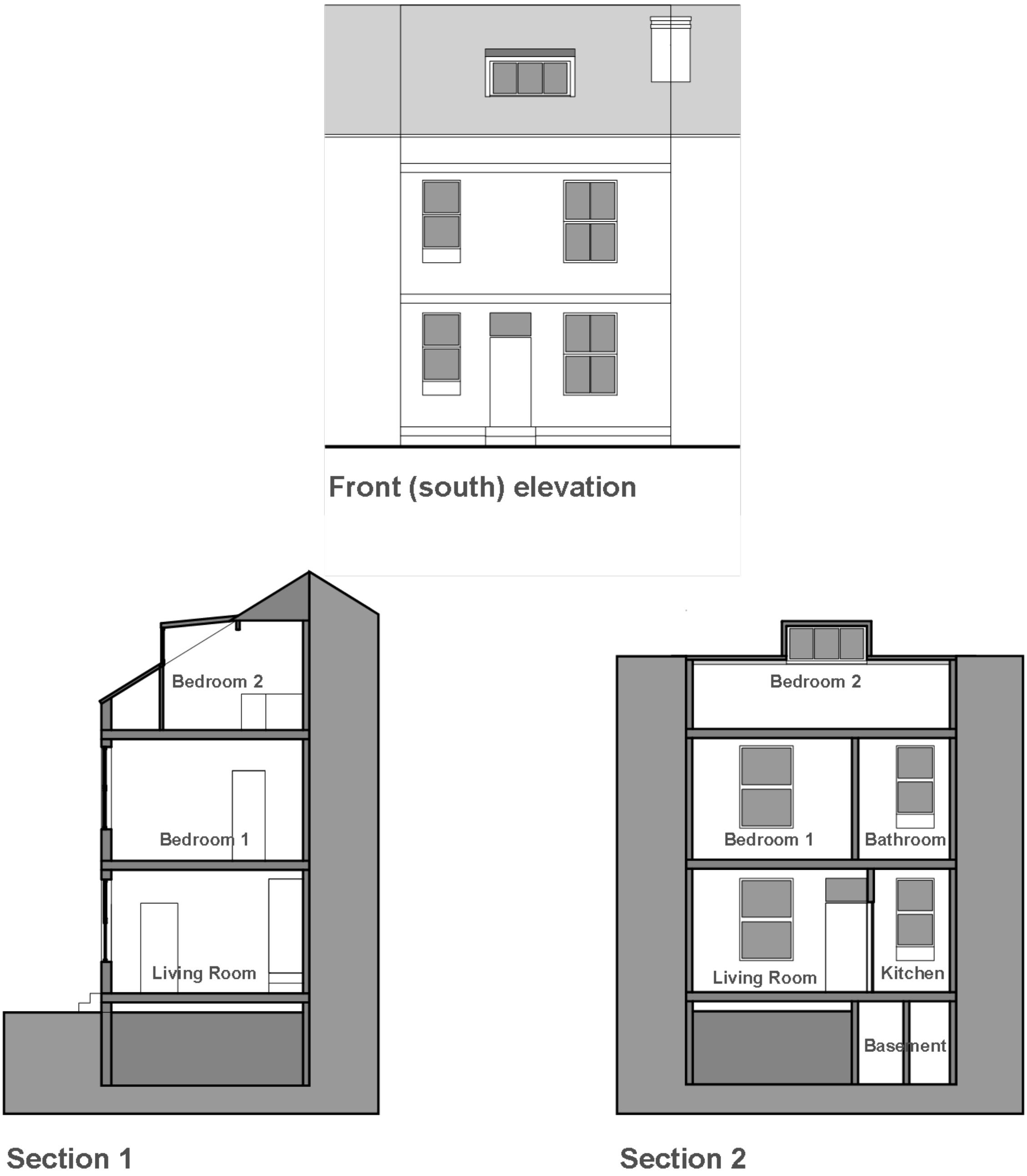

Figure 1-4 House elevation and sections

The dimensions of each fabric element in the home are listed in Table 1-2 and 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
Volume	*181.3 m³*
Total floor	*65.5 m²*
Total heat loss area	*92.3 m²*
Ground floor	23.6 m²
Front external wall	23.0 m²
Windows	8.7 m²
Door	1.8 m²
Sloping roof	7.5 m²
Flat roof	8.4 m²
Party wall rear	32.2 m²
Party wall sides	83.7 m²
Dormer roof	3.0 m²
Dormer cheek	1.4 m²
Knee wall	8.3 m²
Ceiling to eaves void	6.6 m²

The construction element areas are given in Table 1-3. The property had not undergone any previous fabric retrofits. Bedroom 2 (room-in-roof) was already partially insulated prior to the retrofits. This comprised mineral wool loft insulation in the eaves above Bedroom 1 (which could be accessed through a small panel in the knee wall), and between the ceiling joists of the flat roof elements (which were inaccessible). These were detected using thermography and heat flux plates (see Section 2.4), as opposed to seen during a visual inspection.

There were no obvious defects; however, the property showed some signs of damp in Bedroom 1 with mould present along parts of the rear party wall and corner with the side party wall. Although the suspended ground floor timbers were deemed to not be damp, the basement air was humid (RH > 80 %) and mould was present on the basement floor. This may be due to a lack of through ventilation across the back-to-back dwelling.

1.4 Retrofit approach

The retrofit details and nominal plane element U-values for each element are listed in Table 1-3. The U-values were calculated in accordance with BS EN 12524:2000 using the BRE calculator. The material properties were based on the observed materials, thickness of the existing fabric and knowledge of the insulation being installed. The thermal conductivity of the insulation was provided by the manufacturers. Given the importance of repeating thermal bridging through timber floor joists, particular attention was given to this aspect of the calculation.

Table 1-3 Construction and retrofit summary

Detail	Original construction	Retrofit[1]
Airtightness	13 $m^3/(h \cdot m^2)$ @50Pa	None
Floor	Uninsulated suspended timber	a) XPS board between joists 150 mm, λ=0.033 W/(m·K); U-Value 0.19 W/(m²·K) b) Mineral wool between joists 200 mm, λ=0.044 W/(m·K); U-Value 0.18 W/(m²·K)
Wall	9-inch solid brick	None
Roof	Room-in-roof, insulated with approximately 100mm at eaves level and 75mm between the ceiling joists	None
Windows	uPVC double glazed	None
Door	Composite	None

The house in its baseline state is illustrated in Figure 1-5 and the sequence of staged retrofits 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 stage of the ground floor retrofit to quantify the performance changes associated with each separate intervention and the potential for condensation risk. The specific methodologies 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.

[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.

Table 1-4 Phased retrofit stages

	Retrofit stage	Code	Retrofit date
1	Baseline	27BG.B	January 2020
2	XPS suspended floor retrofit	27BG.F.XPS	February 2020
3	Mineral wool suspended floor retrofit	27BG.F.MW	March 2020

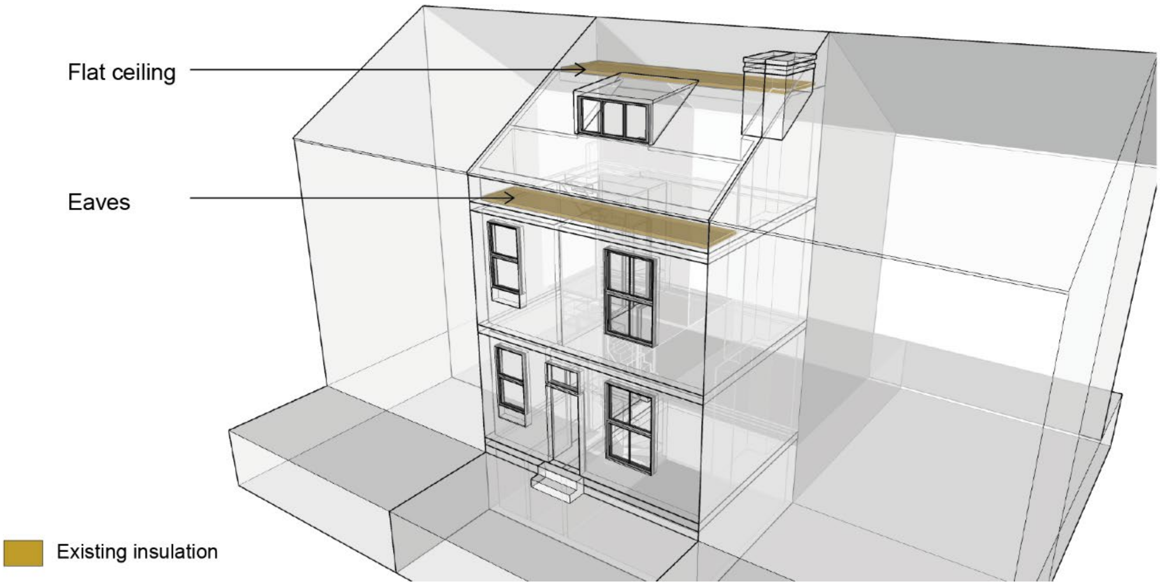

Figure 1-5 Stage 1: Insulation already in the property prior to the retrofit (27BG.B)

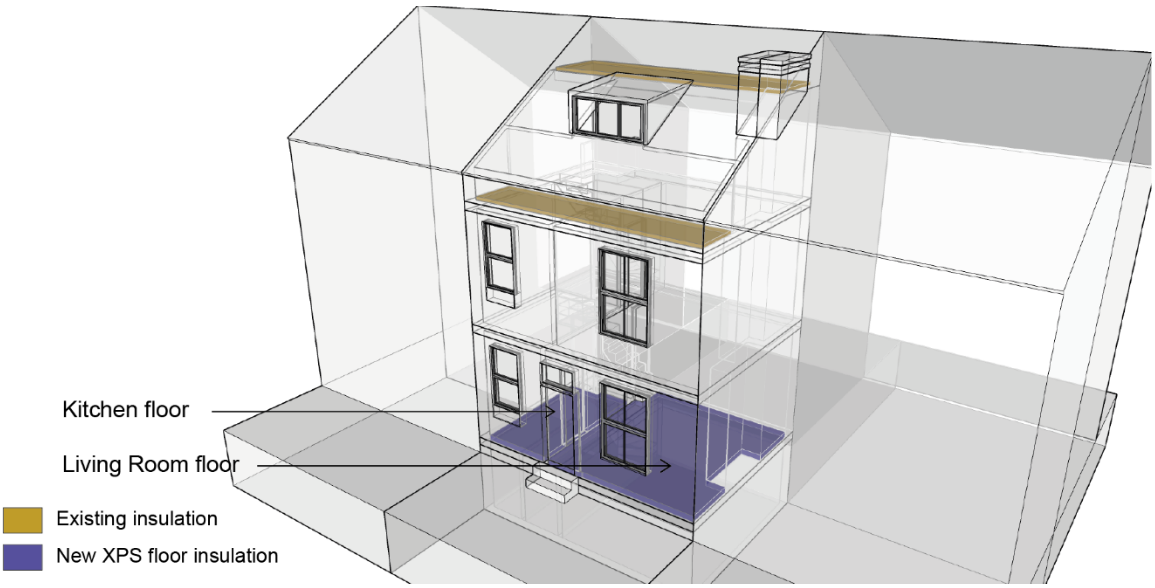

Figure 1-6 Stage 2: XPS floor retrofit to Living Room and Kitchen (27BG.F.XPS)

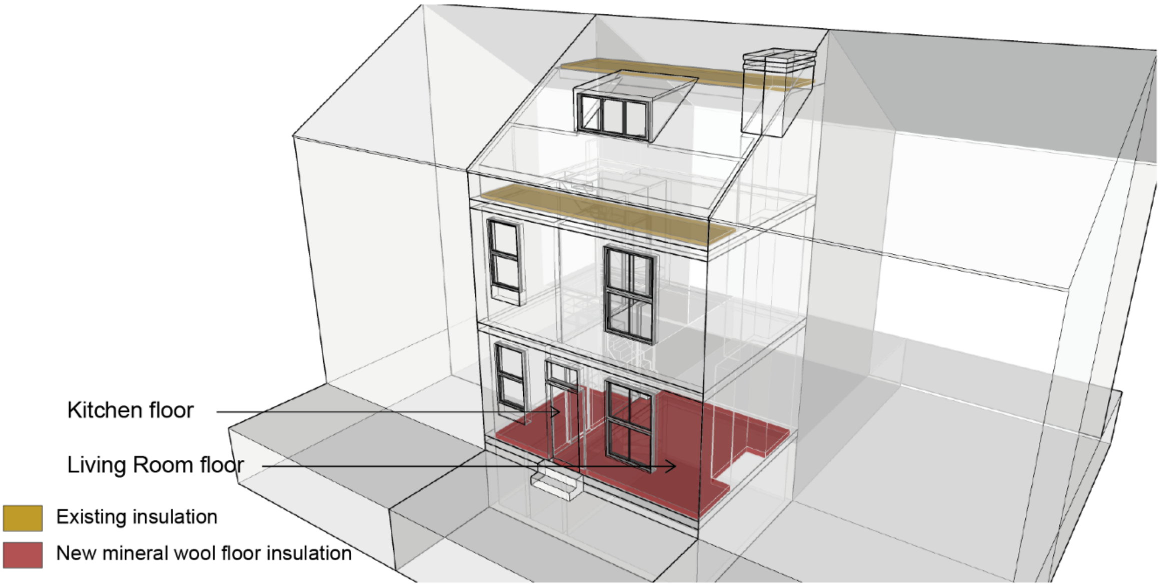

Figure 1-7 Stage 3: Mineral wool floor retrofit to Living Room and Kitchen (27BG.F.MW)

Case study and retrofit summary

Where solid-wall insulation is not practical or desirable, suspended floor retrofits represent one of the remaining retrofit strategies.

27BG provided an opportunity to evaluate and compare the benefits of two different suspended ground floor retrofits in an 1890s solid-walled, mid-terrace, back-to-back case study, comparing a non-rigid insulation product (mineral wool) with a rigid (XPS) alternative.

2 Fieldwork and modelling methods

BPE tests and modelling activities were undertaken at 27BG at each retrofit stage in accordance with the methodologies listed in the DEEP Methods 2.1 Report. This section outlines the specific implementation of these methods at 27BG including any variations and additions.

2.1 Environmental data collection

Internal environmental data logging equipment is described in detail in the DEEP Methods 2.01 Report. The internal environmental data collected at 27BG included air temperature, relative humidity (RH) and CO_2 levels. External environmental data were collected via a weather station located on the Leeds Beckett University Rose Bowl building located approximately 1 mile from 27BG and included vertical solar irradiance, air temperature and wind speed. This was supplemented by an external air temperature sensor positioned outside 27BG.

2.2 Measured survey

A detailed survey of the building was undertaken, and from this a digital version of the house was developed using SketchUp, using the dimensions for each element, to draw up the plans shown in Figure 1-3. Plans, sections and elevations were directly exported as DXF 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 materials.

2.3 Airtightness and thermography

Blower door tests were carried out at all baseline and retrofit stages. The results were used to identify changes related to the retrofits and to estimate heat loss attributable to infiltration (HTC_v). Under depressurisation, qualitative thermography surveys were completed, and additional thermography surveys of specific details were completed under normal conditions to identify changes between each retrofit stage. A low pressure Pulse air test and CO_2 tracer gas test were deployed during the testing programme to compare with the blower door test results.

2.4 Heat flux density measurement and U-values

29 Hukseflux HFP01 heat flux plates (HFPs) were installed on various elements in 27BG, with 12 being located on the suspended timber ground floor (the only element being retrofitted). These were installed to measure improvements in U-values achieved by the fabric upgrades. Nine were placed on party walls throughout the house to quantify party wall heat loss and calibrate the energy and thermal models. The remaining five sensors were placed on other elements in order to provide a broad measure of heat losses through the rest of the fabric. All HFP locations are listed in Table 2-1 and visualised in Figure 2-1, Figure 2-2 and Figure 2-3.

Heat flux from the individual HFPs, along with internal and external air temperature recordings, were used to estimate the in-situ U-values for each element. The location of the HFPs was guided by thermography used to select representative locations. In some instances, more than one HFP was located on a single element since uninsulated building elements routinely exhibit heterogeneous heat flux, meaning individual spot measurements may not be representative. In such a scenario, an average of these HFP values was used to estimate a single in-situ U-value which was considered representative of the whole element.

Multiple HFPs were installed on the suspended timber ground floor to estimate the in-situ U-value of the floor more accurately. This was done because previous research shows that suspended timber ground floors have variable heat flux depending on specific conditions including air flow in the floor void, proximity to the edge of the floor and the position and number of joists present [3, 4].

Of the sixteen HFPs placed on the ground floor, four were placed above floor joists, the remainder were placed on spans between joists. To estimate the U-value of the entire floor surface, the area taken up by the floor joists was calculated, and an area-weighted average was used.

Table 2-1 HFP locations

HFP	Element	Room
V1	Suspended timber floor	Living Room
V2	Suspended timber floor	Living Room
V3	Suspended timber floor	Living Room
V4	Suspended timber floor	Living Room
V5	Suspended timber floor	Living Room
V6	Suspended timber floor	Living Room
V7	Suspended timber floor	Living Room
V9	Suspended timber floor	Living Room

V10	Suspended timber floor	Living Room
V11	Suspended timber floor	Living Room
V12	Suspended timber floor	Living Room
V13	Suspended timber floor joist	Living Room
V14	Suspended timber floor joist	Living Room
V15	Suspended timber floor joist	Living Room
V16	Suspended timber floor joist	Living Room
V17	External wall	Living Room
U4	External wall	Bedroom 1
U5	Ceiling to eaves void	Bedroom 1
P5	Sloping roof	Room-in-roof
P4	Knee wall	Room-in-roof
V18	Party wall (right hand side)	Kitchen
V19	Party wall (rear)	Living Room
V20	Party wall (left hand side)	Living Room
U1	Party wall (left hand side)	Bedroom 1
U2	Party wall (rear)	Bedroom 1
U3	Party wall (right hand side)	Bathroom
P1	Party wall (right hand side)	Room-in-roof
P2	Party wall (rear)	Room-in-roof
P3	Party wall (left hand side)	Room-in-roof

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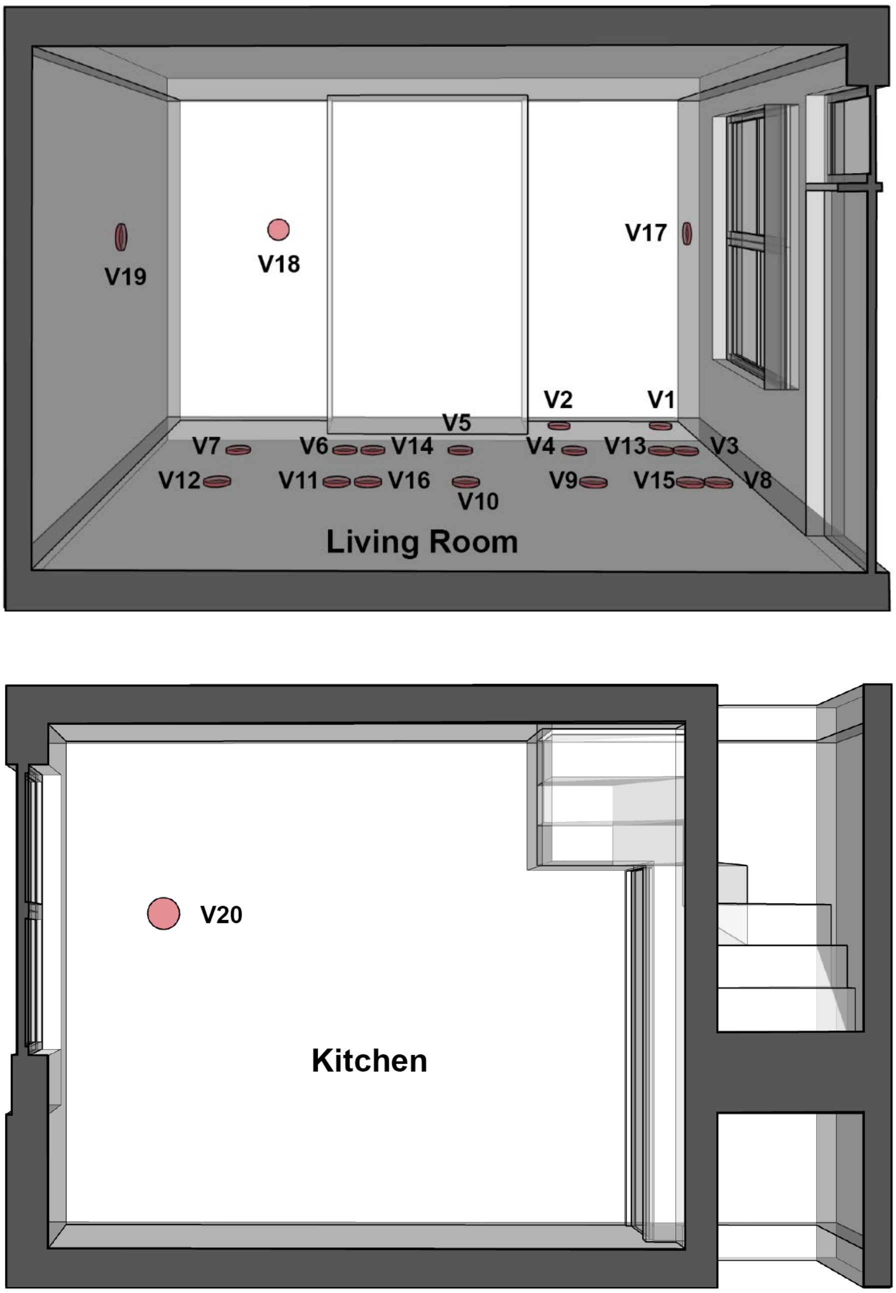

Figure 2-1 Ground floor HFP locations

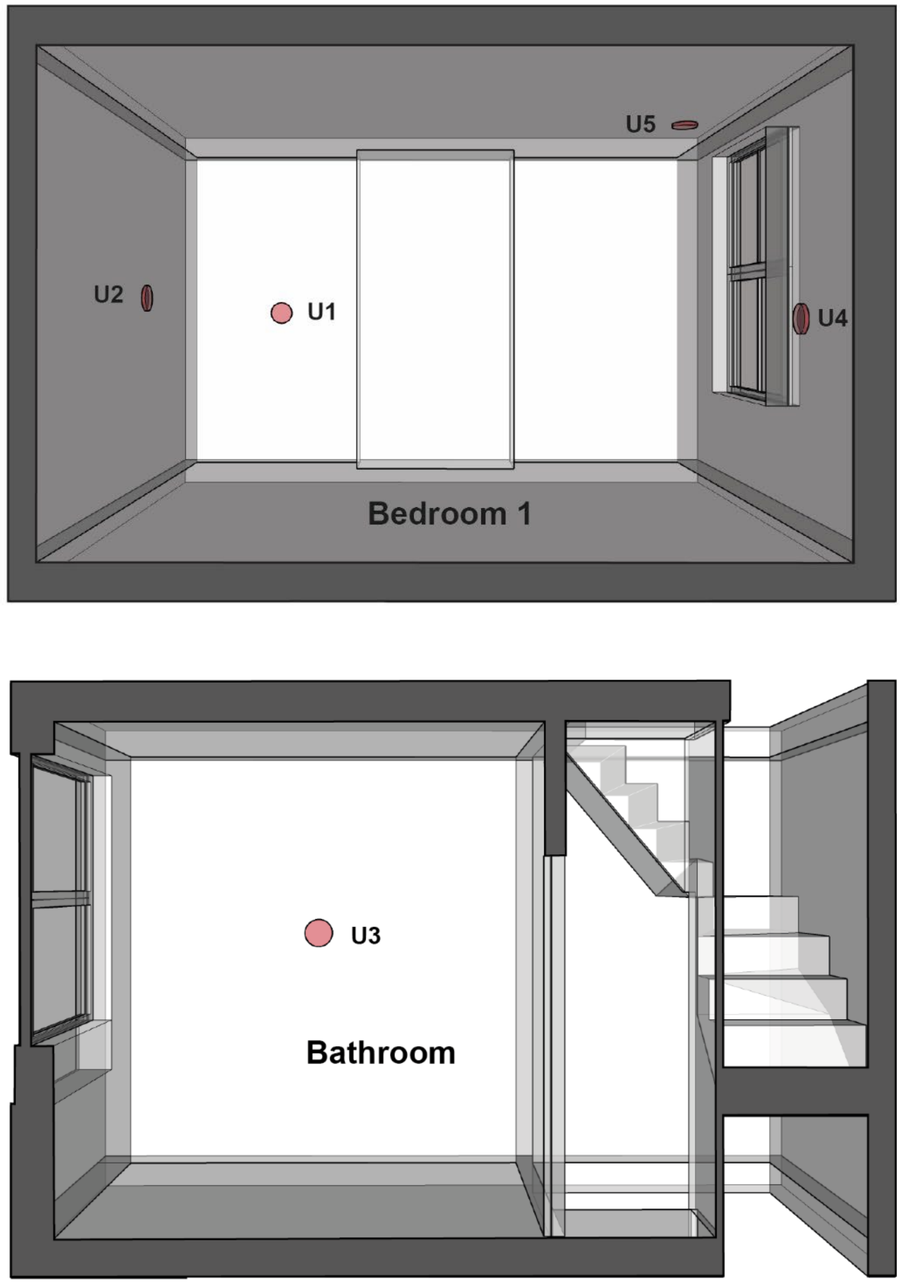

Figure 2-2 First floor HFP locations

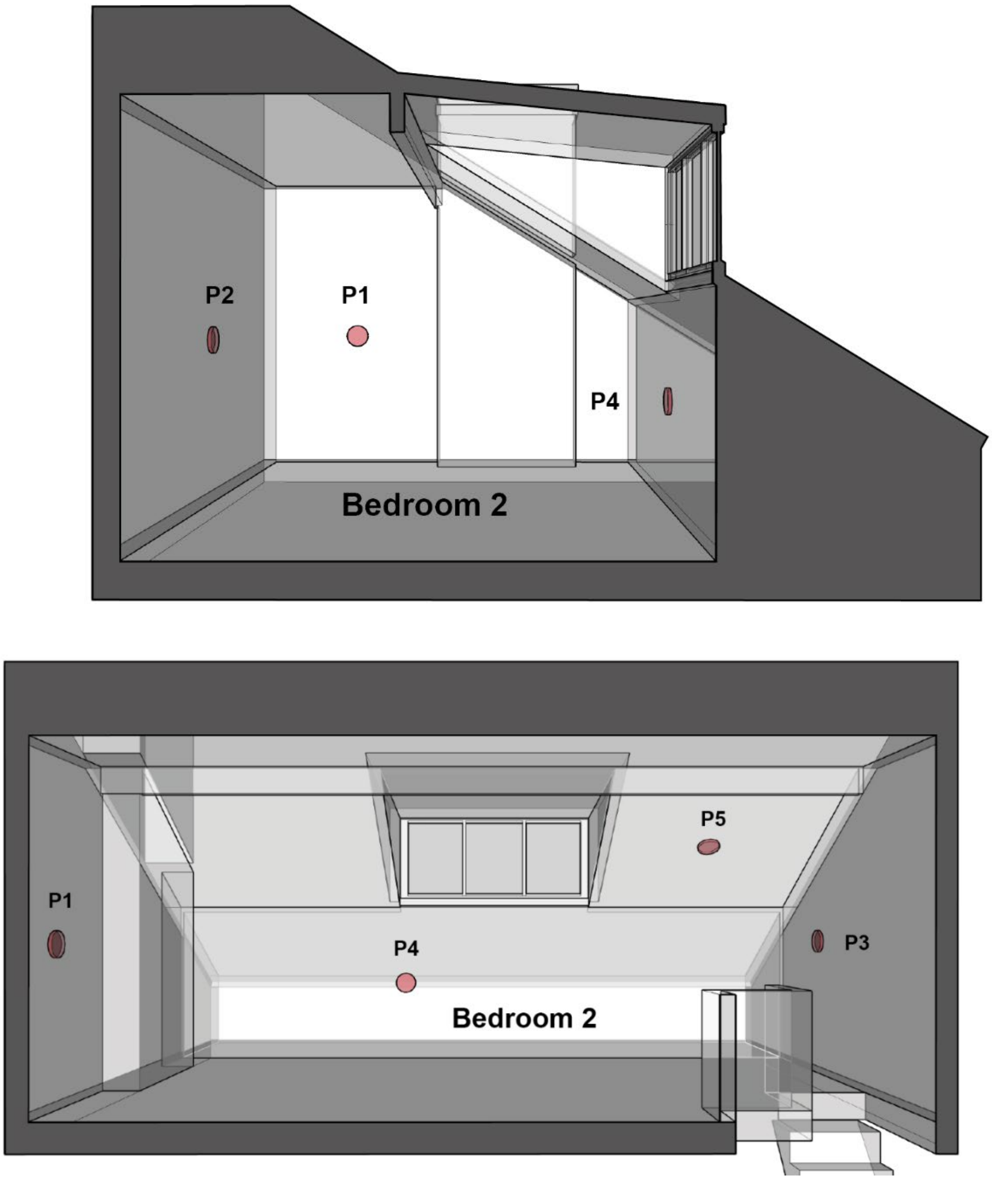

Figure 2-3 Room-in-roof HFP locations

2.5 Whole house heat transfer coefficient (HTC)

Coheating tests were conducted at each stage of the retrofit, as described in the DEEP Methods 2.01 Report, to provide a measured overall HTC. In addition to coheating tests, QUB tests, an alternative rapid test to attain HTC, 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 HTC that BREDEM predicts. These are compared with the HTC predicted by DSM (using DesignBuilder software version 7.0.0.088 [5]) at each retrofit stage. Table 2-2 shows how the approach taken to understanding how the predictions change as the default inputs are modified.

Table 2-2 Modelling calibrations 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]

The models predict annual delivered energy, annual space heating cost, carbon dioxide emissions, SAP score, and EPC band. This allows for evaluation of how successful the retrofits are at achieving policy aims. Simple payback periods for each retrofit can be calculated using the retrofit install costs.

Case study method summary

The detailed evaluation of suspended timber floor retrofits in the 27BG case study was undertaken using coheating tests, blower door tests, and 29 heat flux density measurements on fabric elements, taken before and after each of the two retrofits.

Steady-state and dynamic energy modelling was also carried out to compare against the in-situ measurements. To investigate the appropriateness of using default data in energy models, a 4-step calibration process was adopted.

These methods collectively investigate the energy performance and condensation risk associated with suspended floor retrofits, as well as the usefulness of models to predict these factors.

[2] Provided by Appendix S RdSAP 2012 version 9.94.
[3] Provided by Appendix K RdSAP 2012 version 9.94.
[4] Derived from blower door test.
[5] Derived from BRE calculator.
[6] Derived from HFP measurements.

3 Results

This chapter first presents the results of the in-situ field trials; airtightness tests, U-values and whole house heat loss as measured by the coheating and QUB tests. It describes how the modelled predictions compare with the measured data and how successful four different calibration steps were at improving predicted heat loss, including assessing thermal bridging. The model outputs are discussed in terms of their implications for EPCs, space heating, CO_2 emissions, fuel bills and paybacks.

3.1 Airtightness improvements

The pre-retrofit house had moderately high levels of infiltration, with a mean air permeability of 13 $m^3/(h \cdot m^2)$ @ 50Pa. For context, the average UK infiltration rate is estimated to be approximately 11 $m^3/(h \cdot m^2)$ @ 50Pa [3] and the maximum rate permitted under Building Regulations for new build homes has recently reduced from 10 to 8 $m^3/(h \cdot m^2)$ @ 50Pa [6].

The major air leakage routes in 27BG were mainly through the suspended timber ground floor, at the perimeter of the intermediate floors, via penetrations in the building fabric around services, at the window sills and at the basement door, as shown in Figure 3-1 to Figure 3-5.

The unsealed penetrations and window sills created direct air exchange with the outside. The suspended timber ground floor was unsealed and so the infiltration here illustrates air exchange with the basement.

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

Figure 3-1 Base case infiltration around a window sill during depressurisation

Figure 3-2 Base case infiltration around the ground floor perimeter during depressurisation

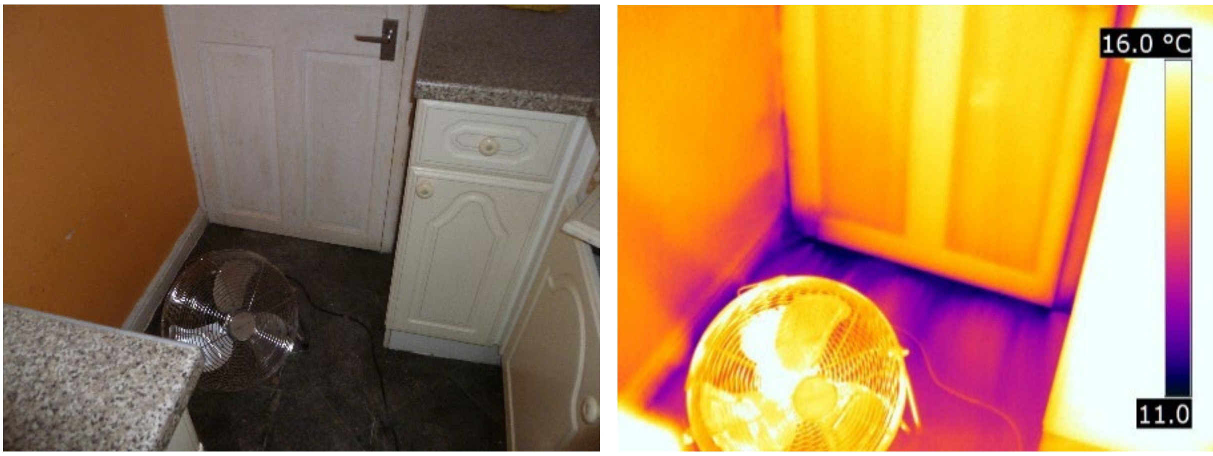

Figure 3-3 Base case infiltration around the basement door during depressurisation

Figure 3-4 Base case infiltration around boxed-in services during depressurisation

Figure 3-5 Base case infiltration around the perimeter of the intermediate floor during depressurisation

The XPS was installed between the floor joists and sealed using expandable foam. Since the joist was too close to the wall, it was not possible to fit XPS at the perimeter so mineral wool was installed here to maintain the insulation layer, as shown in Figure 3-6. Figure 3-7 shows the encapsulated mineral wool installation between the floor joists.

Figure 3-6 XPS installed between joists (left) mineral wool at floor perimeter (right)

Figure 3-7 Mineral wool installed between joists

Following the ground floor retrofits, the infiltration rate increased slightly with the mean air permeability rising from 13 to 14 $m^3/(h \cdot m^2)$ @ 50Pa for the XPS ground floor retrofit and 15 $m^3/(h \cdot m^2)$ @ 50Pa for the mineral wool floor retrofit. The removal of the laminate floor covering in the living room and linoleum in the kitchen prior to the ground floor retrofits would have contributed to this increase. The floor coverings were not replaced for the post-retrofit air tests. However, the scale of change in airtightness is still in line with the uncertainty of the test.

The infiltration for the base case home was initially lower than the 17.5 $m^3/(h \cdot m^2)$ @ 50Pa for the house predicted in RdSAP. The RdSAP model predicted that the air leakage would reduce following the floor insulation, which was not observed in the case study. Although infiltration though the floorboards was reduced post-retrofit, due to the installation of new tongue and groove flooring sheets, as shown in Figure 3-9, air leakage pathways around the floor perimeter persisted.

The results of the blower door tests are shown in Figure 3-8 and the airtightness of the house is well above the maximum allowable for new build homes in all retrofit states. In the baseline state, the RdSAP substantially over-predicted the air leakage taking place in the home, though the prediction was similar in the retrofitted state. Thus, using predicted infiltration to estimate ventilation heat losses in RdSAP can cause inaccuracies in EPC models.

The blower door results and observations suggest there may have been a progressive worsening of the airtightness of the home with deterioration of other building elements, though the difference is within the uncertainty of the test. This increase may be linked to a new air leakage pathway being detected as the study proceeded, as shown in Figure 3-10.

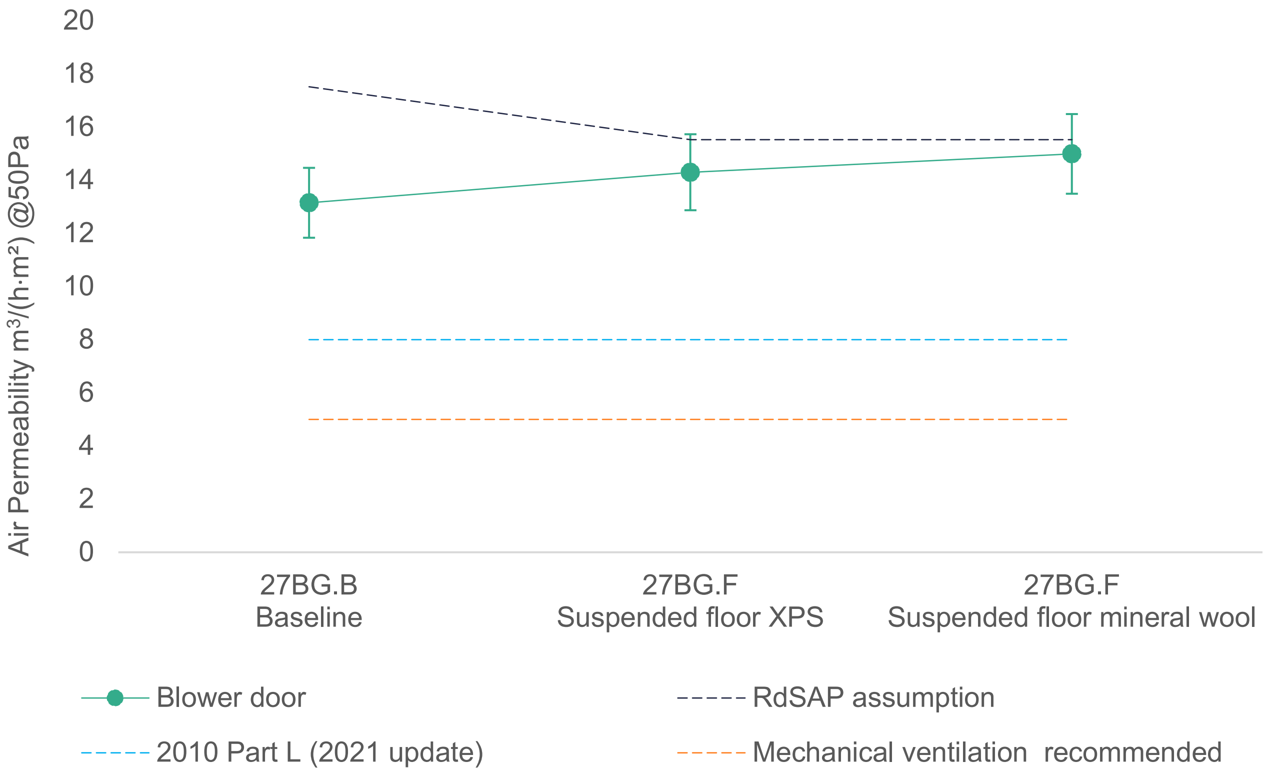

Figure 3-8 Airtightness at each retrofit stage

As mentioned, thermography undertaken during depressurisation confirmed that the air leakage around the ground floor perimeter persisted after the ground floor retrofits, as shown in Figure 3-9. An air barrier membrane was specified to accompany the ground floor retrofits, though it appears it was either omitted or installed unsuccessfully.

This finding suggests that, if floors are insulated without air barrier membranes, savings may not be maximised, as ground floor air leakage may not be addressed by insulation and new floor coverings alone.

Figure 3-9 Infiltration around the perimeter of the suspended timber ground floor after XPS retrofit during depressurisation

Additionally, cracked plasterwork was observed in the room-in-roof knee wall which deteriorated over the course of the test, and may have marginally increased infiltration. This may have implications for the savings measured by the coheating tests as well as the suitability of the blower door test method where there is already damage to the building fabric.

Figure 3-10 Deteriorating fabric causing worsening infiltration between first test (left) and final test (right)

Equation 3-1 can be used to estimate the heat losses associated with the background infiltration rates measured by the blower door tests. Air leakage in the baseline house was used to estimate the heat loss to be 34 W/K. This estimated heat loss increased slightly to 37 W/K for the XPS and 39 W/K for the mineral wool retrofit.

Equation 3-1 Estimating ventilation heat loss (HTC_v) via the n/20 rule

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

This equation uses air permeability rather than air changes per hour at 50 Pa, which is used conventionally [7], since this is the approach adopted in SAP [8]. The shelter factor is also used to mimic the approach used in SAP which is applied to all house types regardless of their form or level of exposure. Clearly this represents another area of uncertainty in relating measured infiltration to heat losses.

Airtightness improvement summary

The increase in infiltration following the ground floor retrofit was within the error of the test, thus air leakage heat losses were not significantly affected.

Infiltration was observed around the perimeter of the ground floor post-retrofit using thermography during depressurisation, indicating that the specified air barrier membrane was either not installed or not effective.

The fabric of the room-in-roof was affected by the pressure tests, suggesting that repeated blower door testing can itself compromise the integrity a home’s airtightness barriers.

3.2 U-value improvements

Three methods were adopted to derive 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 to undertake and so is the least likely to be undertaken in retrofit projects.

A summary of the before and after ground floor U-values for 27BG is presented in Figure 3-11. This compares the default U-values used in RdSAP based on Appendix S [8], the calculated U-values derived from the BRE calculator, and the values estimated from in-situ heat flux density measurements. As shown, the RdSAP defaults and BRE calculator predict roughly the same U-values. The in-situ measured value was actually lower, which means the potential to make improvements may be less in this house than predicted by an EPC assessment. Post-retrofit the RdSAP default, BRE calculator and measured U-value were all similar.

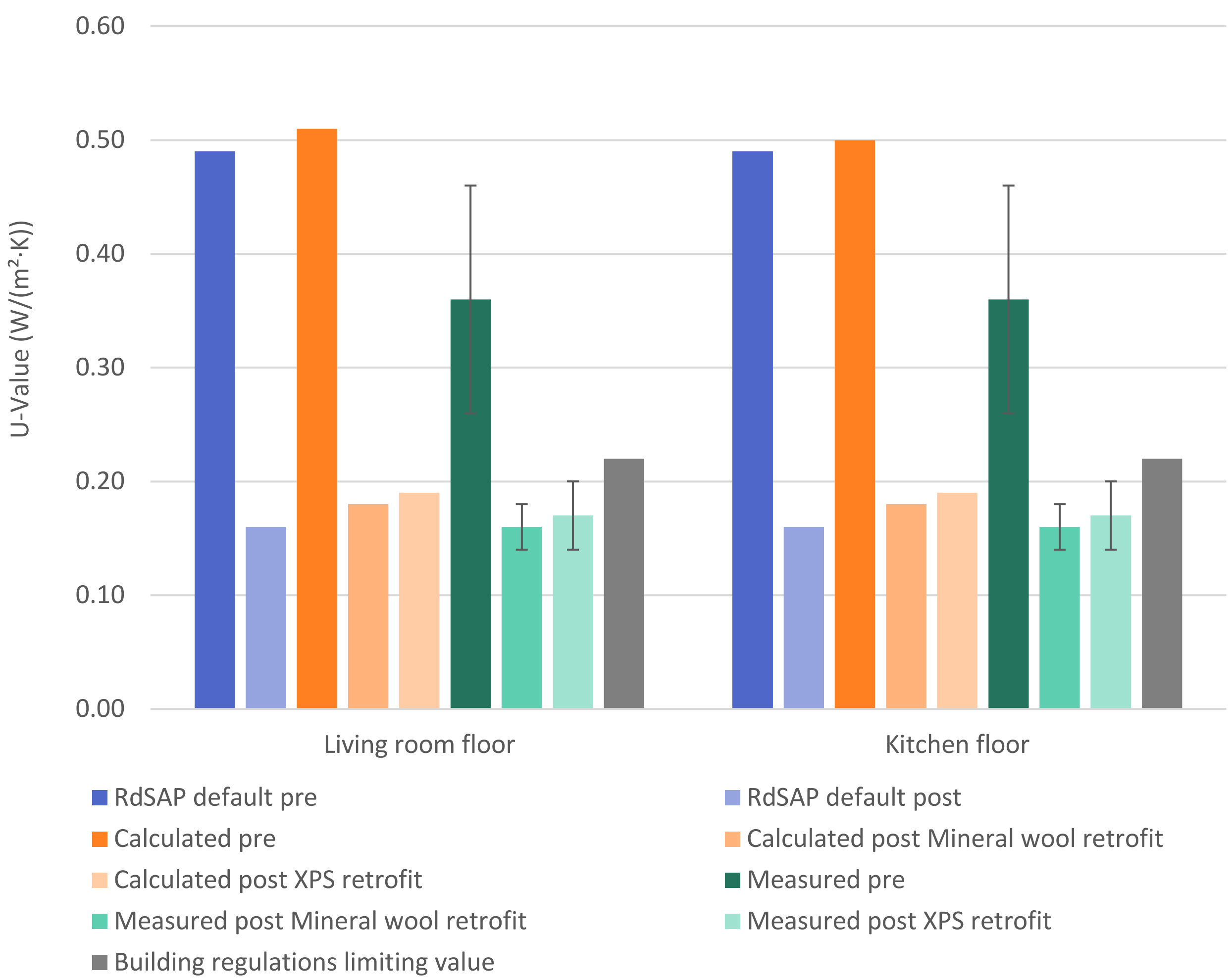

Figure 3-11 Pre- and post-floor retrofit U-values

A 53 % and 56 % reduction in floor U-value was achieve by the XPS and mineral wool retrofits, respectively, meaning both performed equally and successfully reduced the U-value to below the limiting value required in Part L1B of the Building Regulations. Because the calculated and default U-values were higher, this saving appears less than predicted. The pre- and post-retrofit U-values and the percentage improvements in U-values achieved by the floor retrofits are listed in Table 3-1 and Table 3-2, respectively.

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

	Pre-retrofit			Post-retrofit		
	RdSAP default (W/(m²·K))	Calculated (W/(m²·K))	Measured (W/(m²·K))	RdSAP default (W/(m²·K))	Calculated (W/(m²·K))	Measured (W/(m²·K))
Ground floor (Living Room)	0.49	0.51	0.36 ± 0.10	0.16	0.18	0.16 ± 0.02

Ground floor (Kitchen)	0.49	0.50	0.36 ± 0.10	0.16	0.18	0.16 ± 0.02
External walls	1.70	1.86	2.17 ± 0.11			
Dormer knee wall	2.30	1.20	1.52 ± 0.09			
Sloping ceiling	2.30	1.02	1.75 ± 0.12			
Loft	0.50	0.54	0.47 ± 0.02			
Dormer cheeks	2.30	1.63	1.49 ± 0.02			
Dormer roof	2.30	1.71	2.35 ± 0.08			
Ceiling to eaves	0.40	0.27	0.24 ± 0.02			

Table 3-1 shows consistency in U-values across the measured, RdSAP default, and calculated values. However, for the room-in-roof elements they are particularly disparate, perhaps because the characteristics of the existing fabric were difficult to discern. This has implications for the accuracy of energy models and predicted savings.

The percentage changes achieved by the floor retrofits, shown in Table 3-2, are relatively large and very similar, which may not be surprising since they were designed to have the same level of performance. However, as the ground floor had a relatively small heat loss area, it is useful to understand how this impacted the whole house heat loss.

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

Element	RdSAP default predicted reduction (W/(m²·K))	Calculated predicted reduction (W/(m²·K))	**Measured reduction (W/(m²·K))**	RdSAP defaults prediction gap %	**"As-built" performance gap %**
Ground floor (Living room)	0.33	0.33	0.20	0%	-11%

2.09 DEEP 27BG

Element	RdSAP default predicted reduction (W/(m²·K))	Calculated predicted reduction (W/(m²·K))	**Measured reduction (W/(m²·K))**	RdSAP defaults prediction gap %	**"As-built" performance gap %**
Ground floor (Kitchen)	0.33	0.32	0.20	0%	-11%

3.2.1 Contribution of fabric heat loss (HTC_f) to HTC

Figure 3-12 shows what impact the improvement in U-values has on fabric heat loss. This shows a breakdown of each fabric element's contribution to heat loss by factoring in the relative size and heat loss area, with the element's U-value either as assumed by RdSAP, calculated, or measured in-situ. Ther are several points to note in the figure below:

- The heat loss through the ground floor drops from 9 W/K (7 %) pre-retrofit to 4 W/K (3 %) post-retrofit.
- External walls are the most significant element responsible for around 50 % of HTC_f pre- and post-retrofit.
- HTC_f is highest when RdSAP defaults are used pre- and post-retrofit.

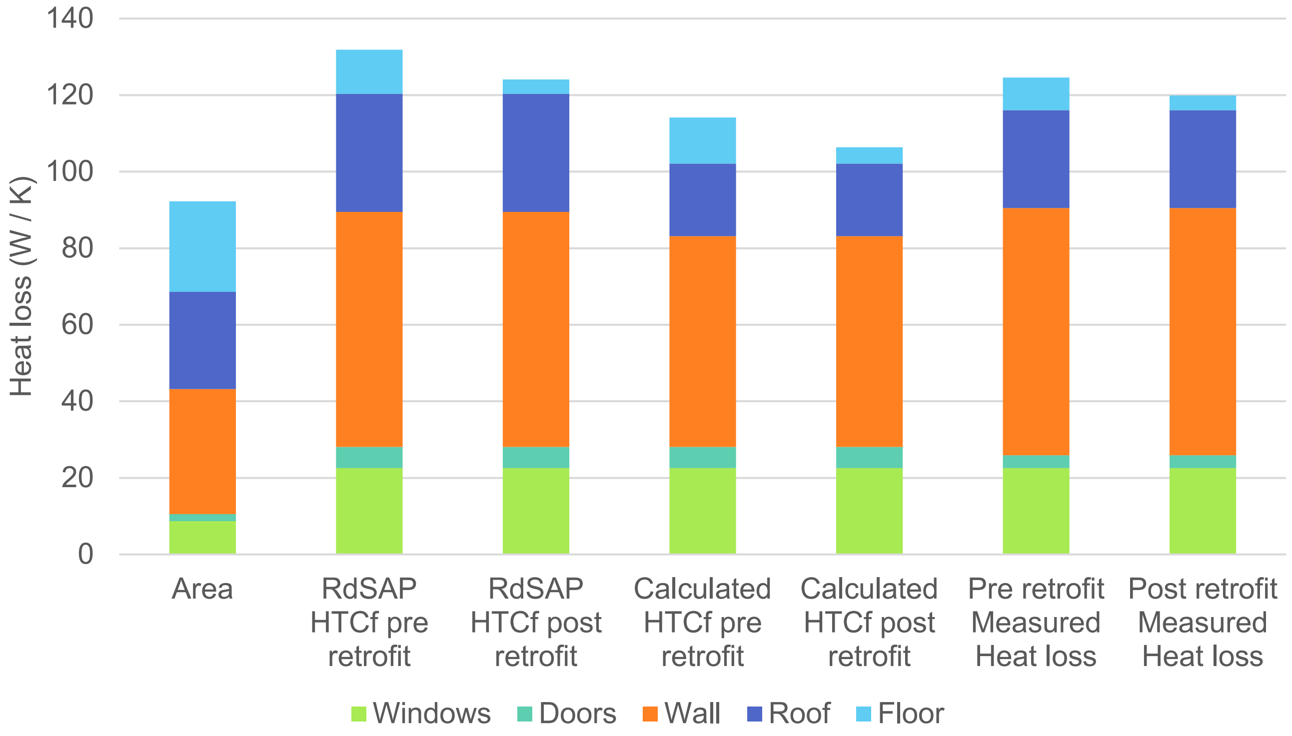

Figure 3-12 Heat loss of fabric elements pre- and post-retrofit, as recorded by heat flux density measurements

U-value improvement summary

The ground floor U-values were measured to be lower than the RdSAP defaults and the calculated U-values pre-retrofit. Post-retrofit the predicted, calculated and measured U-values were all similar.

A 56 % reduction in U-value was measured, however, since floors only make up around a quarter of the heat loss area, this translates to only around a 3 % to 7 %, reduction in total fabric heat loss (HTC_f).

No measurable difference in the performance of the two products was found based on U-values.

3.3 Whole house heat loss (HTC) improvement

As previously stated, one complication with the coheating test in 27BG was the presence of large party walls (PWs). As a back-to-back mid-terrace, 27BG has 3 PWs with a combined surface area of 116 m². The total heat loss area of 27BG is just 92 m², and heat loss to the PWs could therefore be a significant contributor to the home's heat transfer. To account for this heat, HFPs were placed on the PWs and used to estimate the energy being lost to the neighbours. While this procedure was followed in 27BG, a logger failure meant that PW HFP data were collected for only a part of the duration of the coheating. This means that an incomplete record of the total PW heat loss was collected across each test phase. For instance, PW HFPs were collected for 100% of the baseline test but only around 50% of each retrofit stage.

Thus, any PW correction applied would be incomplete and may not have sufficient data points for there to be confidence in the PW heat loss corrections applied. To assess the impact of the floor insulation, we therefore relied on HTCs without any PW correction, though the HTCs with partial PW correction are provided for information. It is preferable to base coheating analysis on HTC values without PW correction, since any error in the PW correction for the retrofit stages makes it difficult to compare between test stages.

Since PW heat loss was not known for each stage, the analysis must assume it to be constant across the three tests. However, as internal temperatures were not recorded in adjacent dwellings this cannot be known with any certainty. If the adjacent homes had different internal temperatures between the tests, there may have been different amounts of heat loss through the party wall in each test which will go unaccounted for. This approach makes the relative changes between the retrofit stages more comparable, though the absolute HTC may not be accurate, i.e., not accounting for PW heat loss means the coheating HTC can be regarded as an overestimate since PW heat losses are expected to be relatively large for this home. The measured HTC for the base case and retrofitted house is shown in Figure 3-1.

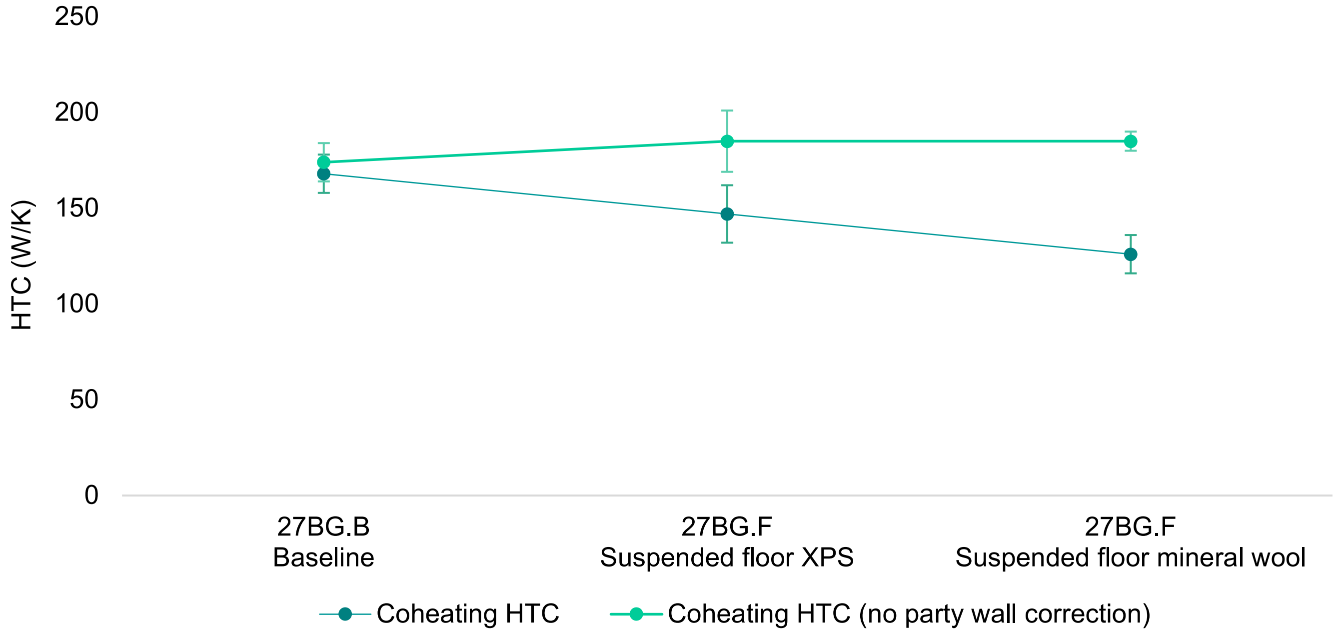

Figure 3-13 HTC with and without PW correction for the baseline and alternative suspended timber floor retrofits

The changes in HTC attributable to the retrofits are described in Table 3-3. As shown, no detectable reduction compared to the base case was achieved by either insulation retrofit. Note that although the HTC value increased as a result of the floor insulation, the uncertainty in these numbers means that the difference is well within the margin of error and therefore cannot be considered significant.

Table 3-3 Test house HTC after each retrofit stage

Retrofit	Code	HTC (W/K)	HTC uncertainty	HTC reduction[vii] (W/K)	Percentage reduction[vii]**Error! Bookmark not defined.**
Base case	27BG.B	174 ± 10	6%	n/a	n/a
XPS suspended ground floor insulation	27BG.F.XPS	185 ± 16	9%	-11 ± 19	(-6 ± 11)%
Mineral wool suspended ground floor insulation	27BG.F.MW	185 ± 5	3%	-11 ± 11	(-6 ± 6)%

On further investigation, in addition to the uncertainty around the PW heat losses, it was noted that the basement temperature showed unusual behaviour, which may have affected ground floor heat losses. During the baseline and XPS insulation stages, the basement temperature was relatively stable at around 12 °C. At the mineral wool insulation stage, however, the basement temperature rose to around 16 °C.

Given that XPS and mineral wool are believed to have similar thermal performance, it is unlikely that this increase in basement temperature was driven by thermal conduction through the floor. The XPS retrofit took place in February, while the mineral wool retrofit occurred in September. It is plausible, therefore, that the basement was thermally charged during the summer, and was discharging heat during the post-mineral wool retrofit coheating test.

The case study provides a useful illustration of the difficulty of measuring the benefits of low impact retrofits in certain house types. The coheating test is, probably, the most robust test available for the measurement of HTC but when evaluating the impact of improvements to a single element in the field, robust elemental measurements are required. In this case the breakdown in the PW heat flux measurement prevented a full evaluation of the impact of ground floor insulation measures on the HTC.

These findings also have implications for methodological development when attempting to measure HTC in homes. The importance of PW heat transfer for these types of homes can be substantial, and without adequate tools to successfully account for this, any estimates of HTC may be flawed. In this instance the PW correction using imperfect PW heat flux data had a much larger impact on the HTC than the floor retrofit.

[vii] Compared to the base case

3.3.1 QUB and the coheating test HTC results

An alternative method of measuring the overall HTC is the QUB method, as described in the DEEP Methods 2.0 Report. This method was undertaken in the home at each retrofit stage to compare against the coheating test. In total, 12 QUB tests of 9 and 10 hour duration were performed on 27BG across the three retrofit stages. This was done to investigate the reliability and accuracy of the QUB test.

Of the 12 tests, 6 were excluded based on the test α value (a ratio of power input, temperature difference and the HTC of the property) being outside the recommended limit. This is a result of the QUB tests taking place immediately after coheating and the internal temperature subsequently changing between tests. In addition, a further test was excluded due to sensor failure during the test. This resulted in compliant tests being recorded for only two retrofit stages, the baseline and the suspended ground floor mineral wool insulation. The tests were completed in February 2020 (baseline) and November 2020 (ground floor mineral wool insulation). Despite the house being mid terraced with two PWs, no PW adjustment was applied to the QUB measurements. The results of the remaining 5 tests are shown in Figure 3-14, compared against the upper and lower uncertainty limits of the measured coheating tests (no party wall correction).

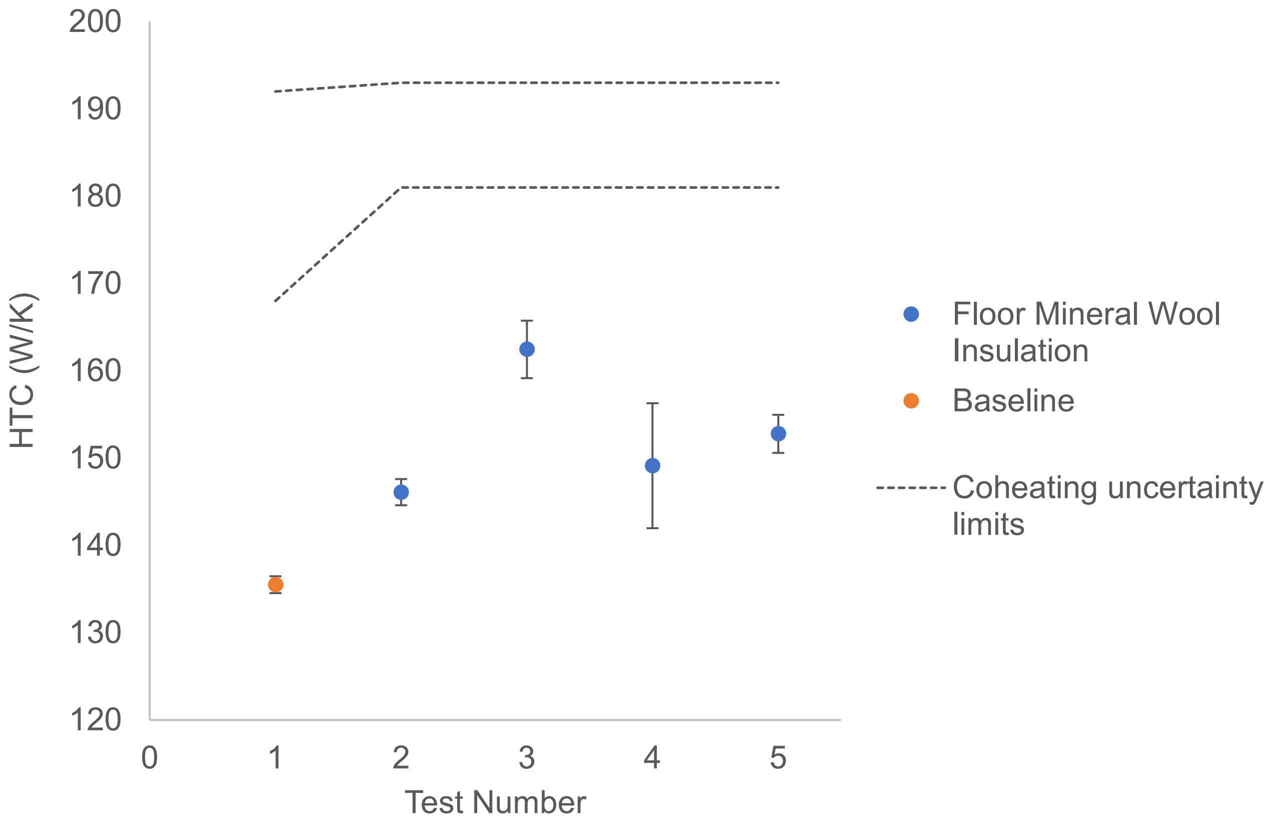

Figure 3-14 Predicted HTC via QUB test (no PW correction)

All the QUB measurements are lower than the uncertainty boundary of the coheating measurements.

The weighted average of the stages where QUB tests were completed are shown in Figure 3-15. No PW correction was applied to these measurements.

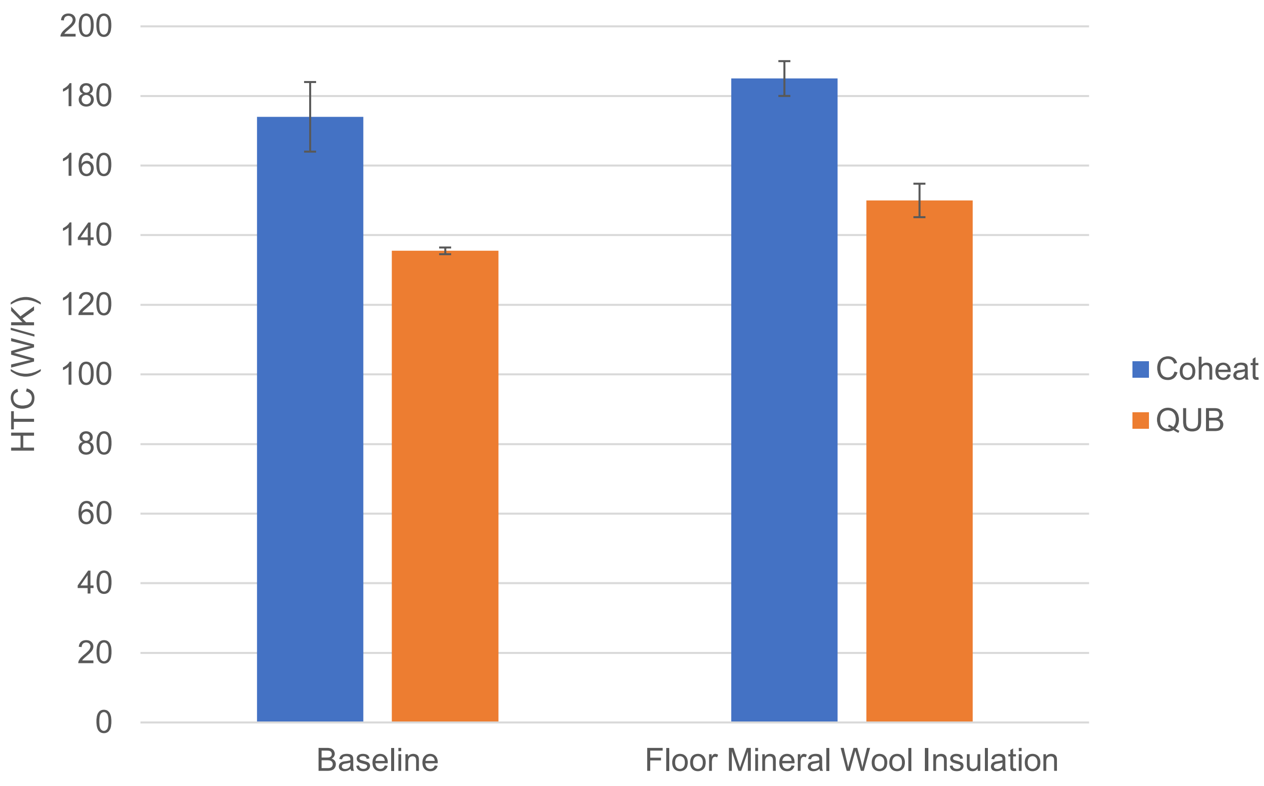

Figure 3-15 Average QUB vs. coheating HTC measurements (no PW correction)

As with the individual tests, the QUB average values are less than the corresponding HTC measured through coheating, by 22 % and 19 %, respectively, for the baseline and mineral wool retrofit stages. Possible reasons could be differing heat flow patterns through elements that do not face the external environment, such as party walls and basements. As mentioned, heat flux of the party wall was not recorded during the QUB tests so corrections for these cannot be applied.

The increase in HTC measured through QUB following the retrofit measures mirrored that seen in the coheating measurements with possible causes being the basement temperature, PW heat flows which were not measured and an increase in air permeability between the two stages. The increase in HTC between the two QUB measurements was 11 %, which was 4 % in the coheating measurements.

Additionally, some external temperature sensors gave spurious readings during the tests. Where this was observed, the tests were not included in the analysis but point to possible inaccuracies in the temperature sensor equipment used. The dispersion of individual measurements could be attributed to varying boundary conditions and environmental conditions, such as wind speed, internal/external temperature differences and solar radiation incident on the property during the day prior to the QUB test. These variables could have had an impact on the heat transfer in the property through varying infiltration rates and solar contributions stored within the fabric. QUB, which measures the overall HTC over a single evening, is more susceptible to dynamic external conditions than the coheating test.

Further investigation is required to determine the cause of the difference between the HTC measurements, variations in individual measurements and the suitability of QUB for properties of this type. These issues are addressed in the other DEEP case study and summary reports.

3.3.2 Thermal comfort benefit of suspended timber floor insulation.

The analysis shows that the benefit in terms of reducing whole house heat loss may be marginal for this type of house, because it has a relatively small floor area, a half basement, and large area of party wall. It is important, however, to consider that floor retrofits can also impact the thermal comfort of occupants via increased floor surface temperatures.

The analysis of pre- and post-retrofit floor surface temperatures for this case study measured an improvement in ground floor surface temperatures following the retrofits. Based on four surface temperature sensors located on the centre of the ground floor, the temperature factor of the floor was calculated. Although temperature factors are often used to quantify condensation risk, they can also inform thermal comfort. The temperature factor is calculated from Equation 3-2:

Equation 3-2 Temperature factor calculation

$$\frac{T_{sur} - T_{ext}}{T_{int} - T_{ext}}$$

Here T_{sur} is the surface temperature, T_{ext} is the external temperature and T_{int} is the internal air temperature. At a temperature factor of 1.00 the average surface temperature is the same as the average internal temperature. At 0.00 the average surface temperature is at the external temperature. Thus, the higher the number, the warmer the floor surface.

A temperature factor was calculated for each day data was collected, and an average of the daily temperature factors is given in Table 3-4. Only data collected between 7pm and 7am was used to exclude the influence of solar energy.

Table 3-4 Ground floor surface temperature pre- and post-retrofit

Retrofit	Average internal temperature (°C)	Average surface temperature (°C)	Difference (°C)	Temperature factor
Base case	20.55 ± 0.02	19.1 ± 0.1	1.4 ± 0.1	0.90 ± 0.01*
XPS suspended ground floor insulation	22.00 ± 0.01	22.00 ± 0.02	0 ± 0.02	1.00 ± 0.01
Mineral wool suspended ground floor insulation	23.15 ± 0.01	22.42 ± 0.06	0.73 ± 0.06	0.94 ± 0.02*

* Statistically significant relationship detected between external temperature and floor surface temperature

The addition of insulation improved the temperature factor in both retrofit scenarios. An additional observation was that, with XPS, the floor surface temperature was decoupled from the external temperature, in that the external temperature had no detectable relationship with the floor temperature at this stage.

This analysis suggests there may have been a small improvement in comfort as a result of the floor insulation. However, occupant thermal comfort is affected by multiple factors including air temperature, surface temperature and air movement, and so more holistic assessments, in a greater range of homes and retrofits, is needed to quantify how retrofits can improve thermal comfort.

It is relevant to note that floor surface temperature has the potential to disproportionately affect occupant comfort as an individual is in physical contact with the floor surface and heat exchange is both conductive and radiative, as opposed to only radiative exchange with other internal surfaces. Investigation of the comfort impact of floor temperature and covering requires properties to be occupied to gather subjective feedback and therefore sits beyond the scope of the present research.

3.4 Measured vs. modelled retrofit performance

The aggregate whole house HTC measured using the coheating test can be disaggregated into the 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.

HTCb (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 HTCf are subtracted from the whole house measured HTC.

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

- The n/20 rule (Equation 3-1) is an approximation and different building types may not follow it, thus HTC_v can only be an approximation.
- HFP placements may not be representative or comprehensive of whole element heat loss so HTCf may be imperfectly estimated.
- Thermal bridging simulations contain simplifications in geometry and use default data for construction material properties, so may not be representative of HTCb.
- Systematic uncertainty in the coheating test cannot be perfectly accounted for, e.g., party wall heat exchange, solar gains, and quasi steady-state conditions achieved.

In this section these three individually determined HTC component are summed to calculate the whole house heat loss, and this is compared to the HTC measured by the coheating test to quantify the gap between these aggregated and disaggregated methods. Following this, the measured HTC is compared to the energy models at each retrofit stage assuming each of the four calibration steps described in this report and in more detail in the DEEP Methods 2.01 Report.

3.4.1 Measured HTC: Aggregated vs. disaggregated approaches

The measured aggregate HTC obtained from the coheating test and disaggregated HTC calculated from summing HTC_v, HTC_b and HTCf are presented in Figure 3-16. The HTC_b shown is taken from the estimate used in the RdSAP model for the home and therefore can only be considered an estimate, adding some uncertainty to this value.

Comparing these two approaches to derive the whole house HTC is called *closing-the-loop* analysis. It is useful for both exploring where heat losses occur and as a reference point for the whole house HTC measured by the coheating test. HTC_f is derived by multiplying the area (m^2) of each fabric element by its in-situ estimated U-value ($W/(m^2{\cdot}K)$), and HTC_v is derived as previously described in Equation 3-1.

As shown, fabric heat loss is responsible for almost three quarters of the whole house heat loss in this house. How much of the remaining heat loss is due to infiltration and bridging depends on the retrofit stage.

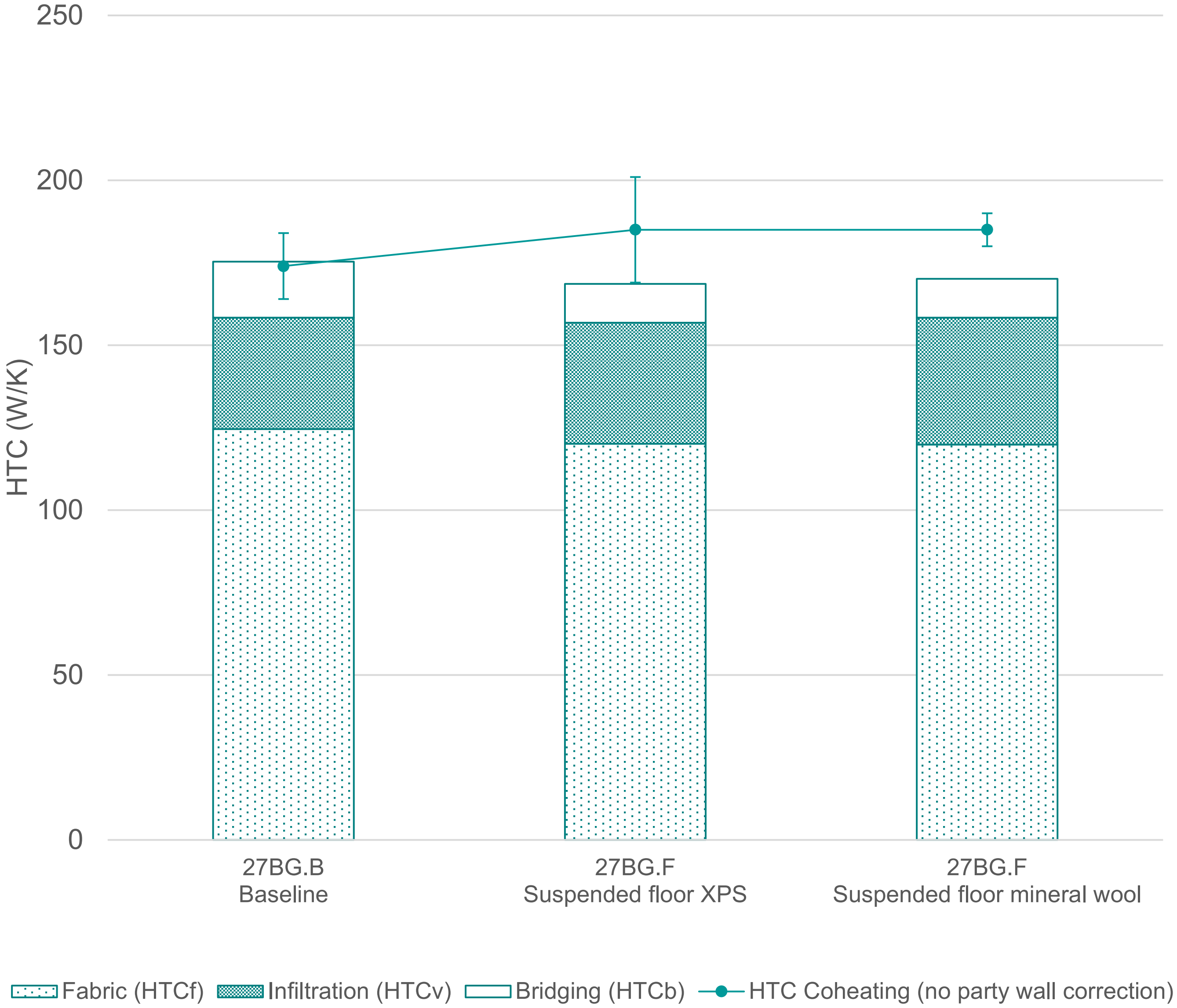

Figure 3-16 Aggregated vs. disaggregated measured HTC

The salient points related to this analysis are:

- The sum of the measured HTC_f and HTC_v and assumed HTC_b is very close to the coheating HTC in the pre-retrofit baseline. This is somewhat surprising since there is uncertainty in the coheating value measured in that it does not account for party wall heat loss and so may be considered an overestimation of HTC.
- The disaggregated method suggests a slight reduction in HTC post-retrofit. This reduction was not detected in the coheating test, though this may be linked to the uncertainty in the coheating test and the party wall correction not being applied.
- The finite number of HFPs used were not able to capture the full heterogeneity of heat loss from fabric elements (repeated or non-repeating bridges, local bypasses or varying insulation thickness), meaning U-values and HTC_f may be underestimated.
- The n/20 method may not be appropriate for estimating the ventilation heat loss in homes like 27BG.
- Heat flux density measurements of unheated spaces such as basements, the knee wall and loft space may result in U-values that are not representative of the heat loss to the outside and so underestimate HTC_f.

3.4.2 Measured vs. modelled HTC calibration step 1: RdSAP defaults

The measured HTC values for each retrofit stage are plotted against the HTC values predicted by the uncalibrated models using default RdSAP input data for infiltration and U-values in Figure 3-17, which shows:

- The RdSAP estimated HTC is substantially higher than the BREDEM estimate. When specific dimensions are used for the roof elements, the HTC reduces substantially as reflected by the BREDEM HTC predictions. Further investigation reveals this is caused by the simplified assumptions RdSAP makes about the room-in-roof geometry and U-values.
- Both steady-state and dynamic models estimate an overall HTC similar to that measured without correcting for party wall heat losses, suggesting the modelled HTC may be overestimating heat losses.
- The modelled reductions of between 3 % and 5 % in HTC are predicted to be modest for ground floor insulation in this type of house, which has a small floor area.
- The modelled predictions for both retrofit scenarios are identical, since the RdSAP defaults do not differentiate between insulation products, and only allow a maximum of 150 mm insulation to be input.

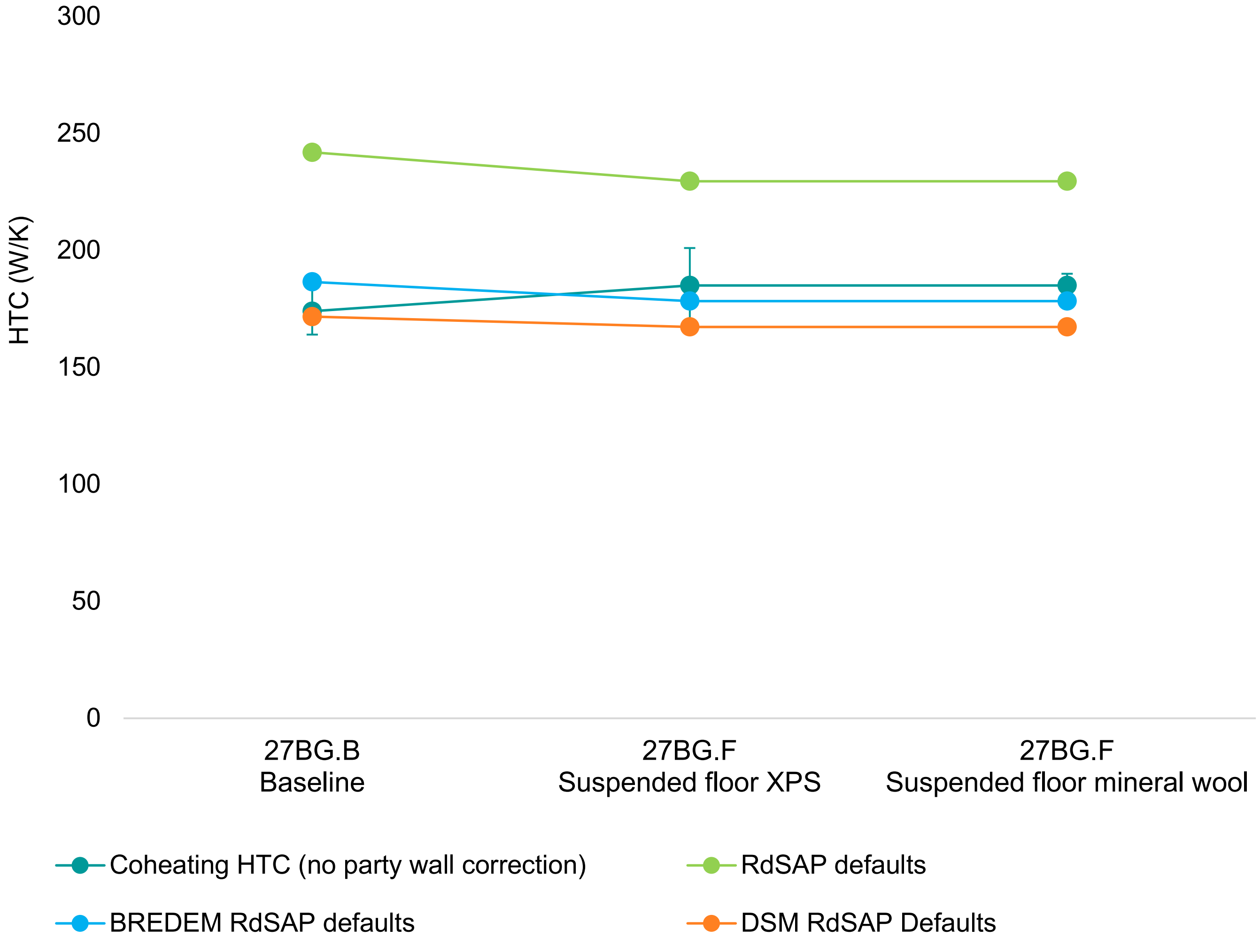

Figure 3-17 HTC Calibration step 1: RdSAP defaults

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

Figure 3-18 illustrates the impact of including the actual infiltration rates measured in the house on the DSM and BREDEM estimates of HTC. The U-values in the models are still assumed to be the RdSAP defaults.

- Including the measured airtightness results in the model substantially reduced the predicted HTC. This was expected as the measured airtightness was lower than the RdSAP defaults assumed.
- The additional infiltration rate that was measured in the mineral wool retrofit, compared to the XPS retrofit, is captured as a slight increase in the predicted HTCs.
- RdSAP does not allow infiltration rates to be altered, so is not included in this phase.

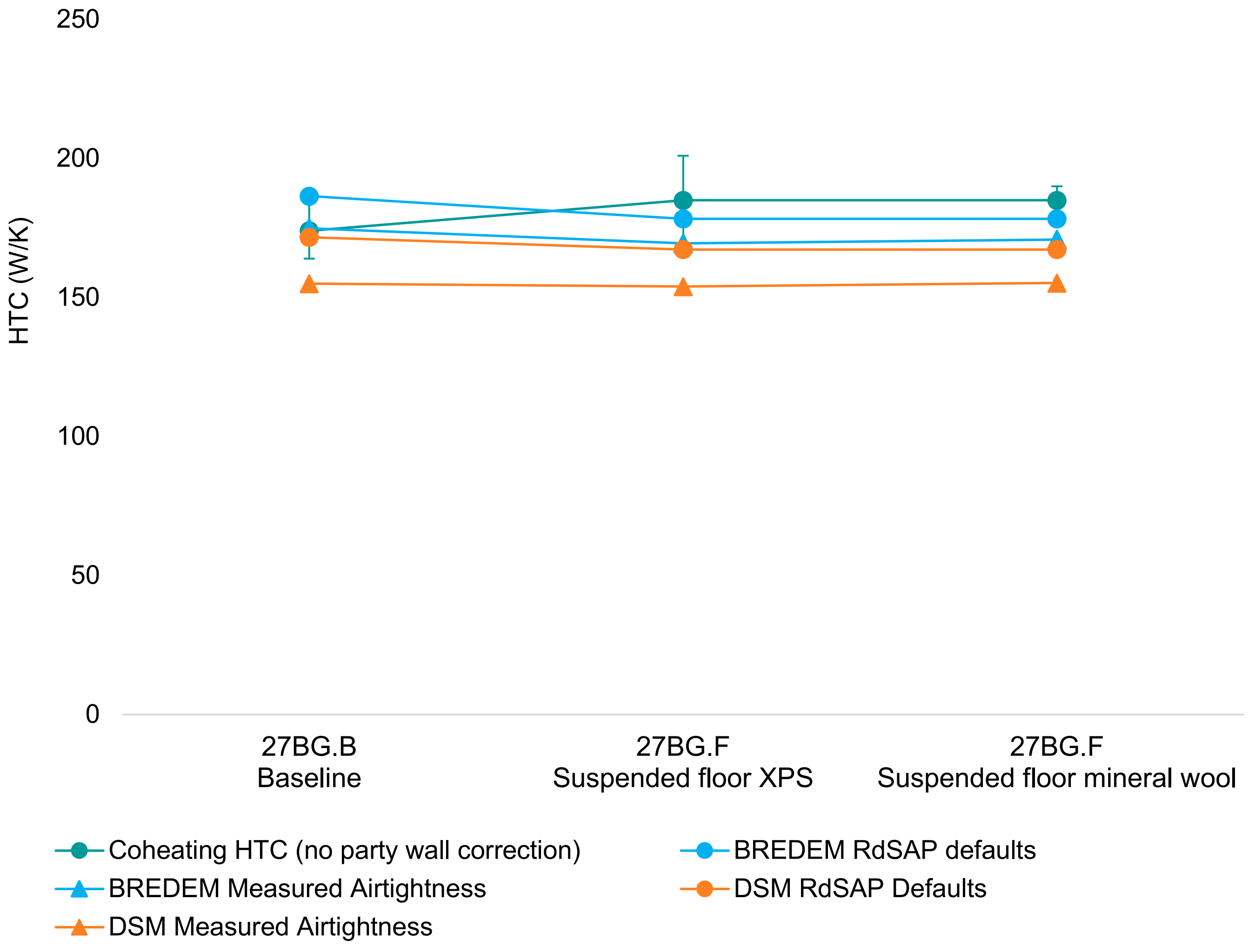

Figure 3-18 HTC Calibration step 2: Measured infiltration

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

Figure 3-19 shows the impact of including the calculated U-values for the fabric elements in the BREDEM and DSM models to add to the measured infiltration rates.

- Adding in the calculated U-values resulted in a further reduction in the predicted HTC, since the calculated U-values in the room-in-roof were substantially better than those predicted in RdSAP, though the calculated wall U-values were marginally worse than the defaults.
- The predicted HTCs were substantially below the measured coheating HTC, which may be expected, since the coheating HTC shown did not account for party wall heat losses so may be overestimated.
- The reductions from the retrofit predicted by the models with calculated U-values and measured infiltration were marginally smaller than predicted using defaults.
- The steady-state and dynamic models' HTC predictions were similar when using the same default airtightness and calculated U-value assumptions for the house.
- RdSAP does not allow calculated U-values to be input and so is not included in this calibration stage.

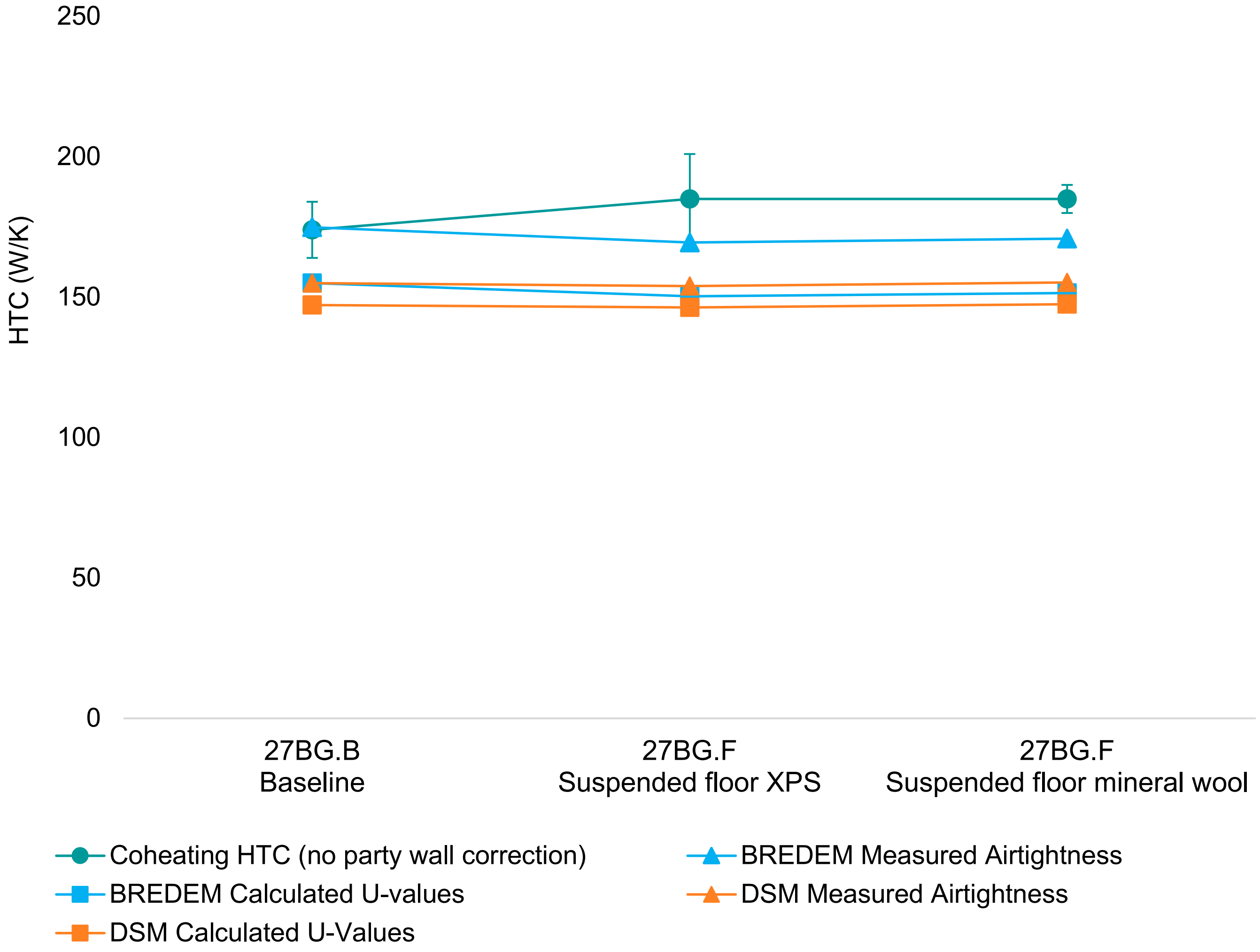

Figure 3-19 HTC Calibration step 3: Calculated U-values

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

Figure 3-20 shows the model outputs when the measured U-values are included.

- The DSM and BREDEM predictions increase when the measured U-values are used in place of calculated U-values, indicating there may have been a different construction makeup of the fabric than assumed. The predictions, as expected, are still below the measured value, since party wall heat losses are not removed from them.
- The roof and external walls specifically have higher in-situ measured U-values than calculated, indicating inconsistencies in the fabric performance or variation in the fabric makeup from those assumed in the calculations.
- RdSAP allows measured U-values to be used in preference to the defaults and, for this house, this has the result of dramatically reducing the predicted HTC, to bring it in line with the measured value.
- The RdSAP predictions are still slightly higher than the BREDEM prediction since there are discrepancies in the way the surface areas and floor U-values are calculated and because the RdSAP model still assumes the default (higher) infiltration rate.

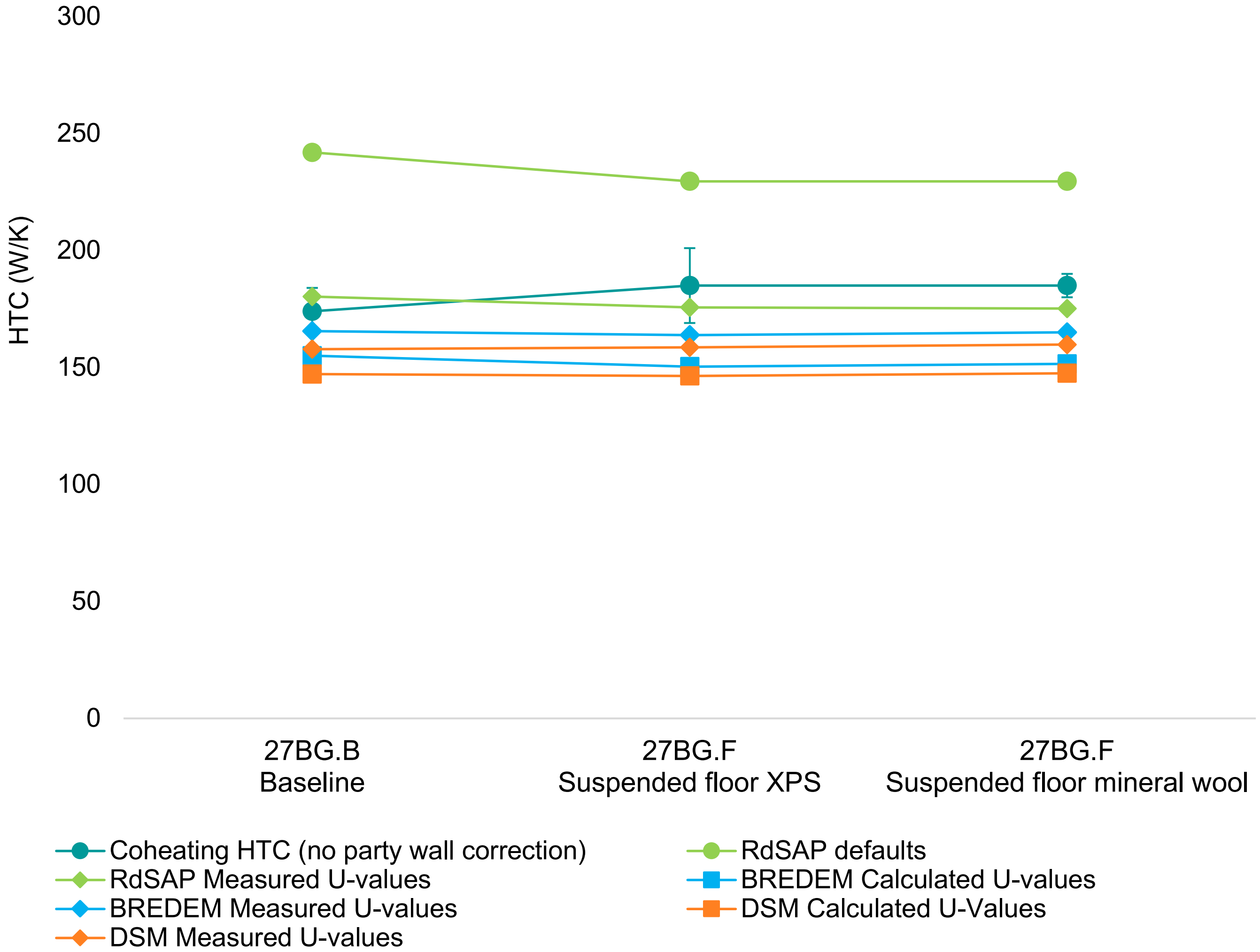

Figure 3-20 HTC Calibration step 4: Measured U-values

When modelling the building performance in DSM software, there are some inconsistencies in the way infiltration is accounted for. Under the Building Regulations for England and Wales, house builders are required to measure the “air permeability” of a dwelling using the units $m^3/(h \cdot m^2)$ @ 50 Pa. RdSAP however uses “air changes per hour” (h^{-1}). Often these are very similar, however they sometimes differ enough to have an impact on modelled performance, as in this case. A comparison of these inputs for 27BG is shown in Table 3-5.

Table 3-55 Comparison of measured air permeability and air change rates @ 50 Pa

Retrofit stage	Permeability ($m^3/(h \cdot m^2)$) @50Pa)	Air change rate (h^{-1}@50Pa)
27BG.B Base case	12.54 (0.63 h^{-1} using n/20)	14.06 (0.70 h^{-1} using n/20)
27BG.F.XPS XPS	13.83 (0.69 h^{-1} using n/20)	15.49 (0.77 h^{-1} using n/20)
27BG.F.MW Mineral wool	13.98 (0.63 h^{-1} using n/20)	16.23 (0.81 h^{-1} using n/20)

When these contrasting results are used in the DSM model, it alters both the predicted HTC and annual gas space heating cost savings. Due to the marginal reduction in U-value and gradual increase in air changes per hour, these alternative inputs mean that DSM predicts a reduction in HTC for the XPS retrofit but an increase for the mineral wool retrofit in the middle calibration stages. It is only when the reduction in bridging is accounted for that a saving is predicted in all cases.

When included in the annual energy demand DSM calculations, this quirk is the difference between a saving and an increase for both retrofits at the second and third calibration stages. Although the absolute values are very small, this illustrates the difficulty in modelling the impact of such low-impact interventions.

For the sake of consistency, and to provide a fair comparison between DSM, BREDEM and RdSAP, it is the converted air permeability rate that is used in the DSM models and included in all HTC and annual energy consumption analyses in DEEP. It could, however, be argued that the measured air change rate provides the more appropriate input value. The relevance of this to the full sample set of DEEP case study dwellings is discussed in more detail in the summary reports.

Measured vs. modelled HTC summary

All the models predict a small reduction in the HTC of the house following the floor retrofits.

The simplification of the room-in-roof geometry built into the RdSAP conventions means that the RdSAP predicted HTC is substantially higher than the BREDEM and DSM models, implying that assessors should be encouraged to input specific room-in-roof details when generating EPCs.

Once this is corrected, all the models, whether they used updated input data or not, predicted lower HTCs than measured in the coheating test. This is not surprising since the coheating analysis could not remove party wall heat losses, which were considered to be relatively large for this back-to-back terrace home as they represented over half the heat loss area.

One of the biggest changes in the predicted HTC was achieved by including the measured airtightness of the baseline home which was around 25 % more airtight than RdSAP predicted. Updating this resulted in a reduction in HTC of 17 W/K. The variability in air leakage across the UK housing stock means that it may be beneficial to allow EPC certificates to incorporate actual airtightness test results in their calculations.

Replacing default U-values with calculated U-values also achieved large reductions in predicted HTC, however, these reductions were countered somewhat when the models were updated with the measured U-values which were closer to the defaults than the calculations assumed.

This shows that uncertainty around construction makeup when calculated U-values are used could mean the updated values are not reflective of the actual fabric heat loss. This uncertainty is one of the reasons calculated U-values cannot currently be used when generating EPCs for existing dwellings where no information on construction details exists.

Updating the default model input data with measured values had a much greater effect on HTC than the floor retrofit itself.

3.5 Predicting EPC band, annual space heating and carbon emissions

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

To do this, all models used the same occupancy profiles and internal heat gain inputs as those defined in the RdSAP conventions, which are described in the DEEP Methods 2.01 Report. This provided a useful comparison between the modelling approaches, based on changes to fabric inputs only.

Dynamic and steady-state models are fundamentally different in that DSM calculates heat balances and demand at an hourly timestep, whereas BREDEM calculates these for a typical day of each month and extrapolates the results to an annual prediction. Thus, the complex interactions between gains and heat demands 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 appears from this research that BREDEM consistently predicts higher annual space heating demand than DSM.

3.5.1 Potential reasons for differences in annual model outputs

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

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

Heating set points and schedules
These have been adjusted to match those used in BREDEM. However, the hourly resolution of the weather data means that in some instances heating demand can occur in warmer daylight hours in 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 temperatures used in the hourly heat balance calculations naturally differ from the total daily average.

Solar gain through glazing
BREDEM limits glazing orientation to the cardinal and ordinal directions whereas the dwelling is modelled in its true orientation 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. This is more pronounced in dwellings with a greater area of south facing plane elements. The reverse can occur during darker winter months although the thermal mass of the constructions can retain some heat after sundown.

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

Weather
Due to the temporal resolution and variability of weather, it is not possible to match the BREDEM inputs in the same way as internal gains. The weather file used in the DSM was selected due to the close similarities between monthly average external temperature values (CIBSE Test Reference Year file for Leeds [9]) as discussed in the DEEP Methods 2.01 Report.

Differences specific to 27BG
For the 27BG baseline scenario, using measured infiltration rate and U-values, BREDEM predicted a space heating demand 2,026 kWh/year higher than the DSM prediction. In the majority of other DEEP case studies, HTC value has the greatest influence on 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 HTC. Using an unrestricted version of BREDEM software, it is possible to overwrite HTC with that calculated in the DSM model.

Following this adjustment, the normalised annual space heating demand in BREDEM for 27BG is 5,308 kWh, compared with the DSM estimate of 4,449 kWh, meaning that BREDEM predicts a demand that is higher by 859 kWh. The BREDEM calculations can be further normalised by using the DSM volume of conditioned space (7.72 m^3 less in the DSM model). Following this final adjustment, the BREDEM estimate is 634 kWh higher than the DSM output, with the DSM model including additional solar gain of 414 kWh. As with many other case study dwellings, this suggests that the differences related to the other variables listed above are negligible.

3.5.2 Impact of retrofits on EPC bands

Several policy mechanisms set EPC targets, and the Government has an ambition that all homes, where practically possible, will achieve EPC band C by 2035 [10]. The impacts of the retrofits in this case study on the expected EPC for each model prediction at each calibration stage are shown in Figure 3-21:

- The ground floor retrofit did not materially change the SAP score and so the home's EPC rating did not change post-retrofit.
- The house, although poorly insulated, received a relatively high EPC band C due to it having a relatively small heat loss area (over 50 % of the elemental surface area was party wall). The only model scenario in which the house was band D, not already band C, is in the base case RdSAP defaults version, since this uses the simplified room-in-roof assumptions which overpredict heat losses.
- Other than the RdSAP default case, updating the default data with measured and calculated data did not affect the home's EPC band.
- 27BG was a similar building type to DEEP case study home 17BG, which was an end-terrace on the same street. Since 17BG had an external gable wall, it had higher heat loss, and was therefore deemed to be band E pre-retrofit. This means that households in inefficient homes which have large areas of party elements (flats and back-to-back homes) have higher EPC bands than their end-terrace counterparts, which could make them ineligible for retrofit funding. This may prove problematic for neighbourhood scale retrofit schemes.

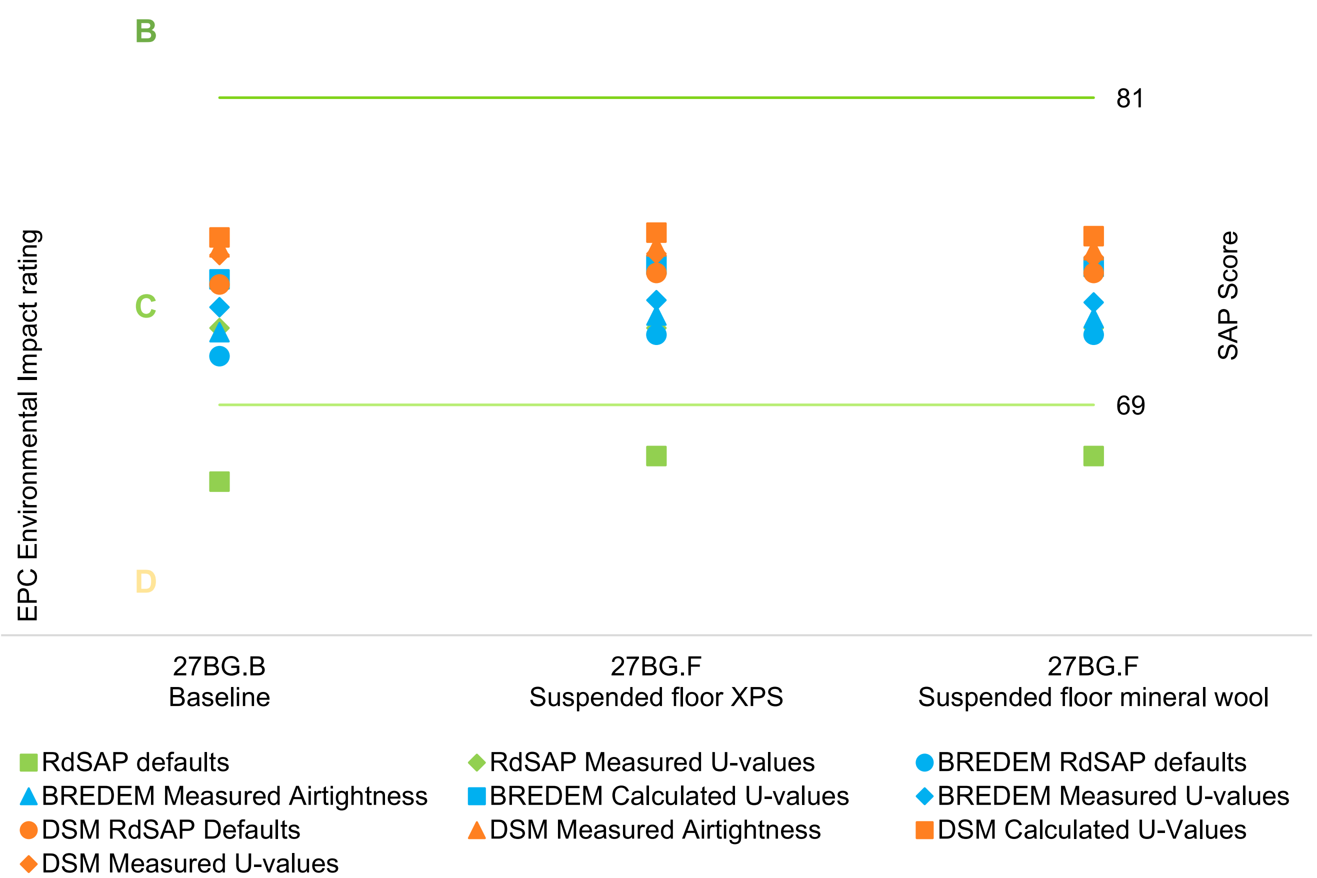

Figure 3-2121 Predicted impact of retrofits on EPC band

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 annual space heating demand for retrofits of 90 kWh/m² [11]. The predicted annual space heating demand for the case study retrofits is shown in Figure 3-22.

- Space heating demand is predicted to reduce to between -1 % (i.e., an increase in heating demand since the increase in infiltration post-retrofit seems to offset any savings achieved by the floor insulation) and 6 % following the ground floor retrofits, depending on which model and assumptions are used.
- DSM predicts lower space heating demand than RdSAP and BREDEM regardless of which inputs are used due to the way internal gains are calculated.
- RdSAP defaults substantially overestimate the heat loss from the room-in-roof.
- The SHDF 90 kWh/m² target is only met with the DSM model, not in any steady-state model, despite the dwelling achieving an EPC band C in BREDEM.

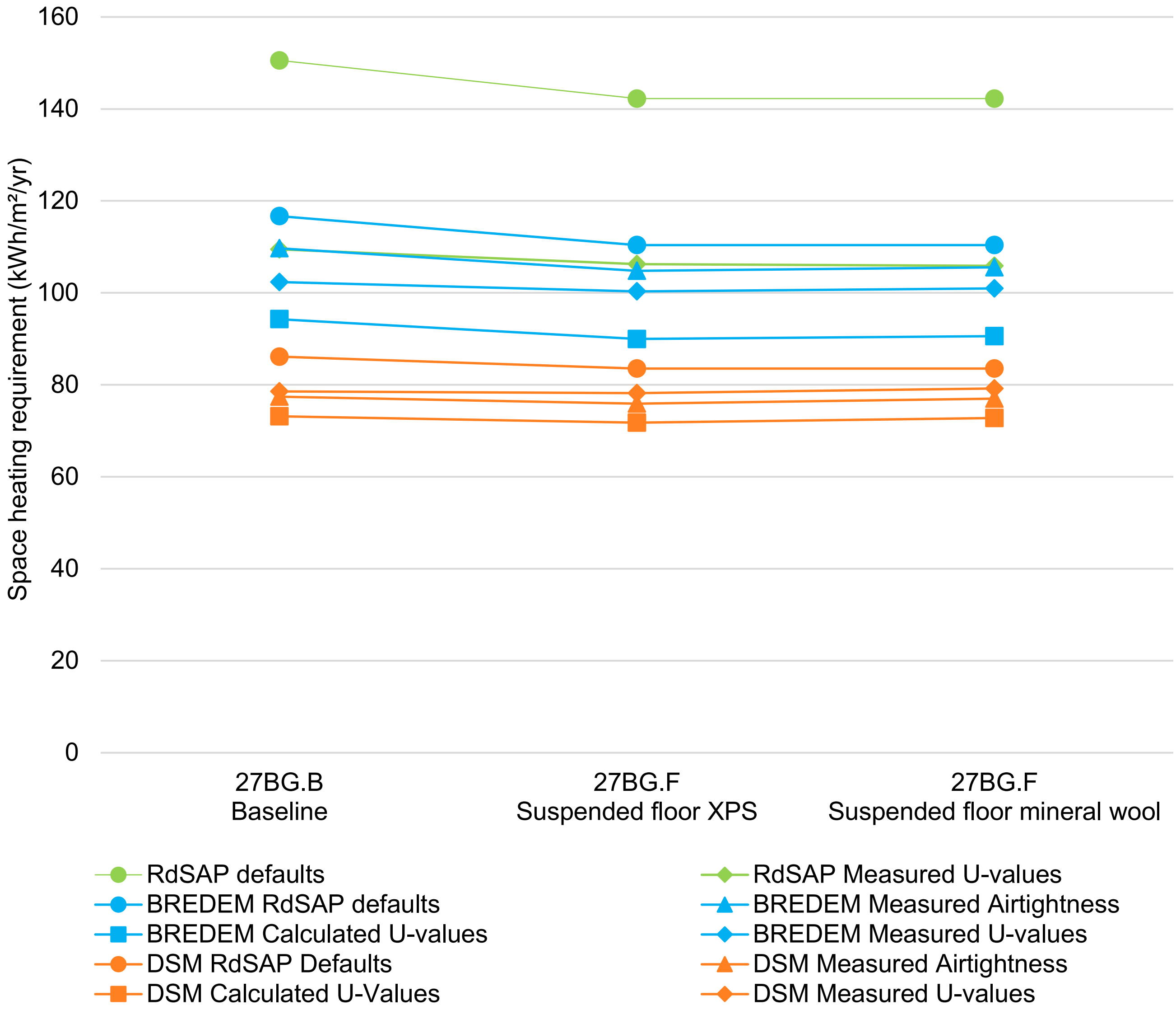

Figure 3-2222 Predicted reduction in annual space heating demand

3.5.4 Impact of retrofits on CO_2 emissions

Heating homes is responsible for around 15 % of the UK's CO_2 emissions [12]. The predicted reduction in CO_2 emissions achieved by the case study home retrofits is shown in Figure 3-23.

- Using the RdSAP age band defaults results in more predicted CO_2 emissions, since it underestimates the baseline energy efficiency of the house.
- DSM generally predicts much lower CO_2 emissions than RdSAP and BREDEM, since it assumes lower annual overall fuel consumption.
- The ground floor retrofits result in no meaningful reduction in CO_2 regardless of which model and assumptions are used, ranging between -1 % (due to a small increase in infiltration) and 4 %.

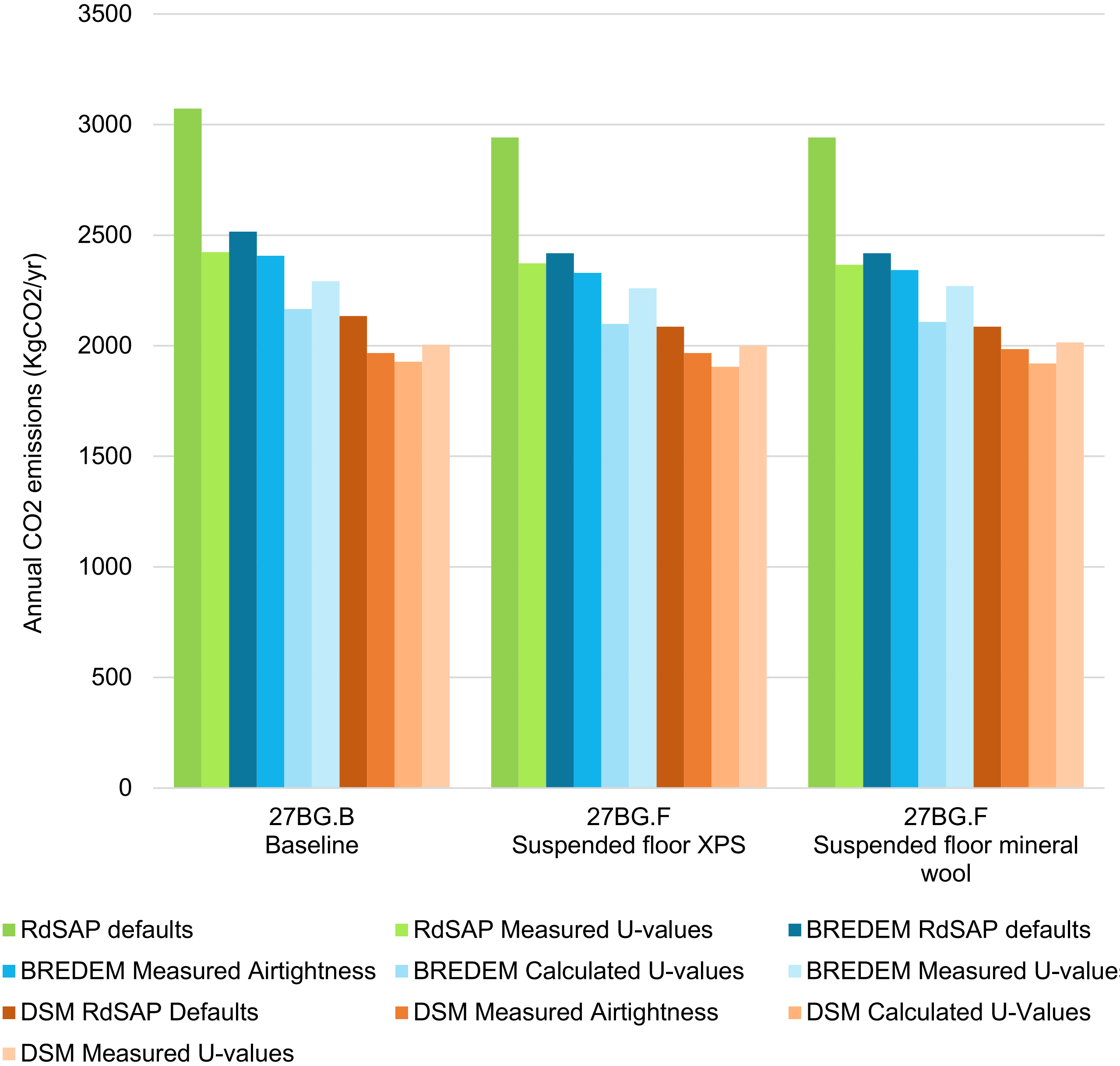

Figure 3-2323 Annual CO_2 emissions pre- and post-retrofit

Predicting EPC band, space heating and carbon reduction summary

Floor insulation was not found to improve the EPC of the home or substantially reduce carbon emissions or fuel bills.

As found in other case studies in DEEP, DSM tends to predict lower annual space heating requirements, meaning retrofit savings are also predicted to be smaller, and EPC scores higher, than using BREDEM and RdSAP.

As found in other DEEP case studies, RdSAP overpredicts space heating demand when defaults around room-in-roof heat loss are used.

This case study suggests that back-to-back mid-terrace houses may have relatively higher EPC scores than their end-terrace counterparts. This is referred to as the penguin effect, and has implications for access to retrofit funding which uses EPC as an eligibility criterion. The penguin effect may also be experienced by blocks of flats, though these are not included in DEEP case studies.

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 [13]. A description of this approach is provided in the DEEP Methods 2.01 Report.

The built form of 27BG means there is no crossflow ventilation across any façades and window restrictors that constrain the opening angles of the windows mean the percentage of openable area for each window is particularly small, between 21 % and 36 %.

Two metrics are used to assess whether the dwelling will overheat. The first is taken from another CIBSE publication, TM52: The limits of thermal comfort: avoiding overheating in European buildings [14]. 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 the sleeping hours the operative temperature in the bedroom from 10 pm to 7 am shall not exceed 26 °C for more than 1 % of annual occupied 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 14 UK regional locations. They use actual year weather data that simulate different heatwave intensities. DSY1 represents a moderately warm summer; DSY2 represents a short, intense warm spell; and DSY3 represents a longer, less intense warm spell [9]. 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. The results for Criteria A are shown in Figure 3-24.

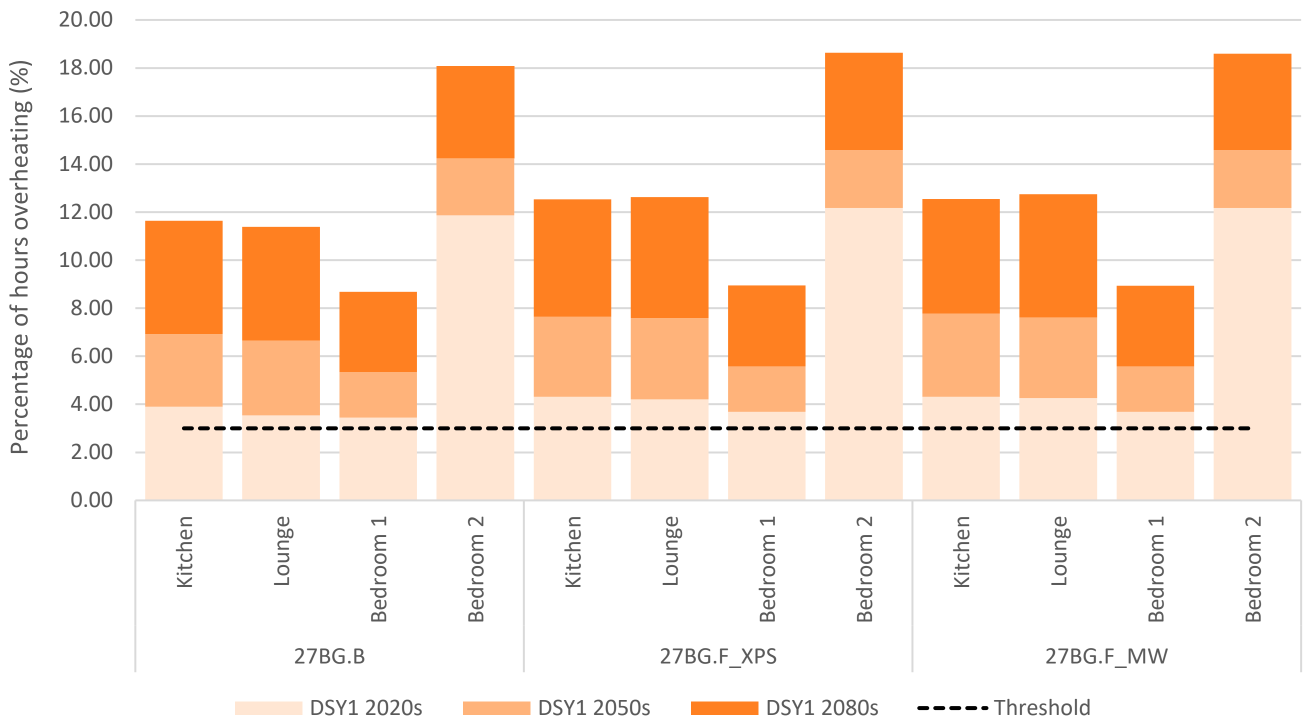

Figure 3-2424 Modelled overheating under TM59 Criteria A

The results for TM59 Criteria A in Figure 3-24 show the percentage of hours when ΔT ≥ 1 K, with a threshold of 3 % of occupied hours. Although the ground floor retrofits increased the extent of overheating marginally, it is the lack of any cross ventilation and small opening areas that leads to extensive overheating, even in the baseline case.

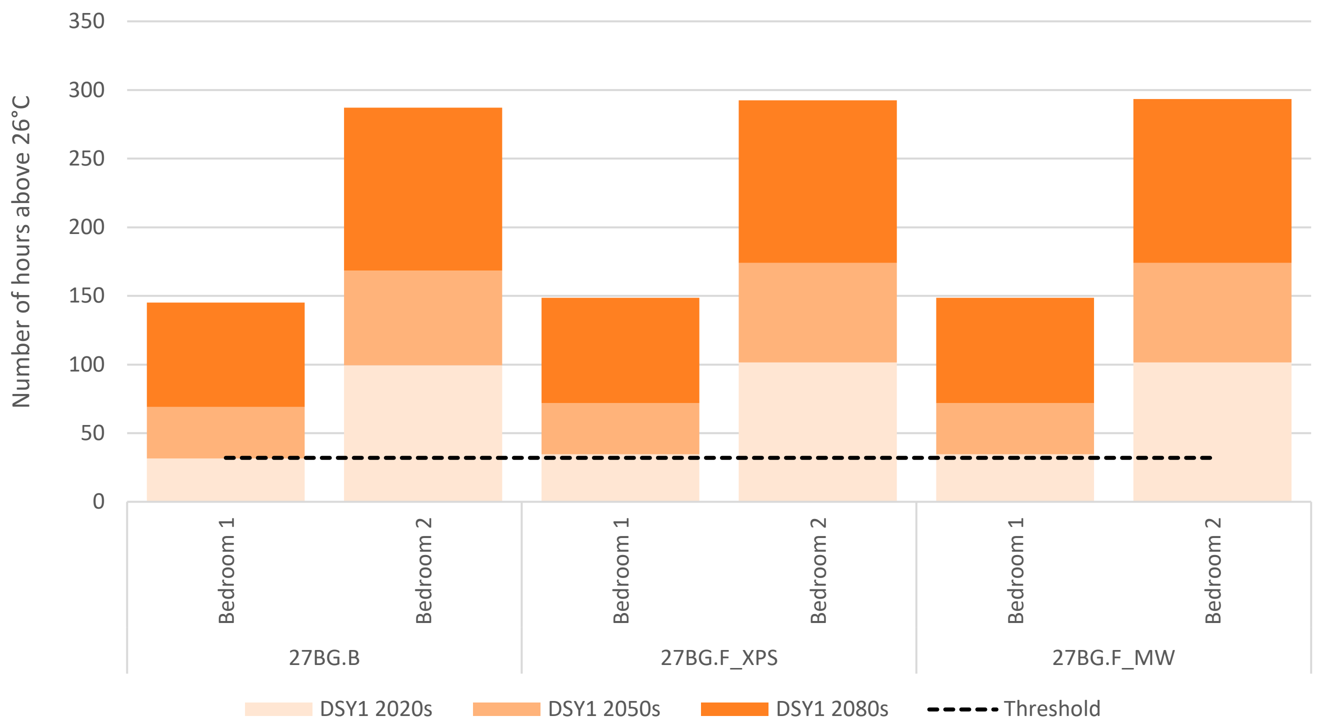

Figure 3-2525 Modelled overheating under TM59 Criteria B

The results for TM59 Criteria B in Figure 3-25 show the percentage of hours that exceed 26 °C with a threshold of 1% of occupied hours (32 hours in total). As described, there is a marginal increase in overheating, but this is not significant in the baseline case. Both sets of results suggest that the dwelling will overheat but the retrofit measures do not significantly increase this risk.

Overheating risk of retrofit summary

While overheating in this case study dwelling did marginally increase after each stage of the retrofit, the lack of any crossflow ventilation means the dwelling was subject to excessive overheating before any retrofit measures were applied.

The addition of ground floor insulation had a marginal impact on overheating, meaning it is slightly more at risk of overheating than pre-retrofit.

3.7 Retrofit costs and payback

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

The costs of undertaking each retrofit are categorised as either enabling works linked specifically to getting the house ready for the retrofit (making repairs etc.) or the cost of the retrofit itself. Decoration costs are excluded from the costs reported here since landlords undertake their own repairs following retrofits and would take on some of the decoration work. Costs associated with decorating are outside the scope of this project, however they have been found to represent around 14 % of the cost of internal wall insulation retrofits [15], though this may be different for ground floor insulation.

The costs of the 27BG retrofits are outlined in Table 3-6. Specifically, it describes the activities that took place, including those not directly associated with the retrofit itself. As shown, a large proportion (almost 40 %) of the cost was spent on enabling works which may not be captured in retrofit cost projections of either Government schemes or householder budgets.

Table 3-66 Cost of retrofits

Retrofit	Retrofit activity	Retrofit costs	Additional enabling work required	Enabling work costs
27BG.F.XPS	Floorboards removed 2 layers of XPS applied between joists Mineral wool applied at floor edges Sealed at skirting bords	£ 2,400	Replace damaged floor Replace cellar ceiling Electrician to make cellar light fitting safe	£ 1,400
17BG.F.MW	Floorboards removed Mineral wool applied between joists Mineral wool applied at floor edges Sealed at skirting bords	£ 2,174	Replace damaged floor Replace cellar ceiling Electrician to make cellar light fitting safe	£1,400

For these reasons, the costs of the 27BG floor retrofits were higher than expected. Other reasons for the higher price may be that this was a one-off install meaning the contractor could not benefit from any potential economies of scale.

Table 3-6 suggests that 62 % of the total retrofit cost was directly spent on the retrofit, while around 38 % was needed for enabling works, essentially replacing the timber floor and calling in an electrician to replace the basement ceiling and lighting. These additional costs are likely the reason the benchmark costs from previous DESNZ studies, identified in Table 3-7, were higher than in this case study. Overall, the suspended ground floor retrofit costs were similar regardless of which product was used, between £151 and £161 /m² installed.

Table 3-7 shows how the costs of the retrofits were split between labour and materials, which may be useful when considering how to reduce the total costs of retrofits in the future and where innovations are needed (time saving vs. manufacturing efficiencies). It appears that the major cost of the retrofits was labour. Labour cost saving innovation in the retrofit industry may therefore be more important for reducing the overall costs than cheaper materials.

Table 3-77 Breakdown of cost of retrofits

Retrofit	Labour	Materials	Cost	Treated area (m²)	Cost per area (£/m²)	Benchmark (£/m²) [16]
27BG.F.XPS	63 %	37 %	£ 3,800	24	£ 161	£ 92
27BG.F.MW	59 %	41 %	£ 3,574	24	£ 151	£ 92

3.7.1 Predicted fuel bill savings

The impact of the retrofits on household dual fuel bills is shown in Figure 3-26, using the SAP fuel prices of 3p per kWh gas and 13p per kWh electricity. These values do not reflect current fuel prices and are shown only as an illustration.

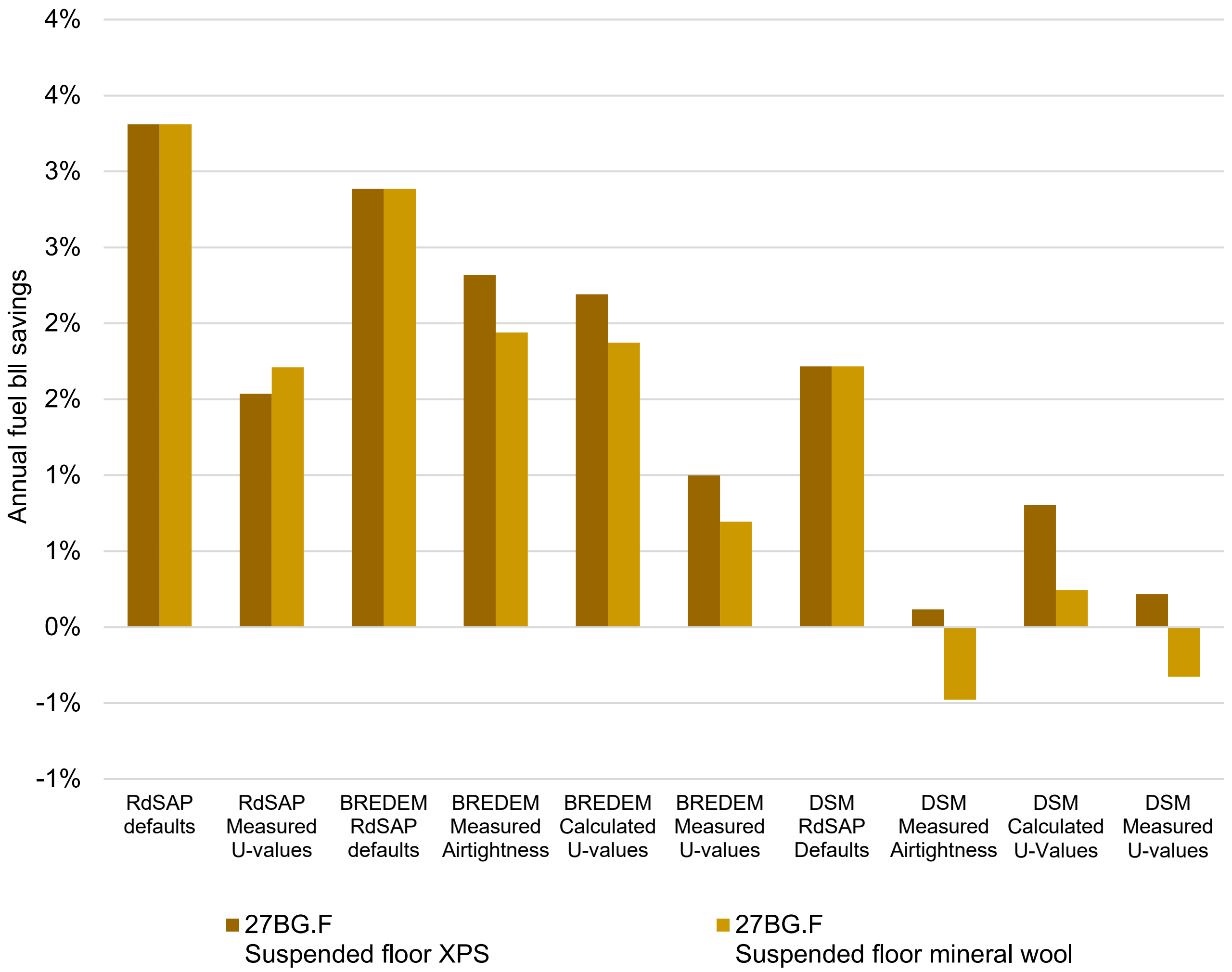

Figure 3-26 Predicted fuel bills

The analysis shows that both insulation types achieve a similar impact on fuel bills. In the worst case, marginally reducing space heating demand by between 1 % (shown as negative savings), where the increase in infiltration offsets the reductions in floor heat losses, and just over 3 %, when using default U-values, though the measured values reveal that savings up to 2 % may be more realistic. The major benefit of floor insulation may therefore be improved surface floor temperatures, which can improve thermal comfort rather than achieving fuel bill savings.

3.7.2 Predicting simple payback of retrofits

Changes to fuel prices will directly impact the predicted savings and have implications for payback periods. However, since little to no savings were modelled, the simple payback time (i.e., not considering fuel price inflation or discount rates) is not a meaningful assessment to undertake. The justification for insulating ground floors may be better articulated by considering the non-financial benefits of floor insulation which can include improvement in floor surface temperatures which can improve an occupant's experience of comfort.

Retrofit costs summary

The retrofit costs for 27BG were higher than benchmark costs, mostly because enabling costs were around 40 % of the total. These included the removal of the cellar ceiling, undertaking electrical works and replacing the timber floor boards. This scale of enabling costs is similar to those found in other DEEP case studies.

This suggests that benchmark costs for floor retrofits in older homes may be optimistic, as the tongue and groove nailed timber floorboards are often damaged in the removal process and need replacing. Enabling costs tend to be necessary, so may need inclusion in cost estimates. The research also confirms the presumption that the installation of floor insulation is disruptive for occupants.

Labour made up over 60 % of the total installation costs and there was no meaningful difference between the costs of the two products used.

RdSAP using age band related defaults predicted a £21 annual fuel bill saving. When measured data for U-values and infiltration rates were included, this fell in some instances to zero or near zero, meaning payback times of hundreds of years.

The number of floor retrofits taking place is increasing in the UK. However this research suggests that more evidence is needed to understand whether models are able to accurately predict how insulation affects heat flow through suspended timber ground floors and how savings manifest in homes with different building forms and floor area to heat loss area ratios.

4 Conclusions

This case study has identified important findings about the performance impacts of retrofitting suspended timber ground floors in solid walled homes as well as investigated the models used to predict performance and risk. The main issues are discussed below.

Floor retrofit performance
Neither steady-state nor dynamic models predicted meaningful reductions in measured or modelled HTC resulting from the floor retrofit. Although floor U-values were halved, the home had a small ground floor area, meaning there was no major change in fuel bills or EPC scores. Surface temperature measurements indicated that thermal comfort may be improved following floor retrofits. Investigations into the success of floor retrofits in different house types is needed before generalisations about floor retrofits for the UK housing stock can be made.

Measurements affected by party walls
This case study illustrates that measuring the HTC of homes with large areas of party wall can be problematic, and that ignoring party wall heat loss means measurements may be unreliable. This has implications for the development of methodologies for measuring the HTC of homes.

Mineral wool vs. XPS insulation
As expected, the reduction in floor U-values observed confirms that both mineral wool and XPS insulation achieved substantial reductions in U-value, around 56 %, and there was no discernible difference in performance between the two. Similarly, there was no significant difference measured on the impact either retrofit had on air leakage, though an increase within the error of the test was detected. Neither retrofit was able to eradicate air movement through the floor indicating the air barrier membrane was not installed or not successful.

Energy model accuracy
Replacing the measured infiltration and measured U-values in the energy models had a much larger impact (just less than 10 %) on HTC than the floor retrofit was predicted to achieve (-1 % to 5 %).

The findings indicate that the practice of allowing a simplified approach to assessing room-in-roof heat loss in RdSAP could cause substantial overestimation of EPCs for house types similar to this case study.

Barriers to installing floor insulation
The process of installing the floor insulation was highly disruptive and damaged the original floors, meaning they were replaced with floor sheeting, which greatly increased the installation costs of the retrofit, indicating that the benchmark costs stated in the literature may be underestimates.

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