Department for Energy Security & Net Zero

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DEEP Report 2.10

Case Study 08OL

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Prepared for DESNZ by

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Executive summary

08OL is one of fourteen case study homes being retrofitted in the DEEP project. The case studies are used to identify the performance of, and risks associated with, retrofitting homes without conventional cavities. The data from the case studies are used to evaluate the accuracy of modelled predictions of retrofit performance and risk.

Replacing the suspended timber ground floor with a new composite floor reduced the home's heat transfer coefficient (HTC) from (167 ± 9) W/K to (148 ± 10) W/K, a (19 ± 13) W/K, or (11 ± 8) % reduction, according to the coheating test. This was mostly due to an improved U-value, though a proportion was due to reduced air leakage (3 W/K), and thermal bridging (< 6 W/K). An attempt was made to correct the coheating test results for the impact of wind, since the pre-retrofit tests were severely affected by two large storms. Without this correction, the results from the coheating tests suggest that the HTC reduced from (208 ± 19) W/K to (147 ± 18) W/K, representing an unrealistic saving given the U-value improvement and the relatively small area of suspended timber floor which was replaced (12 % of heat loss area), and only a 9 % decrease in mean air permeability (from 16.6 to 15.3 $m^3/(h \cdot m^2)$ @ 50Pa).

The retrofit did not improve the energy performance certificate (EPC) rating of the home from its pre-retrofit band D, according to RdSAP. It was only predicted to achieve savings of between £8 (3 %) and £31 (5 %) in fuel bills (based on SAP prices), and only 2 % to 7 % in annual CO_2 emissions. In addition to not making a meaningful contribution to the EPC, reducing bills or carbon reduction targets, the cost of replacing the ground floor (~ £6,000) was three times the cost of a conventional suspended timber ground floor retrofit. It is possible that this would have achieved similar savings, although it is not possible to say conclusively as this alternative was not tested in this house. Thus, although there are broader benefits, such as greater durability and greater life expectancy of the floor, the financial payback is unattractive.

The case study also provides useful data on the airtightness of Dennis-Wild steel-frame homes, showing they have no primary air barrier and, as such, relatively high levels of air leakage, 16.6 $m^3/(h \cdot m^2)$ @ 50Pa, by existing UK standards. Rectifying air leakage pathways through the building fabric with interlinked floor voids, external walls and loft space, would not be simple. Although the new ground floor removed most of the air leakage via the ground floor, this only reduced the air leakage by a relatively small absolute amount of 15.3 $m^3/(h \cdot m^2)$ @ 50Pa (9 %), which is within the error of the test.

Air leakage was also observed to take place between dwellings, with a blower door co-pressurisation test indicating that 14% of the total air leakage measured could be attributed to inter-dwelling air exchange. This has implications for the use of blower door tests and how their results are used as inputs to energy models or for approximating fresh air provision. DEEP case studies have previously observed inter-dwelling air exchange between adjacent solid walled homes, and the results from this case study suggest that this phenomenon can also take place in non-traditional homes. A cavity party wall thermal bypass was also observed, further complicating the air leakage pathways.

An analysis of the overheating risk found that the home was at risk in its uninsulated pre-retrofit state, and that this risk worsened after the ground floor retrofit. The reason is thought to be the interactions between the sub-floor void and the space above. During warmer spells in the summer the ground temperature in the sub-floor void is lower than the air temperature which helps reduce overheating slightly when the ground floor is not insulated.

1 Introduction to 08OL

Case study 08OL is a three-bed, semi-detached Dennis-Wild steel-framed dwelling. In this retrofit project the suspended timber ground floor was removed and replaced with composite pre-insulated panels. The case study provided the opportunity to explore the performance of an alternative novel approach to suspended timber floor ground insulation and understand more about heat loss in non-traditional homes.

1.1 DEEP field trial objectives

08OL is one of fourteen 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 will improve policy advice.
Unintended consequence	More retrofit scenarios need modelling to confirm condensation, underperformance, air quality and comfort risks.
Cumulative impact	Piecemeal retrofits are common, clarity is needed on the impact of 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 may increase installation from 0.5 % of ECO measures.
Airtightness retrofit	Infiltration undermines retrofits, balancing airtightness and indoor air quality is an unexploited ECO opportunity.
Neighbour risk	We investigate whether whole house or staged retrofits affect condensation risk for neighbours.

1.2 DEEP 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 seven discreet research questions developed, which are listed below and used to discussing the findings:

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

The data collected from case study 08OL are not designed to answer all of these research questions but to contribute to the formation of a body of evidence from the DEEP project that may begin to address these questions.

1.3 Case study house information

Shown in Figure 1-1 and Figure 1-2, 08OL is a three-bedroom semi-detached property in West Yorkshire. Built in the 1930s, it is a Dennis-Wild steel-frame house with [1] three external walls (front, side and rear) and a party wall shared with a neighbour. The external walls on the ground floor are of masonry cavity construction, comprising a brick outer leaf and block inner leaf, which is finished at first floor ground level with a projecting brick band course. The first floor external walls have a pebble-dash render stretching from the first floor ground level to the eaves. All external walls have a wet-plastered internal finish.

The steel frame is evident as the mid-span stanchions to the front and rear elevations extend into the rooms and are boxed out at both storeys. The patented cradle roof truss with iron tie rods is present in the loft space. The house has a solid concrete ground floor in the kitchen. The remainder is suspended timber. The intermediate floor is of timber construction. The roof has hipped ends and the loft space is accessible through a loft hatch on the first floor landing. There is a chimney on the party wall, but the living room fireplace is sealed.

Around 10,000 homes across the UK were built by Dennis and Wild using this steel-frame composite system [1]. While this specific construction method was not widely used across the UK for post-war housing, the results of this case study enable research into the pre- and post-retrofit performance of system-built homes with cavity walls.

Figure 1-1 Case study house

The site plan in Figure 1-2 shows the location of the test house.

Figure 1-3 Case study house site location plan

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

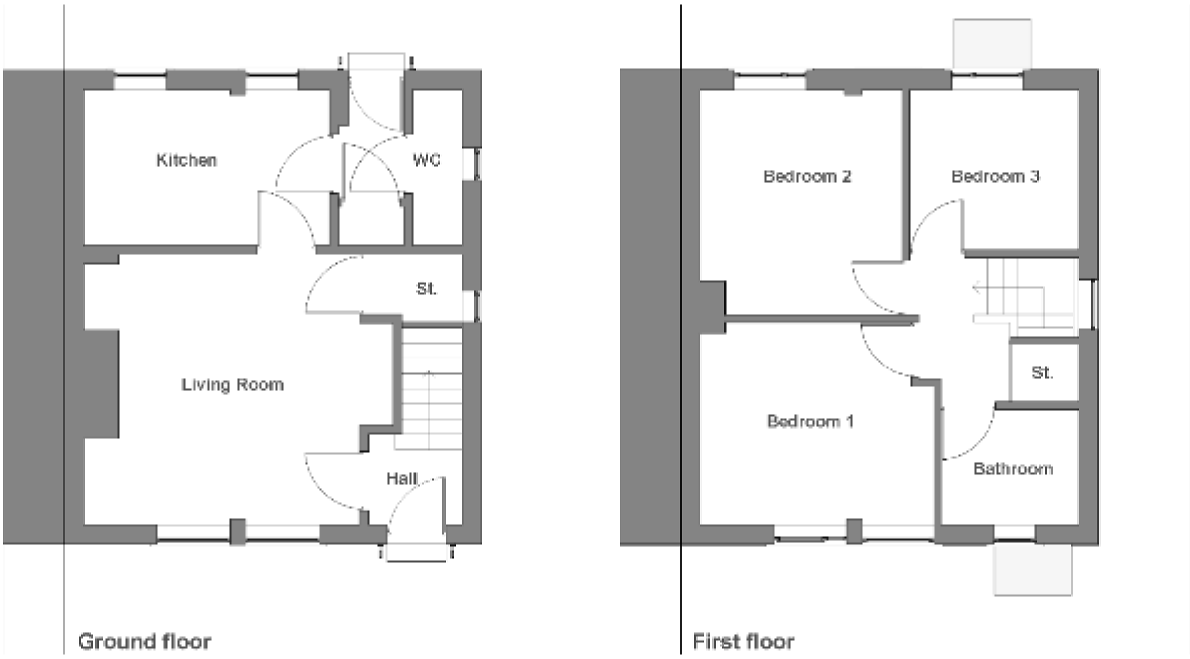

Figure 1-4 House floor plans

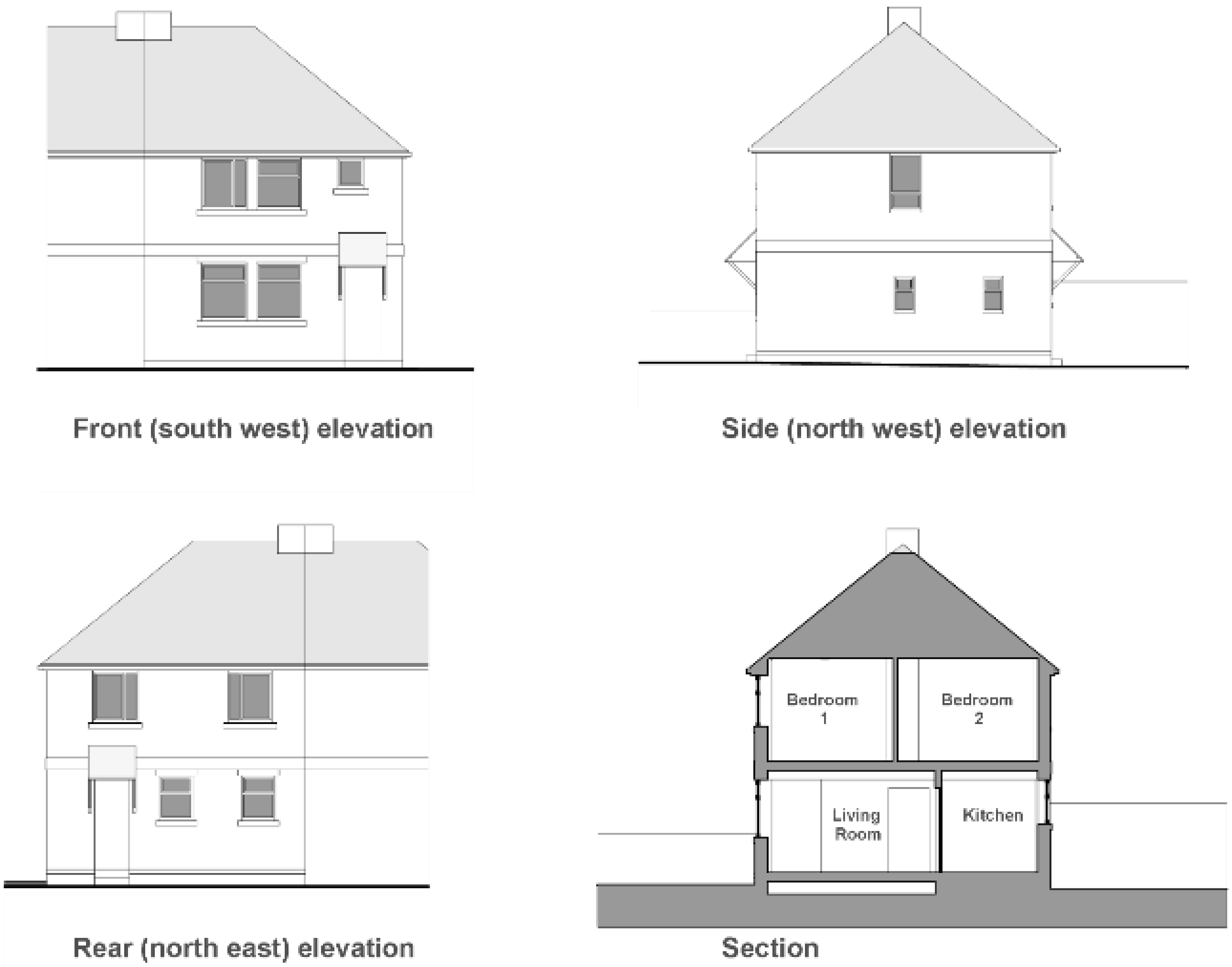

Figure 1-5 Front, rear and side elevations and section

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The dimensions of each element in the home are listed in Table 1-2 and used to calculate heat losses as well as inputs to the reduced data Standard Assessment Procedure (RdSAP) model, the Building Research Establishment Domestic Energy Model (BREDEM) and Dynamic Simulation Modelling (DSM). The dimensions were obtained via a measured survey of the dwelling.

Table 1-2 House dimensions

Detail	Measurement
Volume	*174.14 m^3*
Total floor area	*68.72 m^2*
Total heat loss area	*157.06 m^2*
Ground floor	*34.10* m^2
External wall (ground floor)	34.24 m^2
External wall (first floor)	38.71 m^2
Windows	*11.90* m^2
Door	*3.49* m^2
Ceiling	*34.62* m^2
Party wall	*36.06* m^2

1.4 Retrofit approach

The retrofit details and U-value targets for each element are listed in Table 1-3. The retrofit U-values listed were calculated using the BRE calculator and are based on the observed materials and thicknesses of the existing fabric, as well as knowledge of the insulation being installed. The thermal conductivity of the insulation was provided by the manufacturers. BS EN 12524:2000 [2] was used to determine the thermal conductivity of other construction elements and the plane element U-values include repeating thermal bridges (e.g., ground floor joists) in accordance with BR443 [3] and BS EN ISO 6946 [4].

Table 1-3 Construction and retrofit summary

Detail	Original construction	Retrofit[1]
Air permeability	16.57 $m^3/(h{\cdot}m^2)$ @ 50Pa	None.
Ground floor type 1 (living room only)	Uninsulated suspended timber	Replacement suspended timber ground floor: Oriented strand board (OSB) + composite plastic cassette + 173 mm expanded polystyrene (EPS) @ 0.037 W/(m·K) Target U-value: 0.16 $W/(m^2{\cdot}K)$
Ground floor type 2	Uninsulated solid ground floor	None
Loft	Ceiling joist with 200 mm mineral wool (MW) insulation (75 mm MW between and 125 mm MW above joists) lath and plaster	None
External wall type 1 (ground floor)	Brick + cavity + block + wet plaster	None
External wall type 2 (first floor)	Pebbledash render + block + cavity + block + wet plaster	None
Windows	uPVC double glazed	None
External doors	Timber with single glazed panel	None

The baseline stage is illustrated in Figure 1-5. The retrofit stage is shown in Figure 1-6. Building performance evaluation (BPE) tests, whole house energy modelling and elemental thermal simulations were conducted to quantify changes in energy performance resulting from the retrofit. The specific methodologies for these are described in the DEEP Methods 2.01 Report.

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

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The codes given in Table 1-4 are shorthand to identify each stage to aid the discussion and presentation of results.

Table 1-4 Phased retrofit stages

	Retrofit stage	Code	Retrofit date
1	Baseline	08OL.B	February 2021
2	Ground floor retrofit Installation of new insulated suspended ground floor (living room)	08OL.F	March 2021

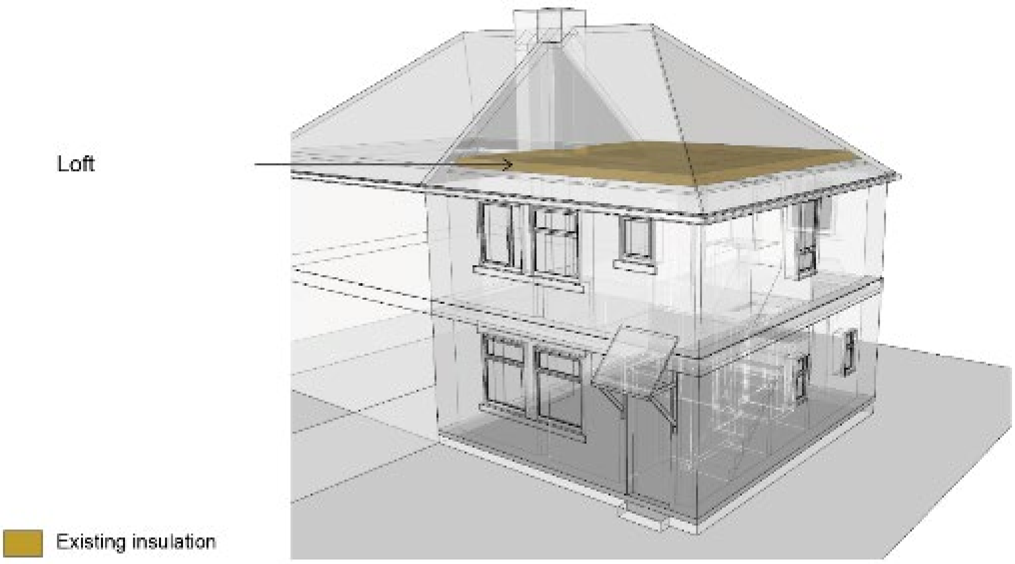

Figure 1-6 Stage 1: Insulation already in the property prior to the retrofit (08OL.B)

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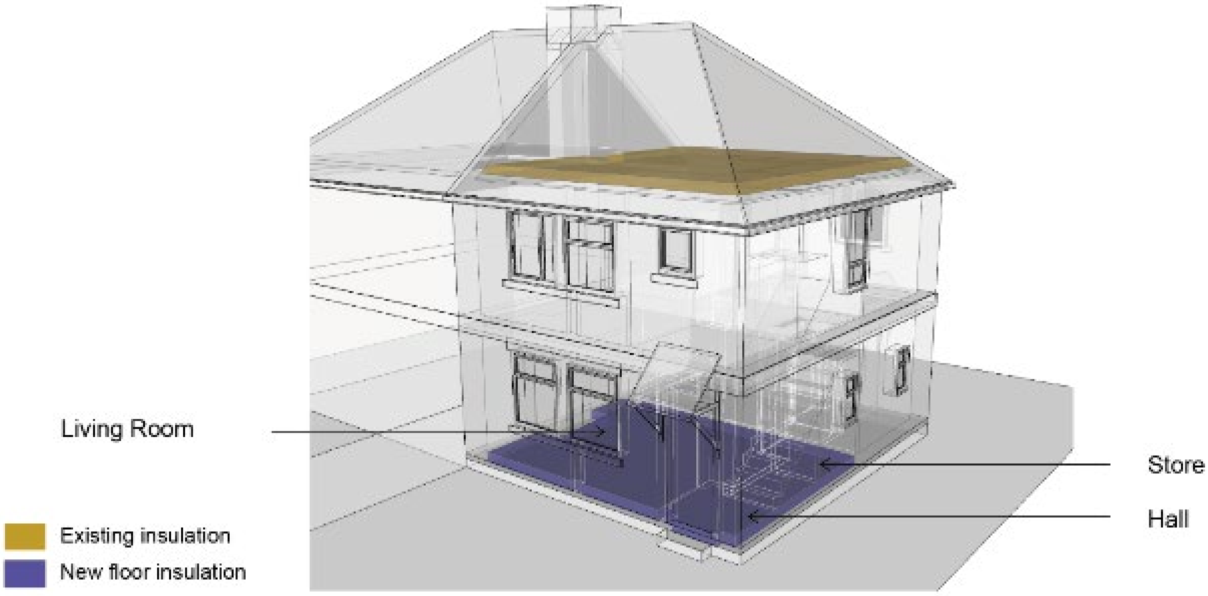

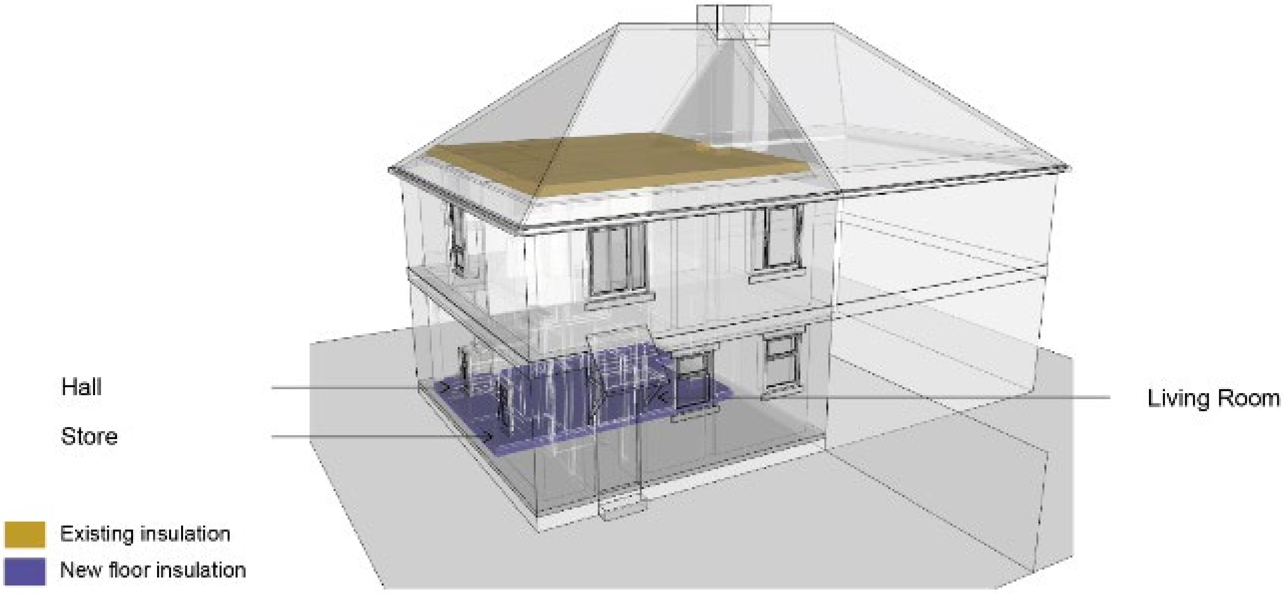

Figure 1-7 Stage 2: Installation of new insulated suspended floor (08OL.F)

Case study and retrofit summary

08OL provided an opportunity to investigate the impact of a novel approach to suspended timber ground floor retrofits on performance. Instead of the conventional approach of installing mineral wool between the timber floor joists on the ground floor, in this home an entire section of the ground floor was replaced with a pre-insulated and composite alternative. This was designed to be airtight and have low thermal bridging at the wall-to-floor junction.

It also provided the opportunity to undertake building performance evaluation tests on a non-traditional house typology, which are much less studied but understood to have particularly poor thermal performance.

2 Fieldwork and modelling methods

BPE tests and modelling activities were undertaken on 08OL before and after the retrofit in accordance with the methodologies listed in the DEEP Methods 2.01 Report. This section outlines the specific implementation of these methods at 08OL 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. Internal environmental data collected at 08OL included air temperature, relative humidity (RH) and CO_2 levels. External environmental data was collected via a weather station located on the south façade of the dwelling and included vertical solar irradiance and air temperature. This was supplemented by an external air temperature sensor positioned outside 08OL on the north façade, attached to a downpipe, to ensure that air temperatures were recorded on both sides of the house.

2.2 Measured survey

A detailed survey of the building was undertaken. From this, a digital version of the house was developed using SketchUp, which was used to calculate the dimensions of each element and to draw up the plans shown in Figure 1-3. Plans, sections and elevations were directly exported to generate the geometry for DSM. DesignBuilder software was used for all the DEEP dynamic modelling, which uses Energy+ as its physics engine. 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 the baseline and retrofit stages. These results were used to identify airtightness changes related to the retrofit. They were also used to approximate the average annual heat loss attributable to background ventilation (HTC_V). Qualitative thermography under depressurisation was undertaken, along with thermography of specific details under normal conditions. This was done to capture and identify any changes between the baseline and retrofit stages. Pulse air tests were also conducted during the testing programme to compare with the blower door tests results.

Ventilation in the home was provided via trickle vents in all rooms and extract fans located in the kitchen and bathroom. These were not altered during the retrofits. It is beyond the scope of the DEEP project to undertake in-use monitoring of internal air quality under occupied conditions, which would have required longitudinal conditions monitoring pre- and post-retrofit.

2.4 Heat flux density measurement and U-values

26 Hukseflux HFP01 heat flux plates (HFPs) were installed on various elements of 08OL to measure the baseline in-situ U-values, assess the improvements achieved by the fabric upgrades, quantify the party wall heat exchange, calibrate energy and thermal models and estimate the plane element fabric heat loss (HTC_f) to compare with the HTC disaggregation.

The HFP locations are listed in Table 2-1 and, for context, visualised in Figure 2-1, Figure 2-2 and Figure 2-3. Thermography was undertaken to identify the most representative location for each fabric element and, where possible, multiple locations for each element were measured.

Table 2-1 HFP locations

HFP	Element	Room
AG1	Ground floor	Living room
AG2	Ground floor	Living room
AG3	Ground floor	Living room
AG4	Ground floor	Living room
AG5	Ground floor	Living room
AG6	Ground floor	Living room
AG7	Ground floor	Living room
AG8	Ground floor	Living room
AG9	Ground floor	Kitchen
AG10	Front external wall	Living room
AG11	Front external wall	Living room
AG12	Side external wall	Understairs store
AG13	Party wall	Living room
AG14	Chimney breast	Living room
AG15	Party wall	Living room
AG16	Party wall	Kitchen
S1	Front external wall	Bedroom 1
S2	Front external wall	Bedroom 1
S3	Ceiling	Bedroom 1
S4	First floor ceiling	Bedroom 1

S5	Party wall	Bedroom 1
U1	Rear external wall	Bedroom 2
U2	Party wall	Bedroom 2
U3	Party wall	Bedroom 2
U4	Party wall	Bedroom 2
U5	First floor ceiling	Bedroom 2

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

It is important to note that the in-situ U-values are based on a limited set of heat flux density measurements, so may not be representative of the performance of the whole element in practice. Similarly, where areas of thermal bridging may be expected, such as near corners, heat flux density measurements provide context to the whole fabric heat loss and inform the weighted average calculations.

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

The 8 HFPs in the living room on the ground floor were moved into different positions on the floor following the ground floor retrofit, as shown in Figure 2-3.

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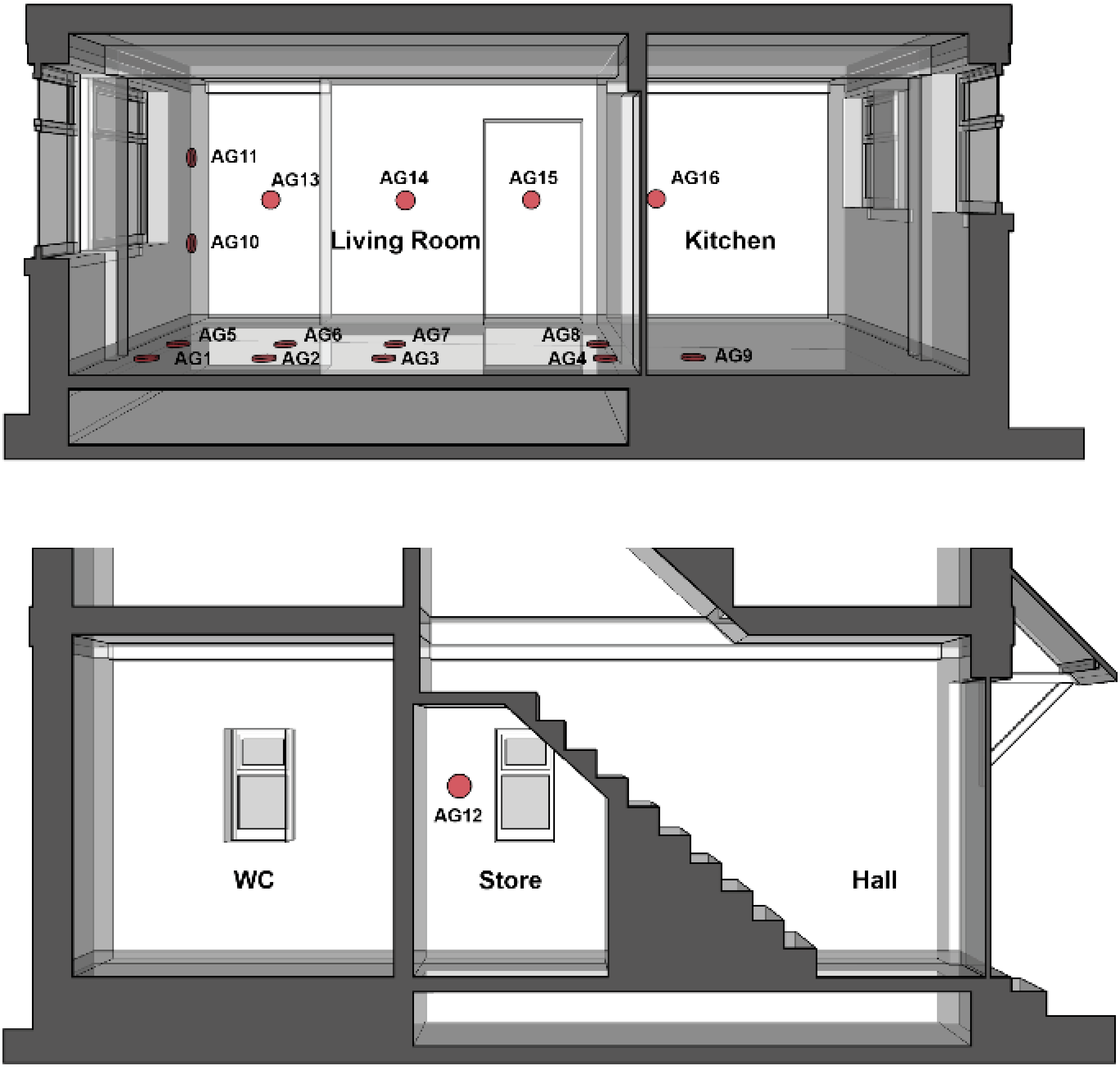

Figure 2-1 Ground floor HFP locations (HFPs AG1-AG8 positioned for Stage 1: Baseline)

Figure 2-2 First floor HFP locations

Figure 2-3 HFPs AG1-AG8 repositioned for Stage 2: Ground floor retrofit

2.5 Whole house heat transfer coefficient (HTC)

Coheating tests were successfully performed at each stage of the retrofit, as described in the DEEP Methods 2.01 Report, to provide a measured HTC. In addition to the 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 in this project are explained in detail in the DEEP Methods 2.01 Report. In summary, RdSAP, BREDEM and DSM (using DesignBuilder software version 7.0.0.088 [5]) energy models were used to calculate the HTC of the case study building at each retrofit stage. This produced a predicted HTC, which was compared against the measured HTC from the coheating test. To understand how the predictions improve as specific data are used to replace default input data, the calibration procedure outlined in Table 2-2 was undertaken.

Table 2-2 Modelling calibration 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 energy demand, annual fuel bills, carbon dioxide emissions, SAP score and EPC band. The success of the retrofits at achieving policy aims can be evaluated, and, along with the retrofit install costs, simple payback periods for each retrofit can be calculated.

Case study method summary

A deep dive into the 08OL retrofit case study was undertaken involving coheating tests, blower door tests, and 26 heat flux density measurements on fabric elements, taken before and after the retrofit.

RdSAP, BREDEM and DSM energy models were created 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 associated with various approaches to retrofit, as well as the usefulness of models to predict them.

[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 firstly presents the results of the airtightness tests, in-situ U-value calculations and whole house heat loss measured by the coheating test. It then describes how the modelled predictions compare to the measured data and how successful the four calibration steps were at improving the predicted heat loss. The model predictions for EPCs, space heating, CO_2 emissions, fuel bills and paybacks are discussed.

3.1 Airtightness improvements

The home was found to be not particularly airtight. Blower door tests identified that the pre-retrofit home had a mean air permeability of 16.6 $m^3/(h \cdot m^2)$ @ 50Pa, which is leakier than the UK stock average of 11 $m^3/(h \cdot m^2)$ @ 50Pa. The suspended timber ground floor constituted <12 % of the building envelope area, and the ground floor replacement only reduced the overall air leakage slightly to 15.3 $m^3/(h \cdot m^2)$ @ 50Pa. This improvement was slightly under the 10 % uncertainty associated with the blower door test method. Despite the small absolute reduction in overall air leakage, qualitative thermography was able to identify an observable reduction in air leakage through and around the suspended timber ground floor.

The framed structure of 08OL created many interconnected voids within the property, and with no designed primary air barrier, air exchange into and out of the habitable space occurred through a wide variety of direct and indirect pathways. While the replacement of the suspended timber ground floor reduced infiltration through that element of the construction, no airtightness-specific measures were undertaken in the rest of the house, so all other air leakage pathways remained for the entire test period. The newly retrofitted suspended ground floor limited air leakage to the floor perimeter, whereas previous air movement through gaps between the floorboards was widespread. Otherwise, there were no detectable differences in leakage paths throughout the dwelling in the air pressurisation tests before and after the ground floor retrofit. Figure 3-1, Figure 3-2 and Figure 3-3 illustrate the differences in infiltration through the original and replacement ground floors.

Figure 3-1 The original living room suspended timber ground floor under depressurisation

Figure 3-2 The replacement living room suspended timber ground floor under depressurisation

Under depressurisation, cooler air from the sub-floor void could be seen entering the living room and understairs cupboard. Prior to the retrofit, the air could be observed entering through numerous gaps between the floorboards and all around the room perimeter. Post-retrofit, the ground floor leakage was limited to around the skirting board at the perimeter.

Figure 3-3 The living room cupboard with original floor (top) and replacement floor (bottom)

Another improvement was observed with the original floor beneath the staircase. The area below the lower half of the staircase was open to the sub-floor void, i.e., the sub-floor air could freely exchange with the under-stair void. The replacement floor extended fully beneath the stairs to provide a continuous air barrier and insulation layer, limiting the air exchange, as shown in Figure 3-4.

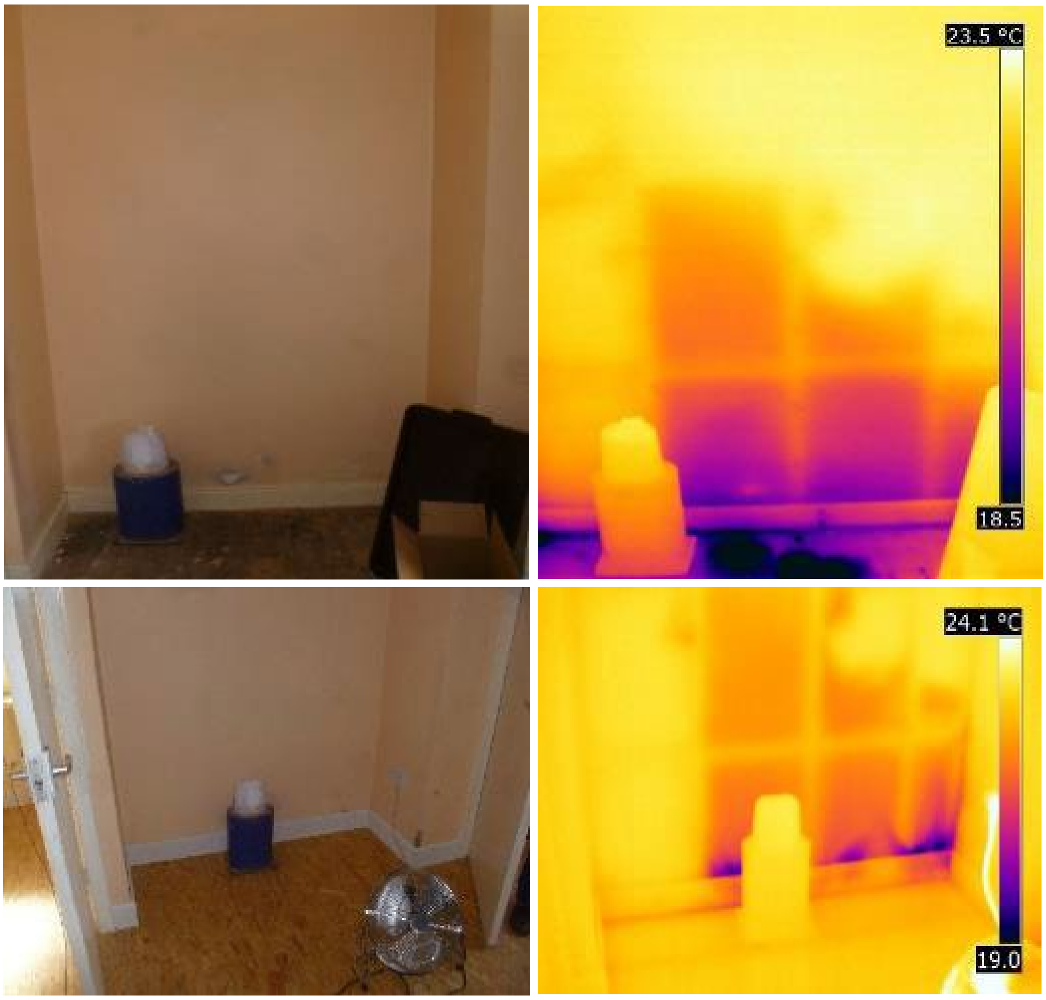

Figure 3-4 The void beneath the stairs with the original floor (top) and replacement floor (bottom)

Many additional air leakage paths were detected, through numerous openings and penetrations in the building envelope, where direct air exchange between the internal and external environments was possible. Some of these could possibly be addressed by draught-stripping or sealing at the point of air leakage. These were most apparent at service penetrations through the external wall in the kitchen, at doors and windows, and at the loft hatch, as shown in Figure 3-5.

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Figure 3-5 Direct air leakage at service penetrations, the rear external door and loft hatch

In addition to direct air leakage being observed between the inside and outside, indirect air leakage was prevalent throughout the home, where the point of air leakage through the external envelope was some distance from the observed point of air leakage into the habitable space. In these instances, air was travelling through many interconnected voids within the dwelling, and simple draught-stripping or sealing would not be straightforward to implement.

Figure 3-7 shows an example of indirect air leakage into the intermediate floor void at the junction with the front elevation from the bedroom above and living room below.

Figure 3-6 Indirect air leakage via the intermediate floor void from above (top) and below (bottom)

Figure 3-7 shows external to internal air leakage occurring in the void behind the bath panel emerging behind the pedestal in the bathroom, and in the old airing cupboard showing cooler air from the loft being drawn down the partition wall void before emerging into the cupboard.

Figure 3-7 Indirect air leakage via boxed in pipework in the bathroom (top) and the airing cupboard wall (bottom)

Figure 3-8 shows the boxed-in vertical steel-frame I-beam pillar in Bedroom 2, where air exchange with the loft-space appears to be relatively unrestricted. Viewed internally, under dwelling depressurisation, cooler air can be seen being forcibly drawn down from the loft space into this void. Viewed externally under natural conditions in Figure 3-9, warmer air can be seen escaping into the loft, which shows as a warmer vertical strip on the first floor wall, illustrating a thermal bypass from the home to the loft space.

Figure 3-8 Boxed-in pillar in Bedroom 2 viewed from inside under depressurisation as cold air is drawn down into the habitable space from the loft space

Figure 3-9 Boxed-in pillar in Bedroom 2 viewed from outside under natural conditions showing warm air from the habitable space travelling through the wall cavity to the loft space

3.1.1 Impact of retrofits on airtightness

As discussed, the retrofit marginally reduced the ground floor air leakage, but most of the existing infiltration pathways existed post-retrofit and were not related to the ground floor. Therefore, as shown in Figure 3-10, only a small, 1.3 $m^3/(h \cdot m^2)$ @ 50Pa or 9 %, reduction in whole house air permeability was achieved. This difference is within the error of the test. The home had a part solid ground floor, and the suspended timber floor represented only 12 % of the building envelope, while the entire ground floor comprised 22 %. This means that savings from this approach may be greater in homes with fully suspended timber ground floors.

Although this is only a single case study, this result suggests that ground floor retrofits of this type may not always result in a significant improvement in the airtightness of non-traditional homes, particularly where there are multiple air leakage pathways unconnected to the ground floor and the dwelling is leaky to start with. Interestingly, the air leakage for the home given by RdSAP was similar to that measured in the base case (within the test error). However, and more importantly, the RdSAP model assumed that the ground floor retrofit would have reduced the air leakage by more than measured.

In neither the RdSAP model nor the measured results did the home achieve a level of airtightness in line with the expectations for modern homes. This is unsurprising given the initial air leakage rate of the dwelling and the limited retrofit work undertaken.

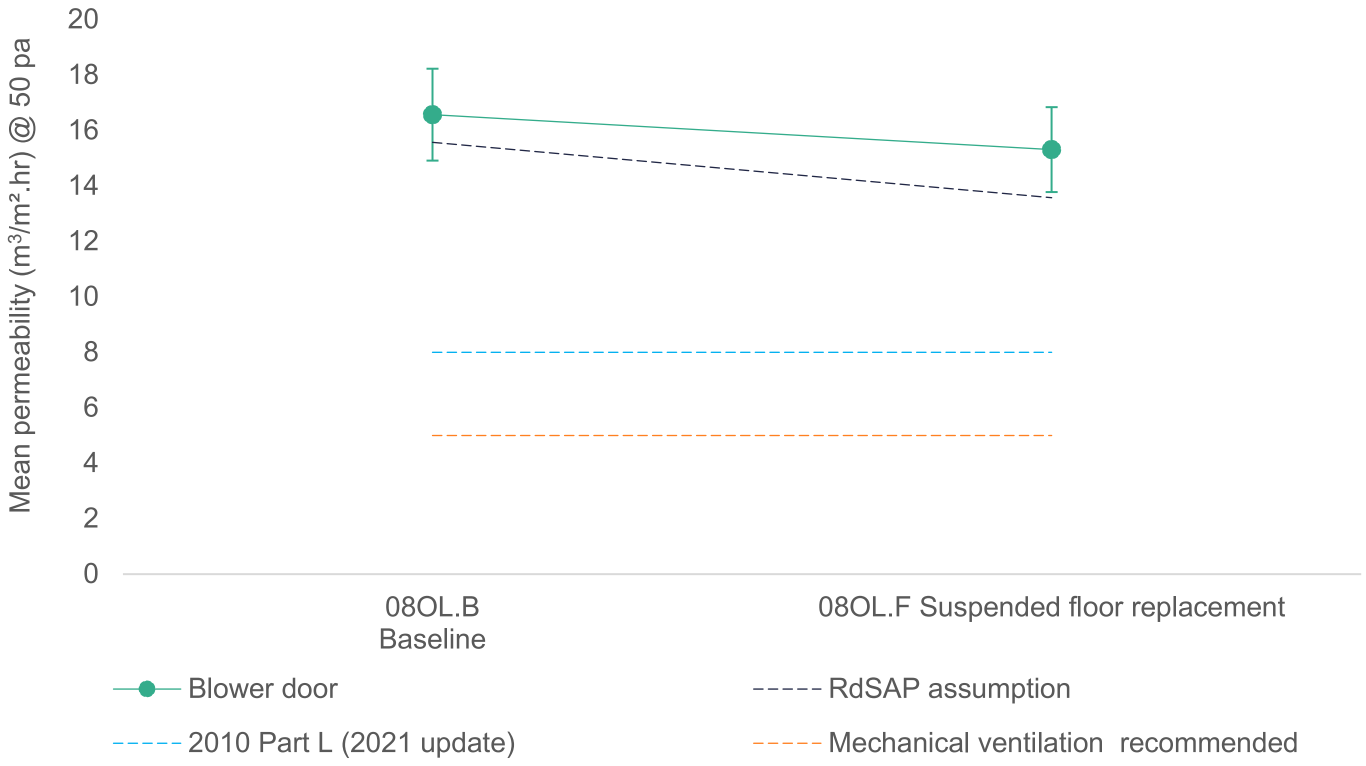

Figure 3-10 Airtightness pre and post-retrofit

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

As discussed, two additional methods were used to derive the air leakage in the dwelling, which were carried out at each retrofit stage. These were low pressure Pulse tests and CO_2 tracer gas decay measurements.

Low pressure Pulse tests

Pulse tests were undertaken both before and after the ground floor retrofit. On both occasions, the displayed test results came with a “warning”, in this instance that the achieved pressure range was too low. The reason for this is not known, though it may be because the home had too much air leakage for the Pulse test in the configuration used to measure. The post-retrofit test was conducted in unsuitable gusty wind conditions, with wind speeds switching between <0.5 and >4.0 ms^{-1}, which may have been outside the boundaries of reliable testing conditions for the Pulse unit.

Counterintuitively, the test results revealed a slight decrease in airtightness from 5.0 to 5.9 $m^3/(h \cdot m^2)$ @ 4Pa for air permeability and 5.4 to 6.3 h^{-1} @ 4Pa for air change rate, pre- and post-retrofit, respectively, the opposite of what was observed with the blower door test and the qualitative observations made using thermography. If the suggested conversion contained in CIBSE TM23 (2022) is used to convert the results @ 4Pa to results @ 50Pa, they would equate to results well in excess of 20 $m^3/(h \cdot m^2)$ @ 50Pa. This is substantially greater than the results measured with the blower door. However, as previously mentioned, there were issues with both tests affecting the reliability of the results.

CO_2 tracer gas decay

Although no timed CO_2 releases were carried out, analysis of the CO_2 decay was possible following periods where the research team had been working in the house and elevated the internal CO_2 concentration enough for the decay back to background levels to be considered. The estimates of ventilation rate obtained through the CO_2 decay showed an increase in airtightness following the floor retrofit. This is in line with the blower door test results.

Analysis of the CO_2 decay indicated a ventilation rate of 0.94 h^{-1} on the ground floor (living room) and 1.03 h^{-1} on the first floor (front bedroom) prior to the floor retrofit. This reduced ventilation rates to between 0.43 and 0.61 h^{-1} on the ground floor and 0.48 h^{-1} on the first floor, following the ground floor retrofit. This is a slightly greater improvement in airtightness than the blower door test results indicated.

3.1.3 Inter-dwelling air leakage.

Co-pressurisation of 08OL with the adjoining property was conducted at the end of the test period, where both houses were held at the same elevated pressure (relative to outside), thus removing drivers for air movement across the party wall. Under pressurisation only, co-pressurisation caused the air permeability of the test house to drop from 15.7 to 13.5 $m^3/(h \cdot m^2)$ @ 50Pa, equating to a 14 % decrease. For other properties tested for this project which had solid party walls, inter-dwelling air leakage was considered to be direct air movement between dwellings, whereas for this test house the presence of a cavity in the party wall complicated the issue.

The party wall cavity itself appeared to continue above the loft insulation level to the ridge, providing a buffer zone for inter-dwelling air exchange and the potential for mixing with external air in the cavity. This was confirmed by thermal images captured in the loft (Figure 3-11). These images indicate a party wall bypass heat loss mechanism in operation in addition to inter-dwelling air exchange, with air in the party wall cavity gaining heat from below the loft insulation and rising up through the cavity. On the leeward side of the loft (to the right of the chimney stack), a warmer area can be seen extending up through the loft space to the ridge.

Figure 3-11 The cavity party wall in the loft, showing a potential cavity party wall bypass heat loss mechanism in effect

Airtightness improvement summary

Thermography indicated that air leakage through the ground floor was reduced following the suspended ground floor replacement, though whole house air leakage remained relatively high, falling slightly from 16.6 to 15.3 $m^3/(h \cdot m^2)$ @ 50Pa, a 9 % reduction, within the blower door test error. Thus, while the new ground floor retrofit itself was airtight, the lack of a continuous primary air barrier within the dwelling, along with numerous penetrations and interconnected cavities in the home, undermined the improvement made by the retrofit, resulting in the air leakage in the home remaining substantial.

As with other DEEP case study homes, inter-dwelling air exchange was observed under induced co-pressurised conditions. The inter-dwelling air leakage was measured to be equivalent to 14 % of the measured whole house air permeability pre-retrofit, i.e., a greater amount than the ground floor infiltration avoided by the retrofit. Additionally, a thermal bypass was observed in the cavity party wall.

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 for EPCs for existing homes.
2. **Calculated U-values:** Used when 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 when 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.

All three methods were used for comparison, and this section reports on the differences between them. The report considers the implications of the method selected on the accuracy of energy and heat loss predictions, the potential contribution of fabric elements to the overall HTC, and the predicted benefit achieved by the retrofits. A summary of the pre- and post-retrofit floor in-situ U-values is presented in Figure 3-12.

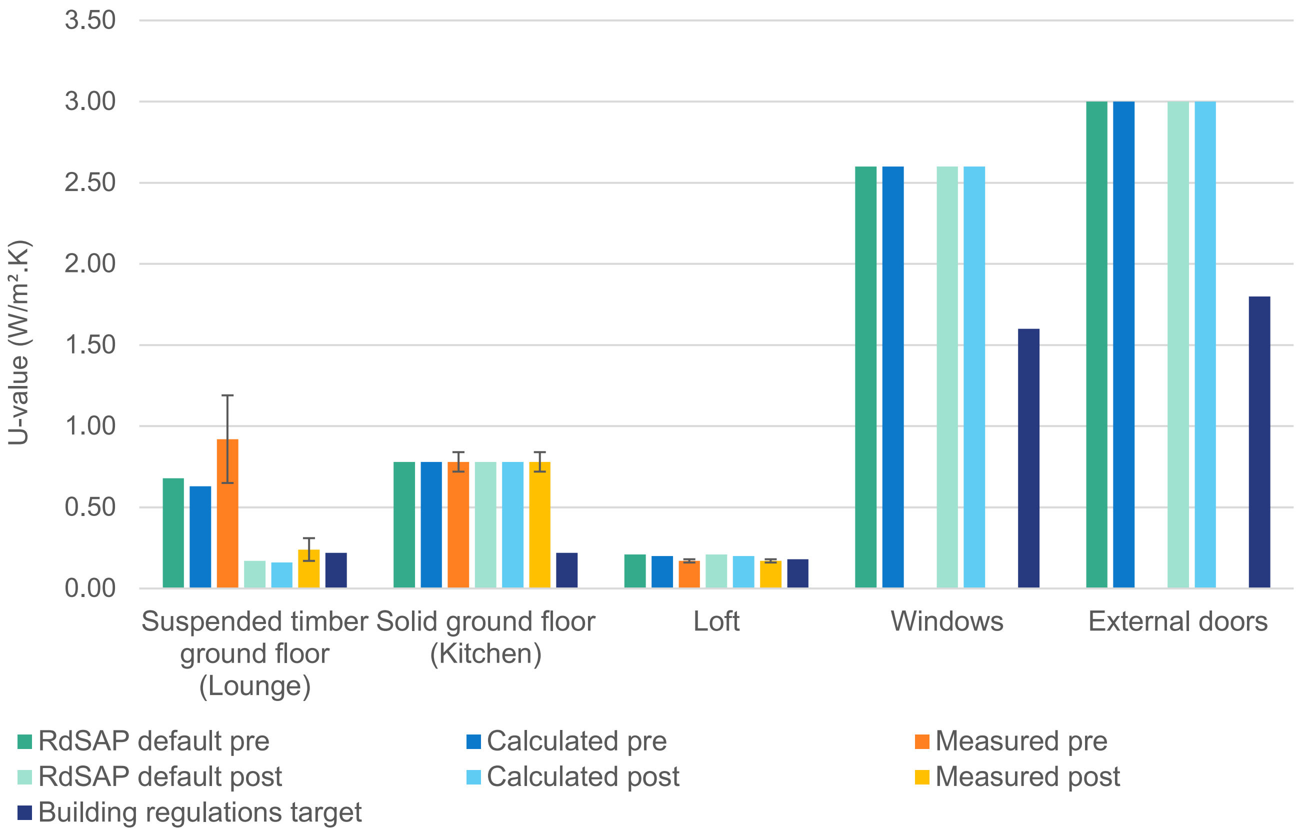

Figure 3-12 Pre- and post-retrofit fabric U-values (excluding walls) (W/(m²·K))

The uncertainty in the pre-retrofit ground floor U-value was substantial, likely due to the floor being suspended with a well-ventilated cavity beneath. Thus, changes in wind would cause variation in the measured U-values. Nonetheless, the measured reduction in the ground floor U-value achieved by installing pre-insulated composite panels (shown in Figure 3-13) was significant (75 ± 28) %. As illustrated in Figure 3-14, the new ground floor had much improved thermal performance.

Figure 3-13 Existing suspended timber ground floor (top left), removal of existing floor (top right), installation of new insulated ring beam support (middle left), new insulated floor panels (middle right), installation of floor panels and sealed edges (bottom left), final chip board finish (bottom right)

Figure 3-14 Temporary removal of the sub-floor void access hatch in the post-retrofit living room floor, illustrating the thermal gradient through the replacement flooring

No other fabric elements were improved, and their measured U-values can be seen in Figure 3-15. The U-values for the glazing and doors could not be measured, since frame heat losses cannot be captured via heat flux density measurements alone.

Of note is the difference in the external wall U-value measurements for the ground and first floors where, at first observation, the first floor external wall appeared to have a similar thermal performance to an insulated cavity wall. This is in stark contrast to the construction method used for this external wall. As previously described, Dennis-Wild steel-framed homes have different ground and first floor external wall constructions, though both should have similar heat losses. Further exploration of the air leakage pathways in the home points to warm air entering the external wall cavities on the ground floor and rising up to warm the first floor external walls. This may be why the first floor external wall appears to have a much lower measured U-value, i.e., the heat flux density measurements showed lower heat flow across the first floor external wall because air in the cavity was warmer. It is, therefore, likely that the external wall U-values on the ground floor are more representative of the external wall U-value for this house.

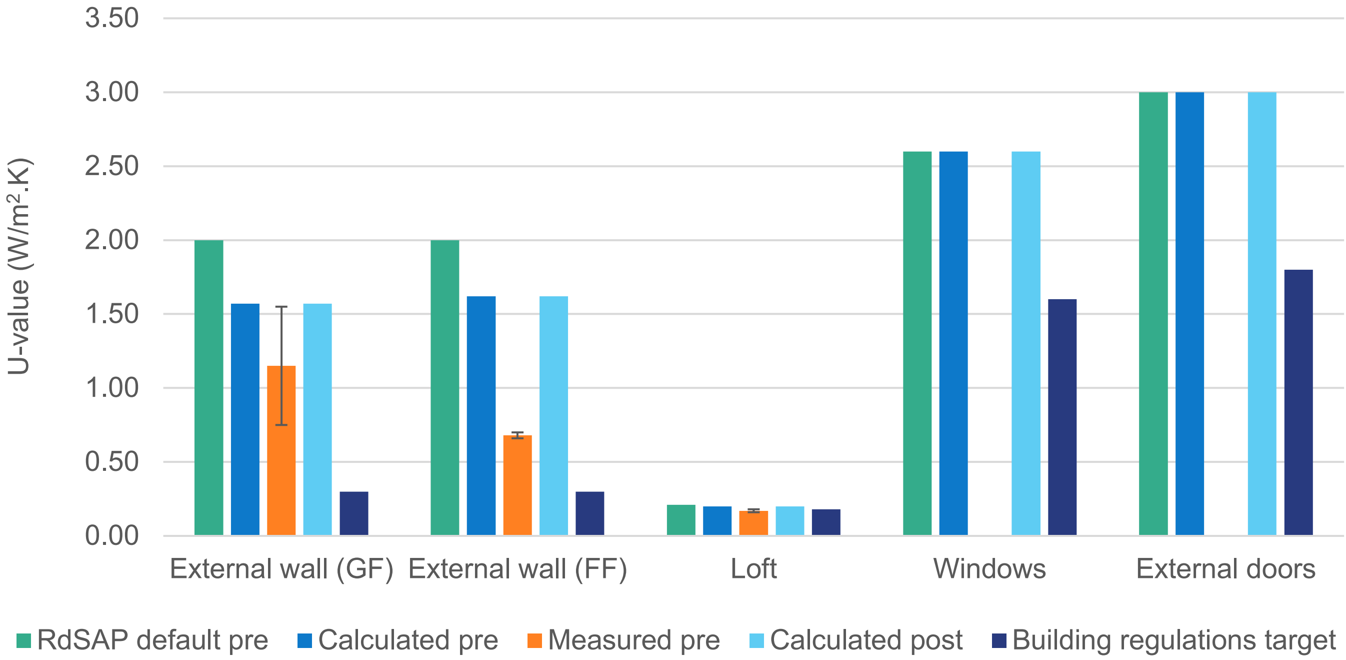

Figure 3-15 Pre- and post-retrofit fabric U-values (external walls) (W/(m^2·K))

A summary of the house in-situ U-values is given in Table 3-1, including the percentage improvements in in-situ U-values achieved for the ground floor.

Table 3-1 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
Suspended ground floor	0.68	0.63	0.92 ± 0.27	0.17 (75%)	0.16 (75%)	0.24 ± 0.07 (74 ± 28) %
Solid ground floor	0.78	0.78	0.78 ± 0.06	-	-	-
External wall (GF)	2.00	1.57	1.15 ± 0.4	-	-	-
External wall (FF)	2.00	1.62	0.68 ± 0.02	-	-	-
Loft	0.21	0.20	0.17 ± 0.01	-	-	-
Windows[7]	2.60	2.60	-	-	-	-
External doors[8]	3.00	3.00	-	-	-	-

Table 3-2 identifies how the measured ground floor U-values pre- and post-retrofit, compare to the predicted U-value used in RdSAP, as well as the U-values calculated using the BRE calculator. As shown, there is no significant prediction or performance gap, however this is because the measurement error is relatively large.

It is worth noting that although the final in-situ U-value achieved was higher than that which was predicted by RdSAP and the BRE calculator, the uninsulated ground floor U-value was also much higher, thus the net improvement in U-value was similar.

Table 3-2 Summary of measured in-situ U-value reductions and gaps in performance (numbers in red show a significant gap)

Element	RdSAP default predicted reduction	Calculated predicted reduction	Measured reduction	RdSAP defaults prediction gap	"As-built" performance gap
Suspended ground floor retrofit	0.51	0.47	0.68 ± 0.28	-0.17 ± 0.28	-0.21 ± 0.28

[7] No HFP recordings were obtained for windows.
[8] No HFP recordings were obtained for doors.

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

Table 3-3 shows the impact the measured improvement in U-values had on the plane element fabric heat loss, i.e., considering the U-values and relative size of the heat loss area of each element. As shown, the plane element fabric heat loss is overwhelmingly through the external walls.

The heat loss attributed to the ground floor was anticipated to significantly reduce by around 14 W/K so that the ground floor, which was predicted to be responsible for around 13 % of the home's overall plane element heat loss, was only predicted to represent around 4 % post-retrofit. However, there was a relatively large uncertainty associated with the external wall in-situ U-value measurements and, because the external walls were responsible for almost half of the plane element fabric heat loss in the home, on a whole house basis the reduction achieved by the ground floor retrofit was not significant, i.e., it was within the overall test error.

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

Element	Pre-retrofit (W / K)	Proportion of heat loss	Post-retrofit (W / K)	Proportion of heat loss
Roof	6	4%	6	5%
Suspended ground floor	19 ± 6	(13 ± 4) %	5 ± 1	(4 ± 1) %
Solid floor	10 ± 1	7%	10 ± 1	8%
External doors and windows	41	29%	41	32%
External walls	66 ± 14	(46 ± 10) %	66 ± 14	(51 ± 11) %
Total	**142 ± 21**	**-**	**128 ± 16**	**-**

The measured in-situ U-values for the external walls and loft were significantly lower than the RdSAP defaults and those predicted by the BRE calculator. Thus, as shown in Figure 3-16, the measured total fabric heat loss was considerably lower. As discussed, however, this may be due to the air movement within the cavity walls driving the perceived lower U-value, and thus this may be an underestimate.

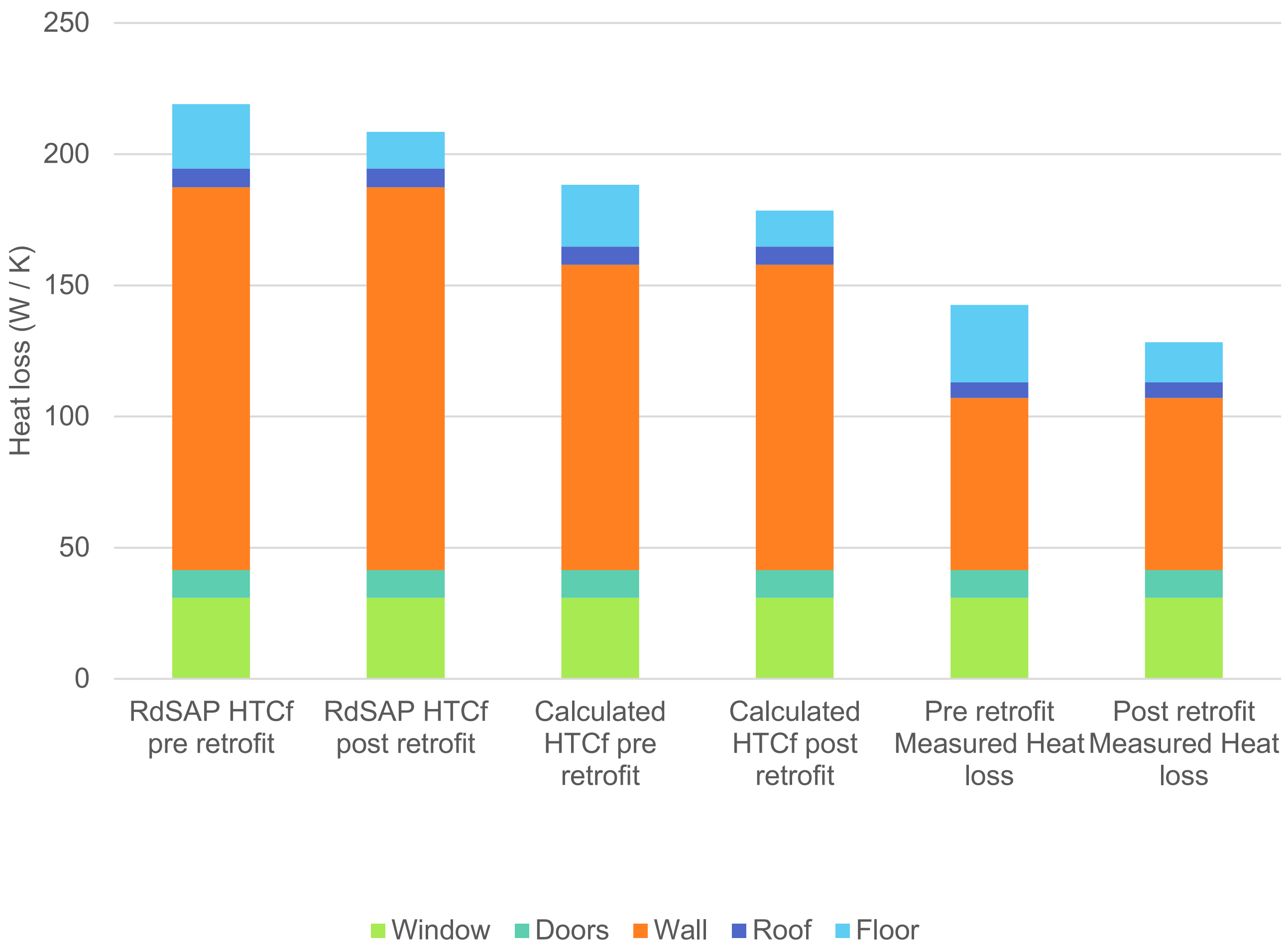

Figure 3-16 Fabric heat loss pre- and post-retrofit

U-value improvement summary

The suspended ground floor U-values were reduced from (0.92 ± 0.27) to (0.24 ± 0.07) W/(m^2·K), which represents a (74 ± 28) % improvement. This is equivalent to a (14 ± 6) W/K reduction (10 %) in the plane element fabric HTC. There was substantial uncertainty associated with the suspended ground floor measurements and the values measured were higher than predicted, both pre- and post-retrofit.

The in-situ U-value measurements of the first floor walls were significantly lower than they were expected to be, since it is thought that warm air was entering the cavity, so the HFPs on the first floor wall were measuring lower rates of heat flow because the cavity air was being warmed.

Since U-value calculations assume that heat is lost directly to the outside, i.e., the first floor heat flux density measurements were affected by a bypass, the total fabric heat loss may have been higher than the heat flux density measurements suggest.

3.3 Whole house heat loss (HTC) improvement

The total measured heat loss for the dwelling at each stage is shown in Table 3-4. As shown, the retrofit appears to have made a statistically significant reduction in HTC (61 ± 26 W/K) despite relatively high levels of uncertainty. This is orders of magnitude higher than was anticipated by an aggregate measurement approach considering the U-value improvements alone, of only a (14 ± 6) W/K reduction in the plane element fabric heat loss.

The test house, as mentioned, had high levels of air leakage. To further investigate this discrepancy, an additional analysis was performed to correct the HTC for the impact of wind. As shown, when wind is considered, HTC is estimated to reduce from (167 ± 9) W/K to (148 ± 10) W/K, i.e., savings are more modest, around (19 ± 13) W/K, in line with the expected reduction.

Table 3-4 Test house HTC after each retrofit stage

Retrofit stage	HTC (W/K)	HTC uncertainty	HTC reduction (W/K)	Percentage reduction
08OL.B Baseline	208 ± 19	9%	n/a	n/a
08OL.F Suspended floor replacement	147 ± 18	12%	61 ± 26	(29 ± 13) %
08OL.B (wind corrected) Baseline	167 ± 9	5%	n/a	n/a
08OL.F (wind corrected) Suspended floor replacement	148 ± 10	7%	19 ± 13	(11 ± 8) %

Figure 3-17 illustrates the impact of the retrofit on HTC with and without wind correction applied.

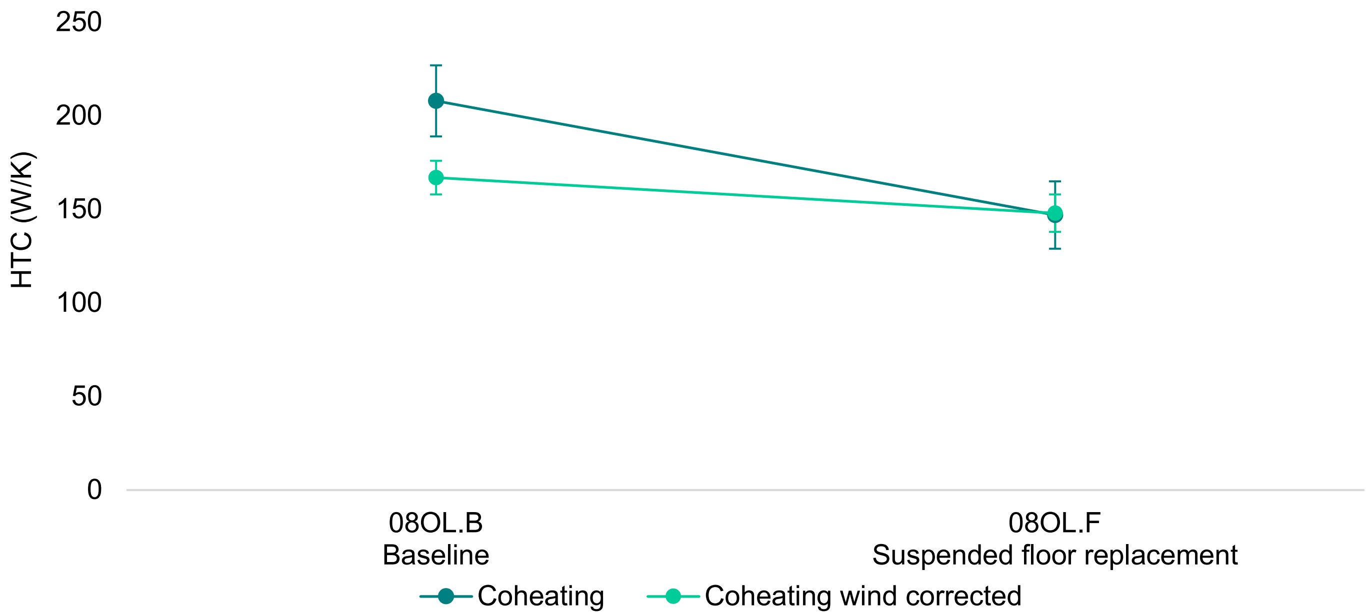

Figure 3-17 Coheating HTC at each retrofit stage

3.3.1 Accounting for the effect of wind on measured HTC

Further investigation suggested that, owing to the home's non-traditional form of construction and the previously identified susceptibility to thermal bypassing, its heat loss was particularly influenced by wind washing, i.e., wind passing through the building structure.

Assessment of wind data from a weather station located 10.2 miles away suggests that the wind conditions varied substantially between the baseline test and the post-retrofit test, both in terms of speed and direction (Figure 3-18). Thus, it is possible that the wind conditions experienced during the baseline coheating test had a greater impact on heat loss than during the post-retrofit test. An attempt was made to quantify the effect of wind on the measured HTC by including wind speed in the coheating analysis. To do this, the daily average wind speed was included as a regression term, alongside solar and ΔT. The coefficients obtained for solar and wind in this regression were subtracted from the input before the final coheating regression, as is standard in a coheating regression analysis.

The above process resulted in a baseline HTC of (169 ± 9) W/K and a post-retrofit value of (148 ± 10) W/K. While these values are both plausible and may better reflect the expected reduction in HTC, the method employed to calculate these values needs wider testing. Indeed, little is understood about the impact of wind on building performance evaluation in general. This is largely because heat loss due to wind is a highly complex phenomena, depending on wind speed, direction, airtightness and exposure. However, given the impact that wind washing can have on properties, particularly in exposed areas of the country, more research into wind effects could be a valuable asset for future retrofit strategies.

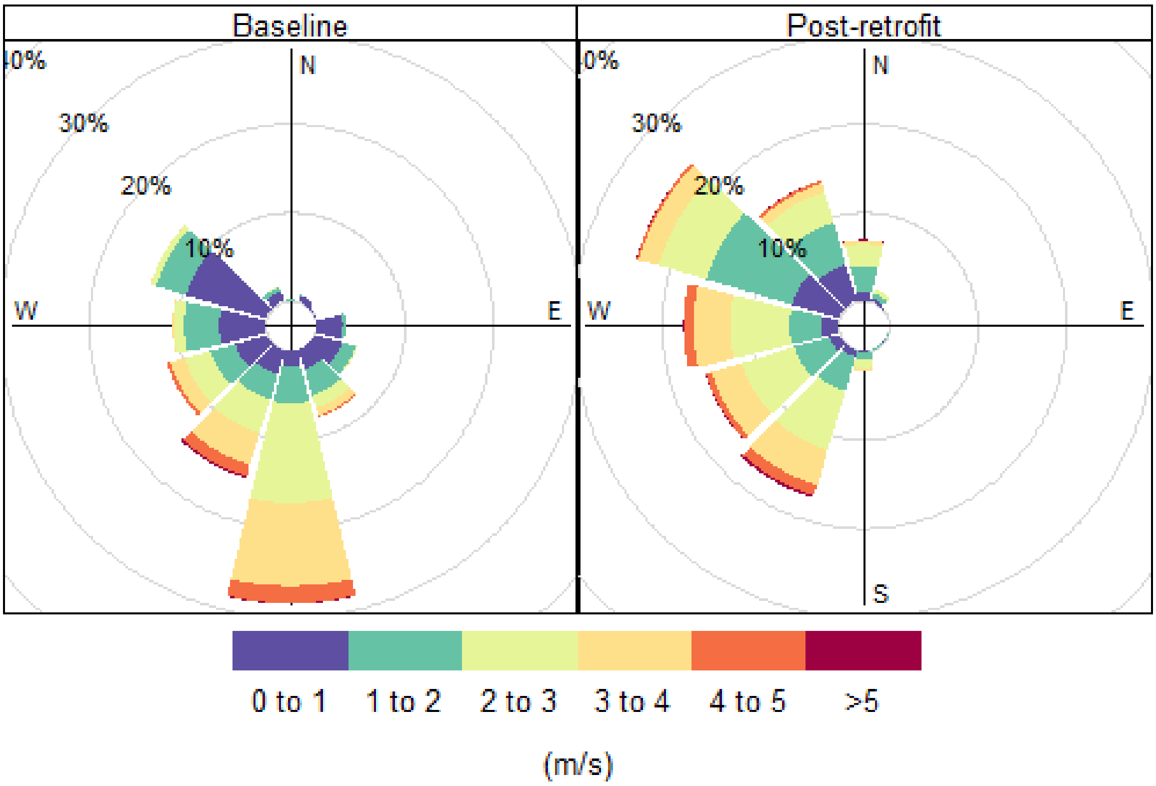

Figure 3-18 Wind roses for the coheating test phases

3.3.2 QUB and the coheating test HTC results

An alternative method of measuring the HTC, QUB, as described in the DEEP Methods 2.0 Report, was undertaken in the home at both retrofit stages to compare against the coheating test. In total, 17 QUB tests were performed on 08OL. This was done to investigate the reliability and accuracy of the QUB test.

Four tests were completed during the baseline stage, and 13 following the ground floor retrofit. The completed tests had a duration of 8 hours for the baseline stage and 10 hours following the ground floor retrofit. The tests were completed in February 2021 (baseline) and April 2021 (ground floor retrofit). When completing QUB tests, the α value (heat loss / heat gain ratio) as described in the DEEP Methods 2.0 Report, is a factor impacting the accuracy of the test. For the baseline stage, all four tests had an α value in the recommended range of 0.4 to 0.7. However, for the ground floor retrofit, only one of the 13 tests had an α value in this range.

Despite this, the other tests are included, as they were only fractionally above the recommended limits, i.e., no higher than 0.78. The use of the results with the higher α values does not appear to have had a significant impact on the overall accuracy of the measurements. The reference HTC used to determine the α value was the result of the coheating test without party wall correction (no party wall heat flux measurements were taken during the QUB tests). The individual QUB HTC measurements are shown against the upper and lower uncertainty boundaries of the corresponding coheating measurements in Figure 3-19. The wind conditions during the QUB tests were less extreme than during the coheating test, with an average wind speed of 1.2 m/s across all tests. As such, the wind corrected coheating measurements, without party wall corrections were used for these comparisons with the QUB tests.

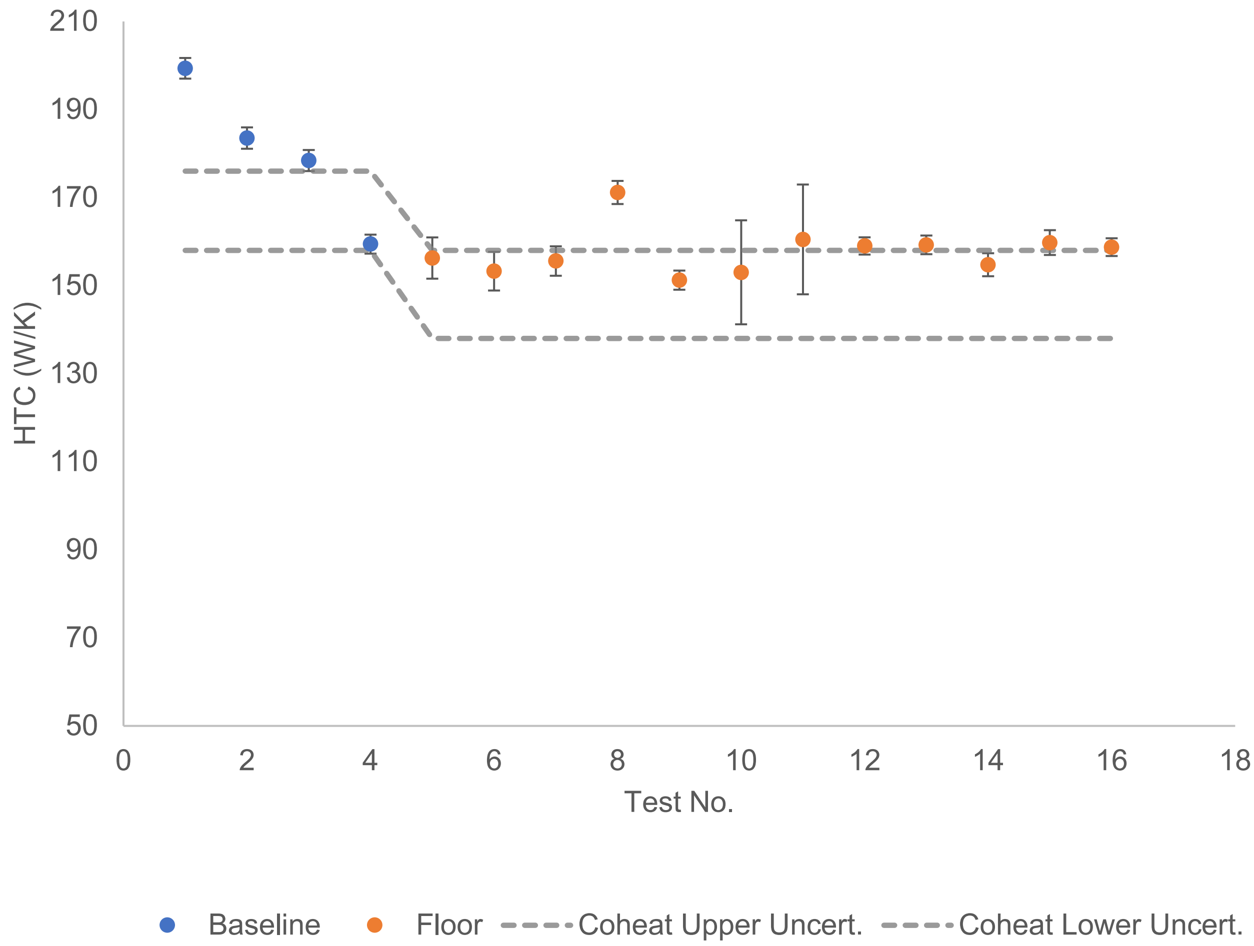

Figure 3-19 Comparing individual QUB HTC and coheating measurements

The measurements undertaken during the ground floor retrofit stage are much more in agreement with the coheating test result than the baseline stage. For the ground floor retrofit stage, all but one of the measurements are within the uncertainty boundaries of the coheating test, whereas only one overlaps in the baseline stage. The dispersion of results during the ground floor retrofit stage is also improved, with a range relative to the mean of 13 %, compared to 22 % for the baseline stage.

The overall uncertainty weighted averages for the QUB measurements compared against the corresponding coheating test results are presented in Figure 3-20. When evaluating these averages, the impact of the retrofit on the test accuracy is less apparent, with a relative difference from the coheating tests of +7 % for both the baseline and ground floor insulation stage.

The difference in HTC between the two retrofit stages indicated by the average QUB tests is -13 %. Despite the QUB measurements indicating a performance improvement on average, several of the measurements in the retrofit stage overlap with measurements in the baseline stage. This indicates that the individual QUB tests do not detect a significant improvement in performance.

The observed accuracy of the QUB measurements in comparison to the coheating test is comparable to published works that identify a difference of between 1 % and 15 %. Generally, the QUB results have better agreement with the HTC after correcting for potential wind washing. Therefore, it could be that the QUB tests were less effected by wind washing either due to the different test protocols, or different wind conditions between the QUB and coheating tests. More data is needed to determine the impact of wind on QUB tests.

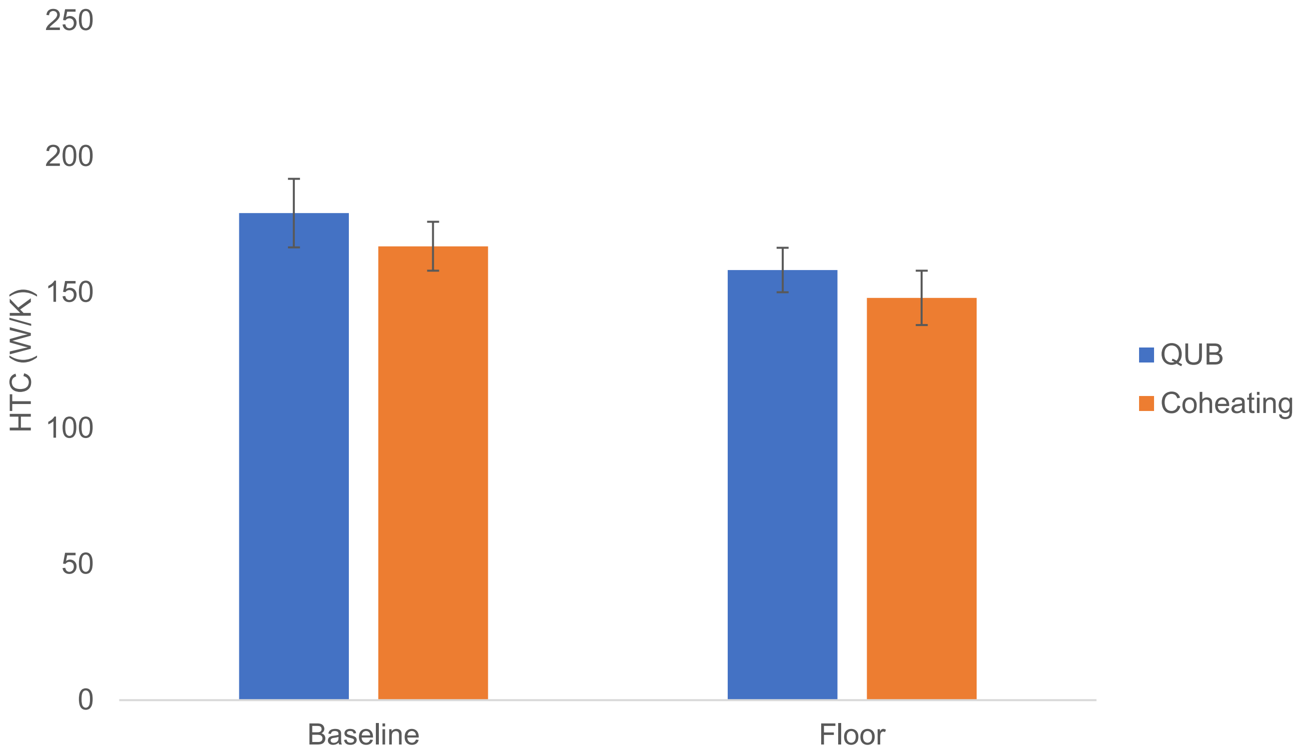

Figure 3-20 Average QUB HTC measurement vs. coheating measurement

3.3.3 Aggregated vs. disaggregated approaches

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.

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 HTC_v and HTC_f are subtracted from the whole house measured HTC.

The infiltration heat losses were affected by the ground floor retrofit. However, as discussed, the improvement in airtightness post-retrofit in 08OL was relatively slight, i.e., within the error associated with the test method. It is still possible to estimate what contribution this small reduction might have had on the whole house heat loss using Equation 1.

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

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

According to this method, the HTC saving achieved from airtightness improvements would be just 3 W/K.

Notwithstanding the result above, more research is needed to investigate the n/20 rule of thumb, and any attempt to disaggregate the whole house HTC into plane element fabric and background ventilation heat loss using the n/20 rule of thumb should be treated with considerable caution. This is demonstrated by a recent publication, in which this rule of thumb is shown to be inappropriate for a sample set of 21 buildings [6]. Investigation using a larger sample set would be required to identify an alternative rule of thumb for a range of UK archetypes.

The ground floor replacement was anticipated to have reduced thermal bridging, since the suspended ground floor was mounted using an insulated fixing, as shown in Figure 3-21. While no calculations were conducted for 08OL, the thermal bridging heat loss attributable to the non-repeating external wall and ground floor junctions can be estimated using SAP 2012 Appendix K default Ψ-values, though these are generally used for new build homes (no defaults for dwellings of this age exist). These defaults are considered to be conservative (i.e., overestimated), and were calculated for the pre-retrofit home to be under 6 W/K. Thus, even if the new floor removed all thermal bridges from the ground floor to wall junction, the maximum reduction to thermal bridging heat loss that could be achieved is likely to be 6 W/K.

Figure 3-21 Insulated floor supports to reduce thermal bridging at the ground floor to wall junction

This means that the reductions from the in-situ measured U-values (14 ± 6) W/K, estimated infiltration (3 W/K), and thermal bridging (6 W/K) heat loss savings, would result in a total saving of around 23 W/K, which is more in line with that measured by the wind corrected coheating test.

Comparing these two approaches to deriving the whole house HTC, is called closing-the-loop analysis. It is useful both for exploring where heat losses occur and as a reference point for the whole house HTC measured by the coheating test. The measured aggregate HTC from the coheating test and the disaggregated HTC calculated by summing HTC_v, HTC_f and HTC_b are presented in Figure 3-22. In theory, the sum of these three heat losses should equate to the HTC measured by the coheating test.

However, as in this case, these often do not align perfectly, and differences may occur for several reasons:

- The n/20 rule (Equation 1) is an approximation and different building types may not follow the rule, hence HTC_v can only be an approximation.
- HFP placements may not be representative or comprehensive of the whole element heat loss, so HTC_f is likely to be imperfectly estimated. In addition, the results obtained from HFPs are based on a series of measurements undertaken under a particular set of weather conditions, which themselves may not be representative of average annual conditions.
- The thermal bridging values used here are estimates from RdSAP which contain simplifications in geometry and assumed construction details, so may not be representative of actual HTC_b and do not take into consideration point thermal bridges.
- 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.

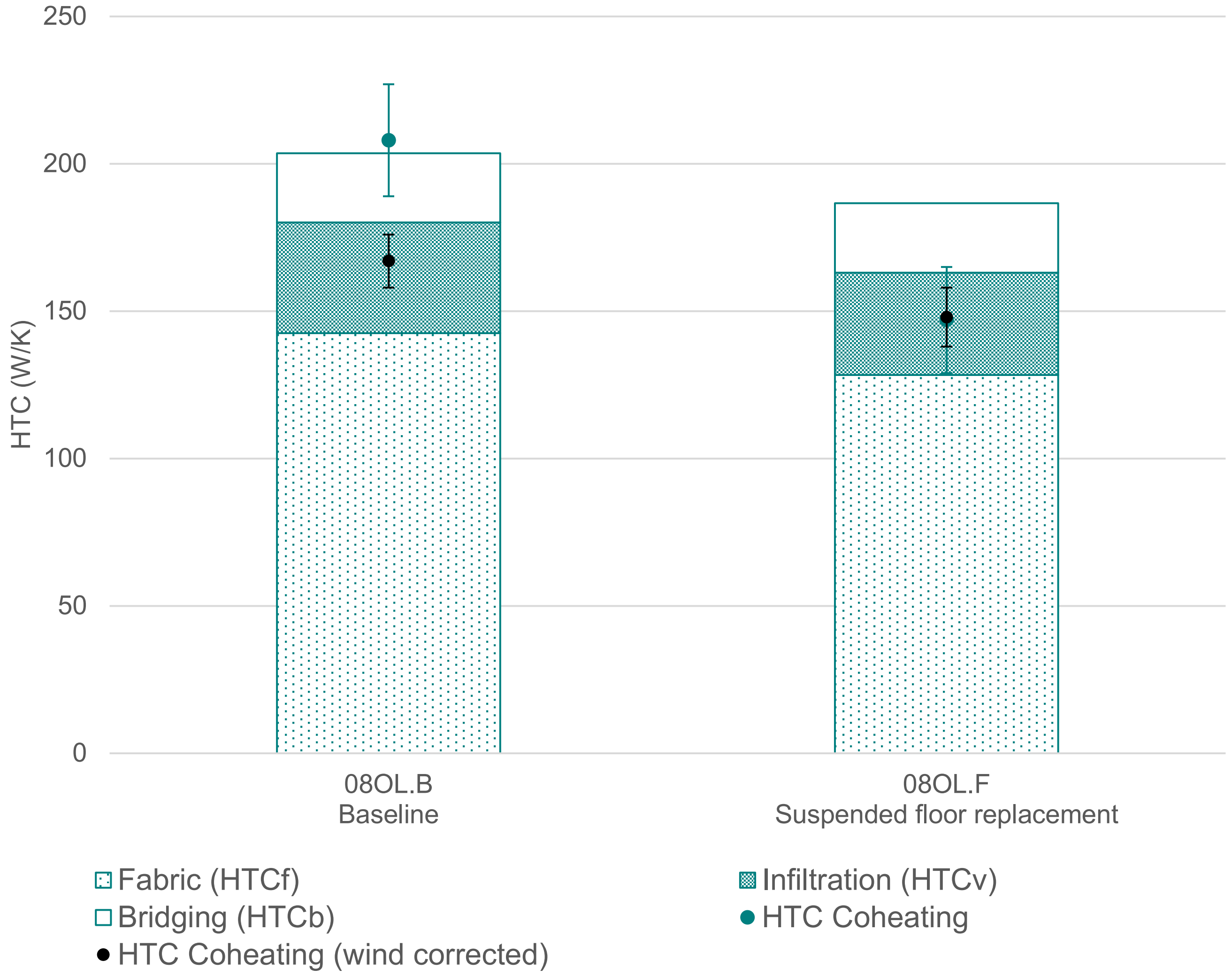

Figure 3-22 Aggregated vs. disaggregated measured HTC

3.3.4 Broader benefits of suspended timber ground floor replacements

In addition to the reduction in heat loss, replacing the suspended timber ground floor with insulated composite panels may also achieve additional benefits. The risk of rot to ground floor timbers is removed, the ground floor may have a longer life expectancy and it is an opportunity to ensure there are no underlying problems that may cause issues in the future.

For example, in 08OL it was observed that the sub-floor void vents were partially blocked by debris and dirt, and hot water pipes located in the sub-floor void were not fully insulated (Figure 3-23). These issues were later rectified.

Figure 3-23 Floor void vents blocked and water pipes not effectively insulated pre-retrofit

Whole house heat loss improvement summary

The initial coheating test results appeared to suggest significant savings were achieved by the retrofit beyond what may have been anticipated. However, on closer inspection the test appeared to be heavily affected by wind washing, since the house archetype had very high levels of infiltration.

When wind washing was taken into account, the new suspended ground floor was anticipated to have reduced the home’s HTC from (167 ± 9) W/K to (148 ± 10) W/K, corresponding to a reduction of (11 ± 8) %. More research is needed to explore how wind can be accounted for in coheating tests and how wind washing affects heat loss in various house typologies.

The savings measured were in line with the predictions from measured U-values and air leakage reductions and those that may be expected from reductions in thermal bridging.

3.4 Measured vs. modelled retrofit performance

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

In this step, the default input values for airtightness and U-values are used. The measured HTC values for each retrofit stage are plotted against the HTC values predicted by the uncalibrated models using default RdSAP input data in Figure 3-24.

- HTC is substantially overestimated in steady-state models, in part because these do not account for as much solar gain received by the property, while DSM can capture this.
- The HTC predicted by the DSM model is substantially overestimated compared to the wind corrected figures, both pre- and post-retrofit.
- The proportion of savings predicted by the ground floor replacement are roughly the same for all models; 4% in DSM, 5% in RdSAP and 6% in BREDEM.
- The models predict a slightly smaller saving than the (11 ± 8) % measured by the coheating test when corrected for the influence of wind, perhaps as no improvement in thermal bridging is accounted for in the models.

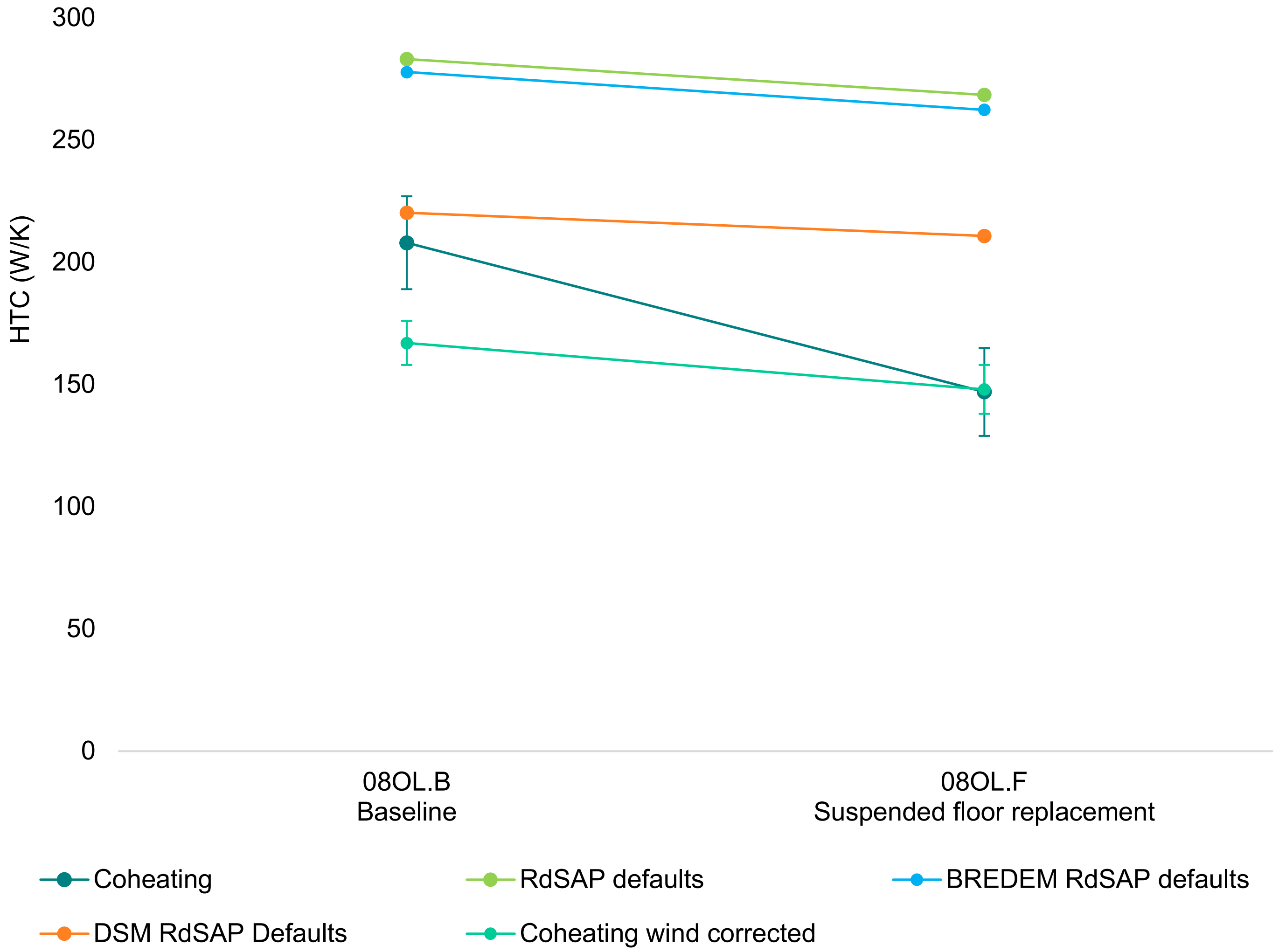

Figure 3-24 Measured vs. modelled HTC calibration step 1: Default data

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

In this calibration step, the models use 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 can be seen in Figure 3-25.

- RdSAP is not shown since it is not possible to change airtightness levels in the software.
- The airtightness level assumed in the models is almost identical to the HTC measured in the home using the blower door test. Therefore, there is virtually no change in the model predictions when the measured airtightness is included.
- The measured improvement in the airtightness achieved by the ground floor retrofit is marginal and so the scale of retrofit savings is also unchanged.
- Other DEEP case studies tend to have better airtightness levels than the models predict and so this calibration step often reduces the modelled HTC to be more in line with the measured HTC. It is not known if the airtightness of these non-traditional homes is generally lower than conventional brick and stone solid walled homes.
- If new default airtightness levels are created to represent building typology, as opposed to age-bands, it would be useful to explore whether these types of homes require their own airtightness default values.

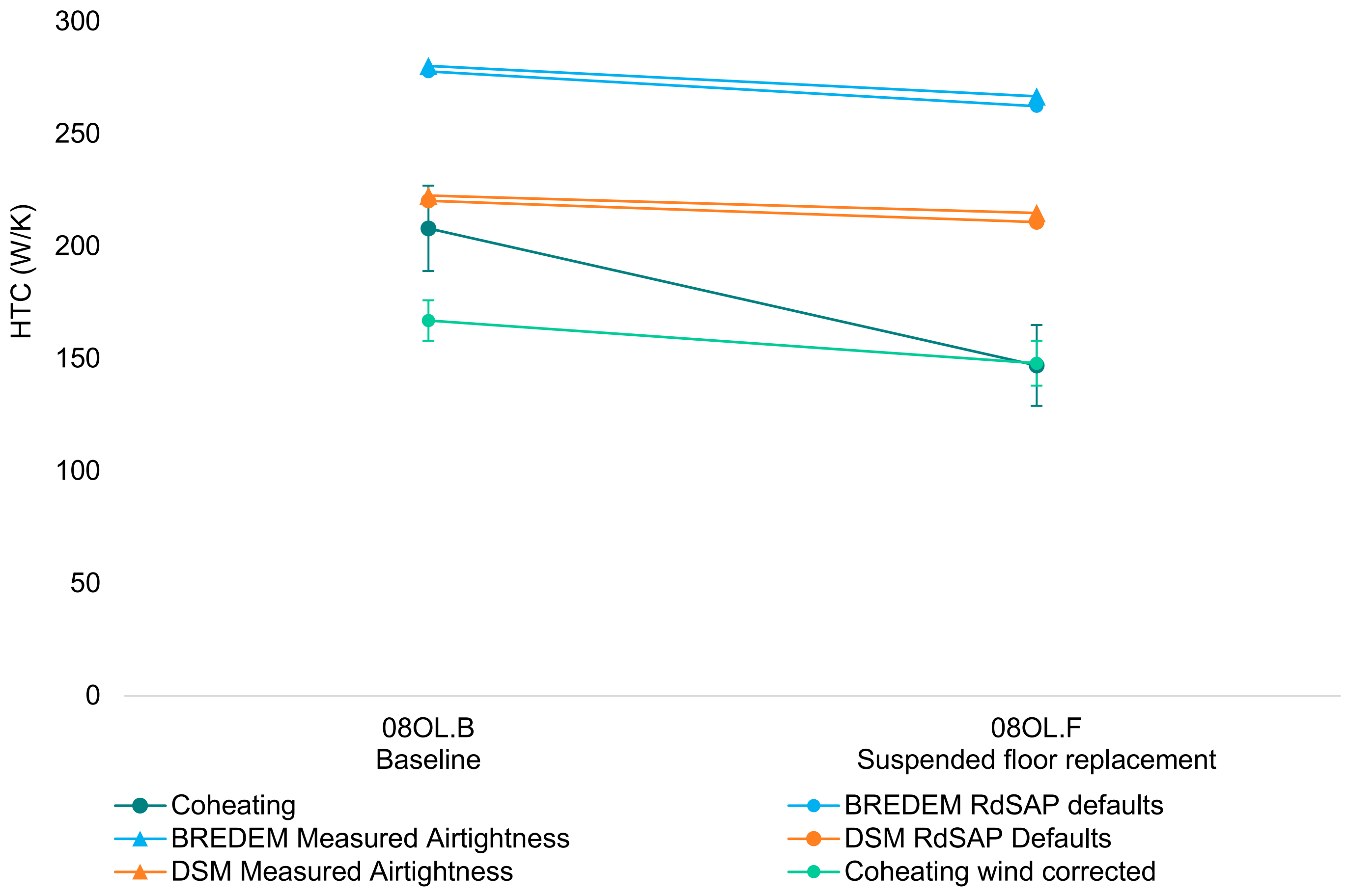

Figure 3-25 Measured vs. modelled HTC calibration step 2: Measured infiltration

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

In this step, the models include U-values defined using the BRE calculator, based on detailed surveys. The input data required for the BRE calculator 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 is shown in Figure 3-26.

- RdSAP is not shown, since it is not possible to include calculated U-values in the software. The BREDEM prediction is representative of the impact this has on steady-state models.
- The calculated U-values for the external walls are lower than the default values predicted, and this results in the modelled HTC falling more in line with the coheating tests when the calculated values are used.
- Since the calculated ground floor U-values pre- and post-retrofit are similar to the default values assumed in the models, the reduction in HTC achieved by the retrofit is similar to previous calibration stages.
- The construction of the non-traditional case study home was relatively complicated and so the calculated U-values may not fully account for the precise construction makeup of the case study home or how the elements interconnect. It is possible, therefore, that the calculated U-values are not necessarily fully representative of the heat loss taking place in the home.

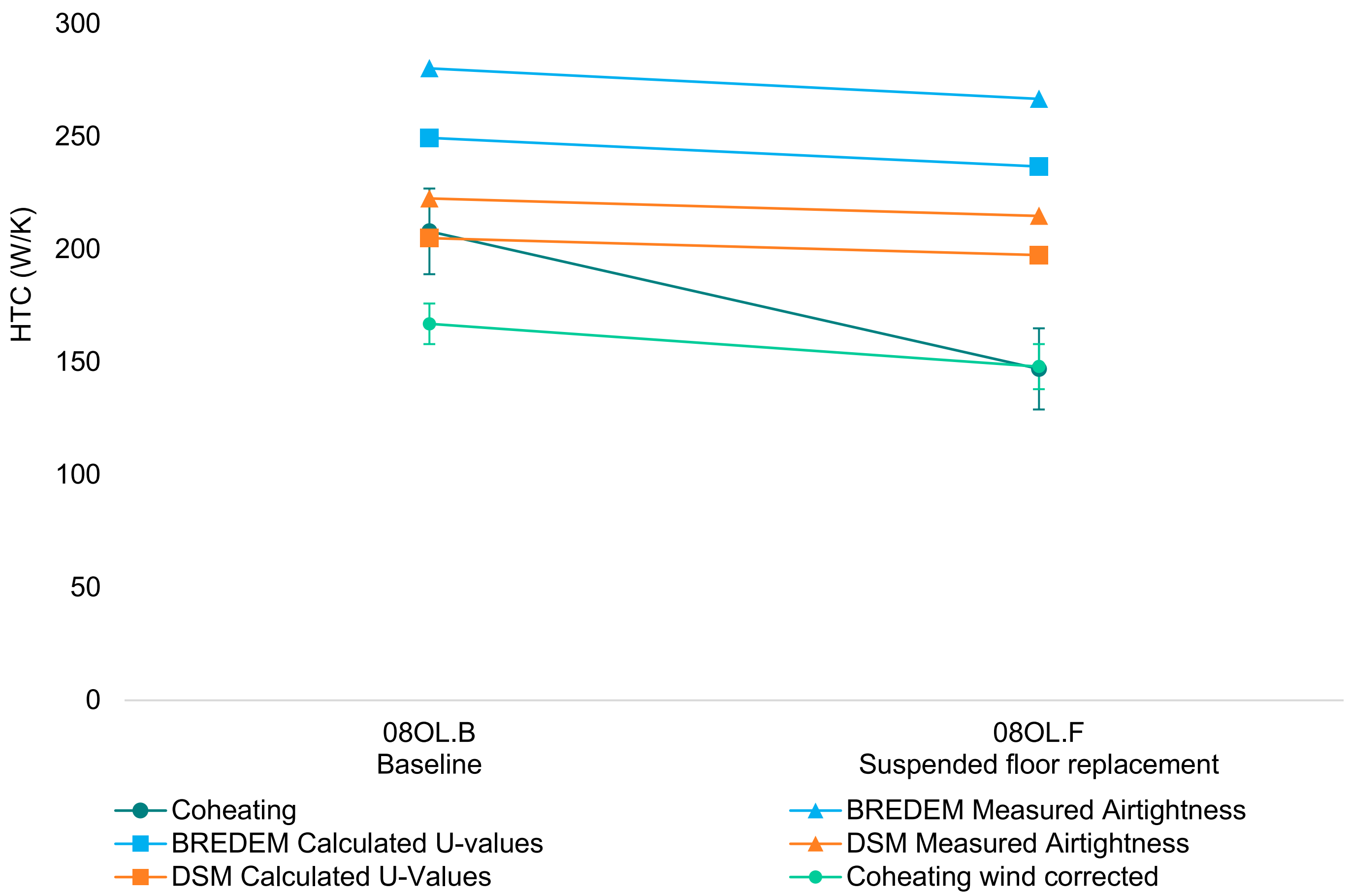

Figure 3-26 Measured vs. modelled HTC calibration step 3: Calculated U-values

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

In this step, the models use measured U-values, which requires resource intensive in-situ testing. The impact of this compared to the previous calibration stage is shown in Figure 3-27.

- The measured external wall U-values for the uninsulated home are lower than both the RdSAP and calculated U-values, and so when these values are included in the models, the HTC predictions drop to be more in line with the coheating test results. However, most of this drop can be attributed to the potentially flawed heat flux density measurements recorded in the first floor external wall (caused by suspected warm air entering the empty cavity) which have a high level of associated uncertainty.
- The measured U-value of the suspended timber ground floor was also slightly worse than calculated and so the improvement achieved by the retrofit is slightly greater than predicted for the previous modelled stages. The reduction in the modelled HTC was between 6 % and 9 %, which is more in line with the wind corrected measured savings.
- The spot heat flux measurements undertaken on the elements other than the ground floor (where a grid of HFPs were used) may not be able to provide a fully representative whole element U-value, since in this home there were many instances where internal air movement was observed within various fabric elements, as identified in Section 3.1. Consequently, there was heterogeneity with respect to the heat losses in the external walls, as well as bypass mechanisms into the party wall, loft space and, pre-retrofit, the sub-floor void. It is therefore probable that the in-situ U-value measurements are not fully representative of the complex elemental heat losses taking place.

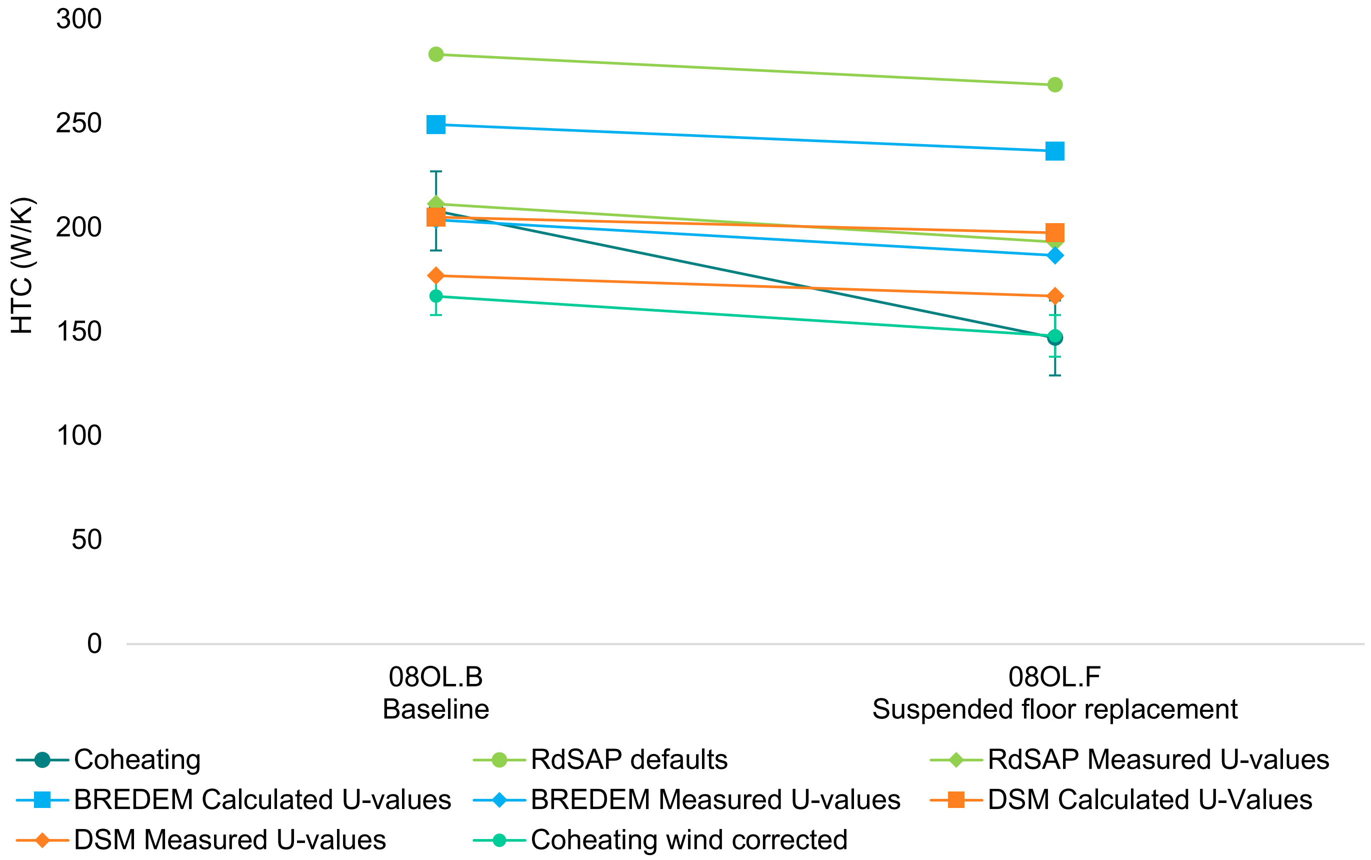

Figure 3-27 Measured vs. modelled HTC calibration step 4: Measured U-values

Measured vs. modelled HTC summary

When using the default inputs in EPCs, the HTC predictions from the steady-state models were much higher than the DSM values, which were in turn higher than the coheating test results. Inputting the calculated and measured U-values substantially reduced the HTC values for the house, since the thermal performance of the external wall was anticipated to be better than the defaults predicted.

The retrofit savings were similar regardless of which model was used, being between 4 % and 6 %. These savings increased when the measured U-values were used as inputs to the models, to between 6 % and 9 %, since the pre-retrofit suspended timber ground floor U-value was measured to be higher than the default.

The airtightness of the case study home was relatively similar to the defaults used in EPCs and the saving in airtightness achieved by the retrofit matched that assumed by the default model inputs.

The spot in-situ U-value measurements were unlikely to fully capture the heterogeneous heat flow through the building fabric in this home, especially since it had no defined continuous primary air barrier, resulting in multiple bypass mechanisms and interconnected voids in the external walls, loft space and ground floor void.

Even after all the inputs were updated, the steady-state predicted HTC was still higher than that measured by the coheating test, though the DSM result was more in line. This illustrates the difficulty in comparing measured HTC with modelled heat loss in homes, even when default inputs are updated with measured and calculated values.

3.5 Predicting EPC band, annual space heating and carbon emissions

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

All the models used matching occupancy profiles and internal heat gain inputs as defined in the RdSAP conventions and described in the DEEP Methods 2.01 Report. They provide a useful 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 demands from the RdSAP, BREDEM and DSM models differ substantially. This has implications for predicted space heating requirements, carbon reduction and fuel bill savings.

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 gains and heat demand that take place over a diurnal cycle are only capable of being captured in DSM. It is beyond the scope of this project to confirm which approach is more accurate, but the RdSAP and BREDEM models consistently predict higher space heating demand than DSM.

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

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 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 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 calculation of 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 the internal gains. The weather file used in the DSM was selected due to the close similarities between monthly average external temperature values (CIBSE Test Reference Year file for Leeds) as discussed in the DEEP Methods 2.01 Report.

Differences specific to 08OL
For the 08OL baseline scenario, using measured infiltration rate and U-values, BREDEM predicts a space heating demand that is 2,910 kWh/year higher than the DSM prediction. 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.

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The DSM models mimic the coheating test conditions and therefore use a top-down method to calculate 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 08OL is 7,065 kWh, compared to the DSM estimate of 5,745 kWh, meaning BREDEM predicts a demand that is higher by 1,320 kWh. The BREDEM calculations can be further normalised by using the DSM volume of conditioned space (15.52 m^3 less in the DSM model). Following this final adjustment, the BREDEM estimate is 695 kWh higher than the DSM output.

The orientation of 08OL could have an impact on the model outputs. The gable wall is orientated almost to the south, meaning all the external walls are exposed to the sun all year round. Increased external surface temperatures during sunny periods result in reduced heat loss when compared to steady-state calculations. There is in this instance however, very little difference between the internal solar heat gains in RdSAP, BREDEM and DSM.

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 [7]. The impact of the retrofits on EPC in this case study, as predicted by each model at each calibration stage, is shown in Figure 3-28. The space heating demand predicted by DSM is the only output that differs in the comparative EPC calculations.

- The DSM models predict that the pre-retrofit home achieved EPC band C, while the steady-state models suggest the home achieved band D. This is due to the differences described between the two modelling approaches (e.g., DSM considers useful solar gains, geometry, etc.).
- The ground floor replacement makes only a slight improvement in the SAP score of between 1 and 2 points, which is not enough to bring the home into a new SAP band, except in the case of the BREDEM model, which incorporates the measured U-values. In this case, the uninsulated home is considered to be on the borderline between bands C and D. However, this may be an overprediction of performance, since the measured U-value for the first floor external wall is much lower than expected, due to warm air entering the wall cavity. This means that the U-value derived may not be representative of the actual heat loss through the element, meaning it is underpredicting heat loss.
- Although replacing the suspended timber ground floor reduced the U-value of this floor, it only made a marginal reduction in the HTC of the home. This finding suggests that adopting this type of retrofit measure in non-traditional homes where the external walls have not been thermally upgraded may have only a limited impact on the EPC band, maybe because the ground floor only represents a small heat loss area in this type of home (12 % of the total in this particular case).

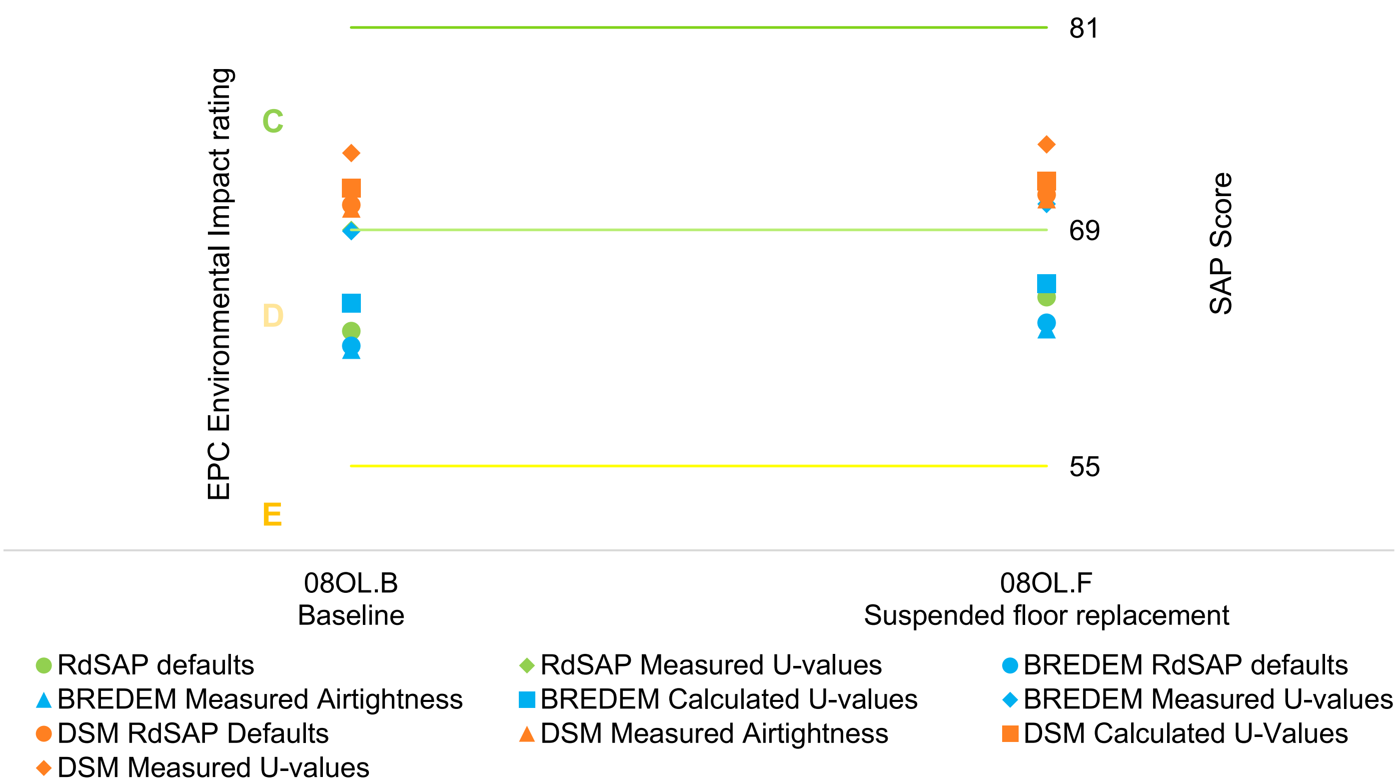

Figure 3-28 Predicted EPC pre- and post-retrofit

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/m²/yr for annual space heating of retrofits [8]. The predicted annual space heating demand attributable to the retrofit undertaken in this case study is shown in Figure 3-29.

- None of the models predict that the retrofit will help the home achieve the SHDF target. The DSM model which incorporates measured airtightness and U-values already predicts meeting the threshold pre-retrofit.
- DSM predicts lower space heating demand than steady-state models due to the way the model accounts for useful gains, hourly weather and geometry, as previously discussed.
- The savings predicted by the models are relatively small, between 5 % and 10 % in the steady-state models, though only between 3 % and 4 % in the DSM models.
- Incorporating the measured U-values into the models substantially reduces the pre- and post-space heating requirements. This is because the first floor wall U-value was measured to be much better than the default and calculated inputs. However, it is thought that this may be an overestimate of the fabric performance (due to warm air entering the wall cavity), and not be representative of the actual space heating demand in the home.

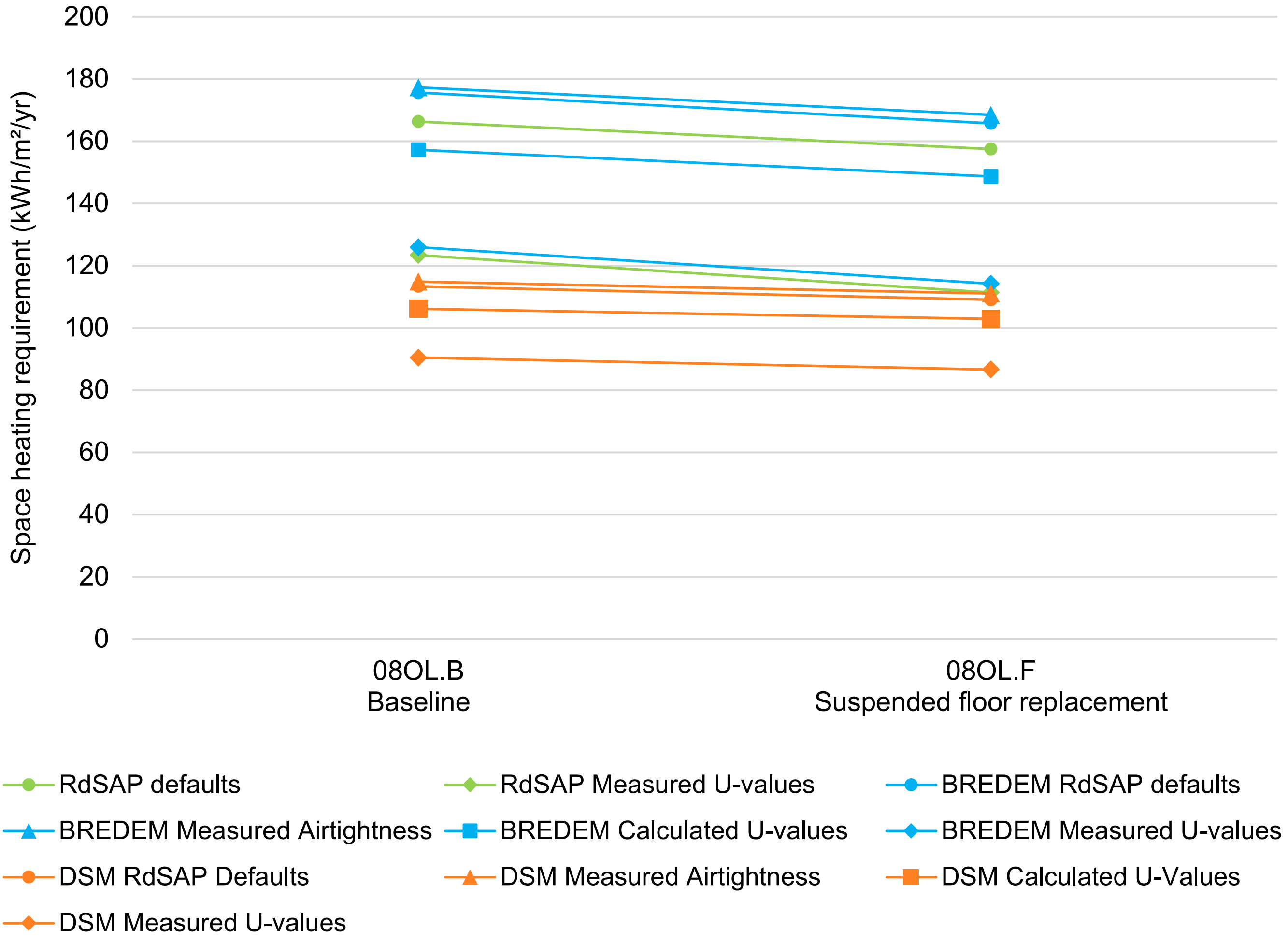

Figure 3-29 Annual space heating demand

3.5.4 Impact of retrofits on CO_2 emissions

Heating homes is responsible for around 15 % of the UK's CO_2 emissions [9]. The predicted reduction in CO_2 emissions achieved by the case study home retrofits is shown in Figure 3-30.

- The retrofit does not substantially reduce the amount of CO_2 predicted to be emitted by the home, only achieving between 4 % and 7 % reduction in the steady-state models and between 2 % and 3 % in the DSM models.
- The savings are relatively modest since, although heat loss through the ground floor is somewhat reduced, the CO_2 emissions for the home are dominated by the space heating demand for the majority of the home which is not directly affected by this retrofit.
- The home only had a partial suspended timber ground floor, as is the case for a substantial number of homes in the UK. A hybrid solution for solid and suspended floor retrofits may be more effective at reducing emissions.

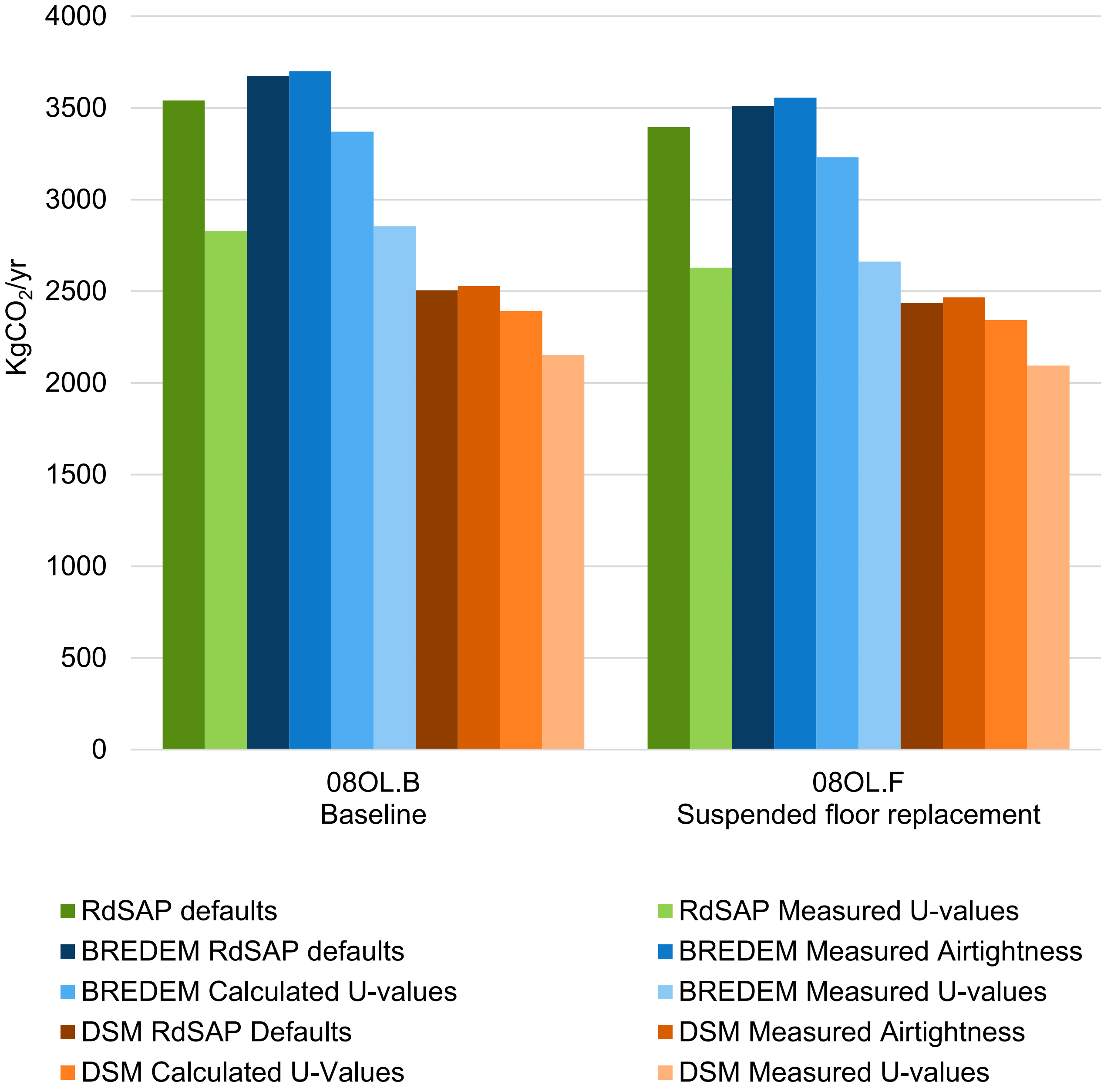

Figure 3-30 Annual CO_2 emission savings achieved by the retrofit

Predicting EPC band, space heating and carbon reduction summary

Non-traditional homes like 08OL are likely to have EPC band D ratings, and suspended ground floor retrofits are not likely to be sufficient to bring these homes up to band C.

Annual space heating may be reduced by between 3 % and 10 %, which is relatively substantial, however this translates to only marginal reductions in CO_2 emissions of between 2 % and 7 %.

DSM models tend to predict much lower space heating demand in homes generally, owing to the ability to consider more realistic inputs such as solar gains, and so also produce lower retrofit saving estimates, suggesting that the savings predicted by EPCs may be higher than achieved in practice.

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 [10].

Two metrics are used to assess whether the dwelling will overheat. Criteria A of TM59 is taken from another CIBSE publication, TM52: The limits of thermal comfort: avoiding overheating in European buildings [11]. 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 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. 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 [12]. Assessment was also carried out for future weather scenarios, using the DSY1 files for the 2050s and 2080s high emission scenarios at the 50th percentile. As with all naturally ventilated homes, it is the percentage of openable area in the windows that has the strongest influence on overheating risk, these are illustrated in Figure 3-31

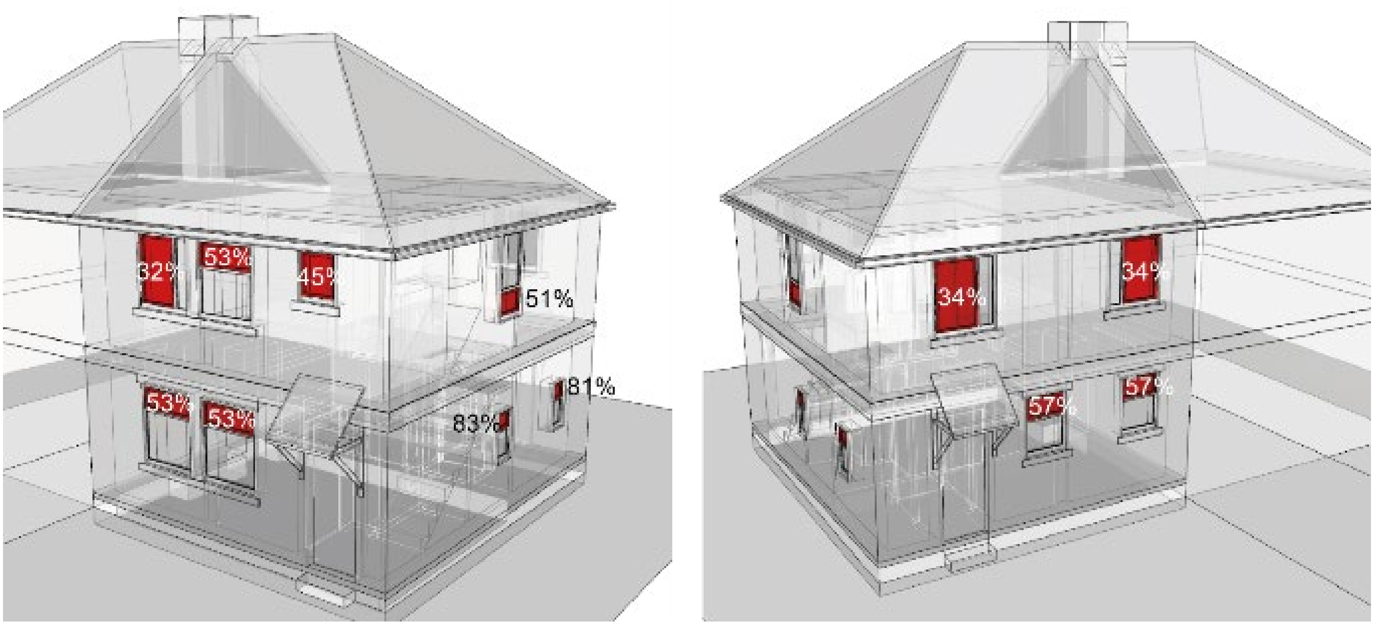

Figure 3-31 Percentage of opening area for openable windows

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As shown in Figure 3-32, under Criterion A the home was anticipated to overheat pre-retrofit and this risk increased post-retrofit. The reason is that in the summer the sub-floor void was cooler than the external air and provided some limited cooling to the building when the floor was uninsulated. Post-retrofit this cooling effect was eliminated.

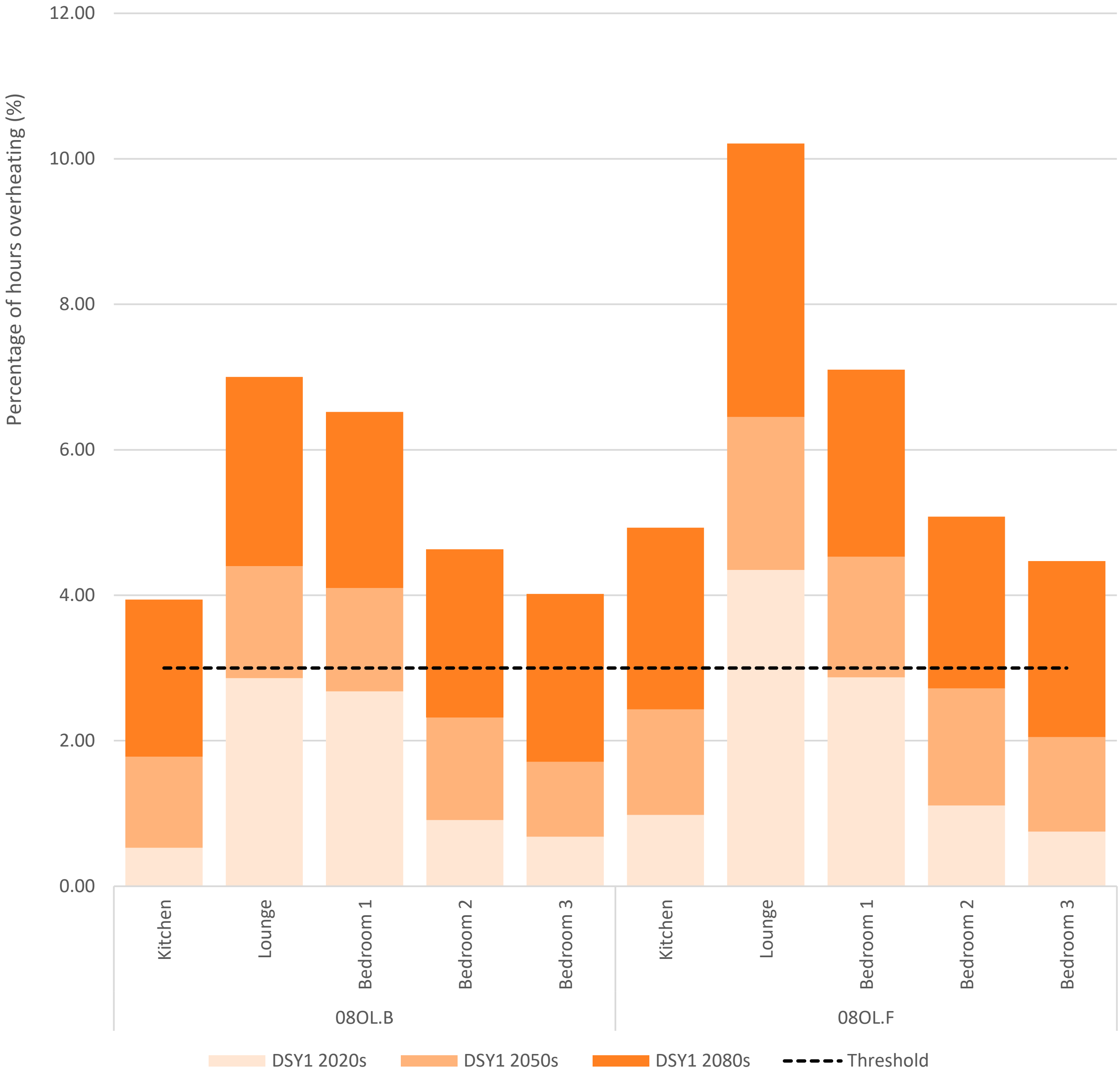

Figure 3-32 Modelled overheating under TM59 Criteria A

When considering Criterion B, the risk was predicted to already exist in the bedrooms, and this was likely to worsen post-retrofit, as shown in Figure 3-33.

2.10 DEEP 08OL

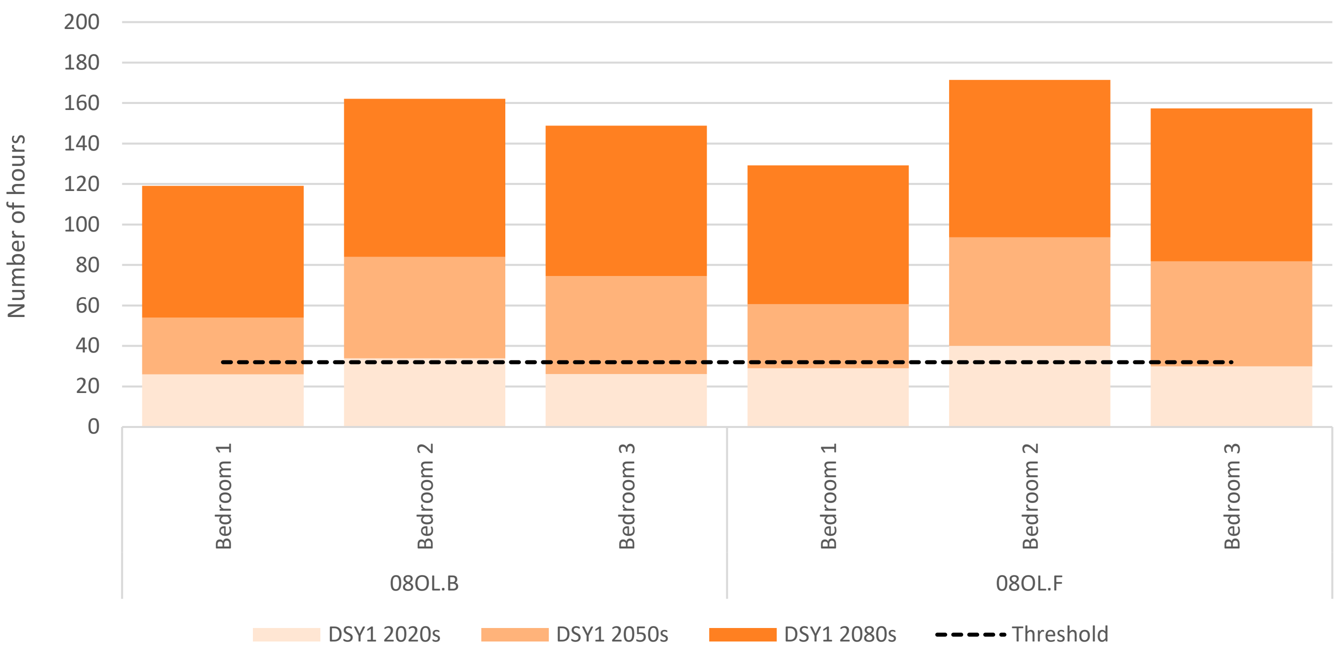

Figure 3-33 Modelled overheating under TM59 Criteria B

Overheating risk of retrofit summary

The overheating risk in non-traditional homes like 08OL appears to be relatively high. There are a number of reasons for this, including limited crossflow ventilation, especially during night-time hours when internal bedroom doors must remain closed under the TM59 methodology. This type of dwelling is also relatively lightweight in terms of thermal mass.

Overheating is exacerbated by the poor thermal performance of the external walls which allows for greater heat transfer into the dwelling through these opaque elements.

Following the ground floor retrofit the overheating risk increased, because in warmer periods during the summer the ground temperature in the sub-floor void can be cooler than the air temperature, which helps mitigate the overheating slightly. This mechanism was inhibited post-retrofit.

The increase in overheating risk following the ground floor retrofit is consistent across all the DEEP case study dwellings, and with the findings of Loughborough University presented in Report 6.04 overheating risk from domestic retrofit.

3.7 Retrofit costs and payback

This section looks at the costs of undertaking the retrofit described in this case study. However, it should be noted that, as this is only a single case study, these should not be used to generalise the 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.

It is important to note that the cost data presented here may not be representative of the national retrofit market. Since retrofits tend to be labour intensive, there are variations across the country based on regional differences in construction labour markets. The data discussed here originate from a single case study and so only one house type and retrofit specification is explored. Additionally, the costs are expected to be higher than benchmarks, as the project does not benefit from any the economies of scale of neighbourhood schemes.

Decoration costs are excluded from the costs reported here, since the landlords undertake their own decent homes repairs following retrofits and would take on some of the decoration work. Additionally, costs associated with decorating are outside the scope of this project. These costs are found to represent around 14 % of the cost of internal wall insulation [13], though it is recognised that they may be different for external wall insulation, loft insulation, ground floor insulation and new windows and doors.

A fixed total retrofit cost of £6,154 is shown in Table 3-5. The cost per square metre is substantially higher than benchmark values. However, this may not be surprising since in this approach the floor was removed and replaced, rather than having insulation added to an existing floor.

Table 3-5 Breakdown of cost of retrofit

Retrofit	Total cost	Treated area (m^2)	Cost per area (£/m^2)	Benchmark (£/m^2) [14]
Replacement of suspended timber floor with composite panels	£6,154	21	£296	£95

3.7.1 Predicting annual fuel bills

The impact of the retrofit on household dual fuel bills is based on SAP fuel prices of 3p per kWh gas and 13p per kWh electricity. These values are substantially out-of-date at the time of writing, but the indicative annual fuel bills savings are shown in Figure 3-34 for context.

DSM predicts substantially lower fuel bills, mainly due to the hourly heat balance calculations, associated variations in heat gain assumptions and the total conditioned volume. This illustrates the uncertainty that exists surrounding predicting fuel bills using energy models and the type of input data used.

The predicted annual dual fuel bill reductions for the house vary from just over 1 % to just over 5 %, depending on which model is used. This is a large range of absolute savings and the RdSAP EPC model predicts the highest savings using updated measured inputs.

Overall, these savings are marginal in the context of the overall retrofit cost and relative to the other heat losses in the home, especially through the external walls. Thus, it is likely that suspended ground floor retrofits alone would not make a material difference to the householder's annual energy bills.

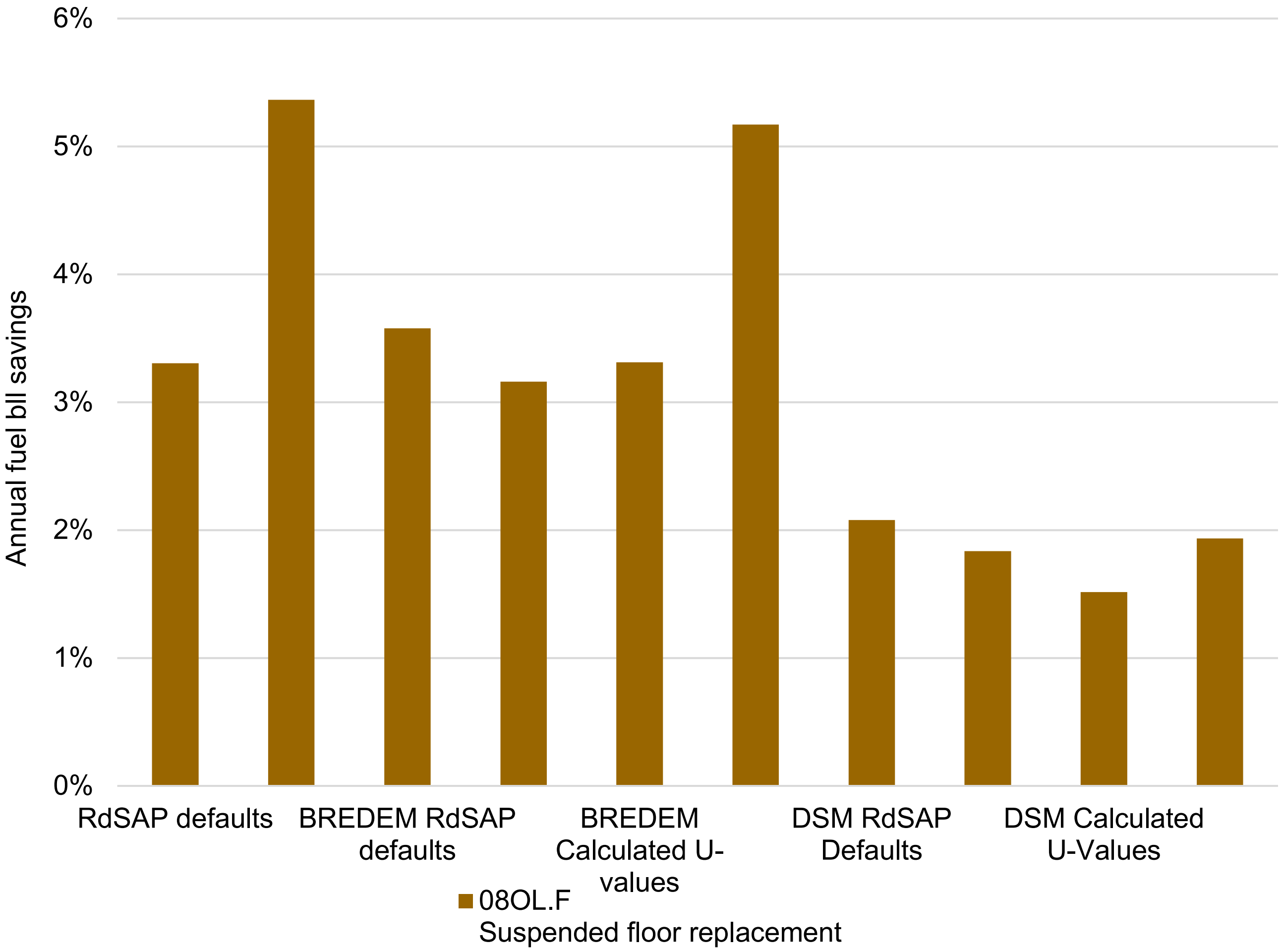

Figure 3-34 Predicted annual fuel bill savings

3.7.2 Predicting simple payback of the retrofit

The simple payback periods (i.e., not considering fuel price inflation or discount rates) calculated from the retrofit costs and annual fuel bill saving estimates for this case study are shown in

Figure 3-35. Recent fuel and retrofit price increases will significantly affect payback rates and so the values are shown only for illustration, and are based on the SAP 2012 fuel price assumptions. The results indicate the following:

- Payback rates vary enormously depending on which model and input data are used. For instance, DSM predicts lower space heating demand and therefore smaller savings. However, it also predicts much longer payback periods.
- As the savings are relatively small for all models, regardless of what input data are used, the anticipated payback of the retrofit is not financially attractive.

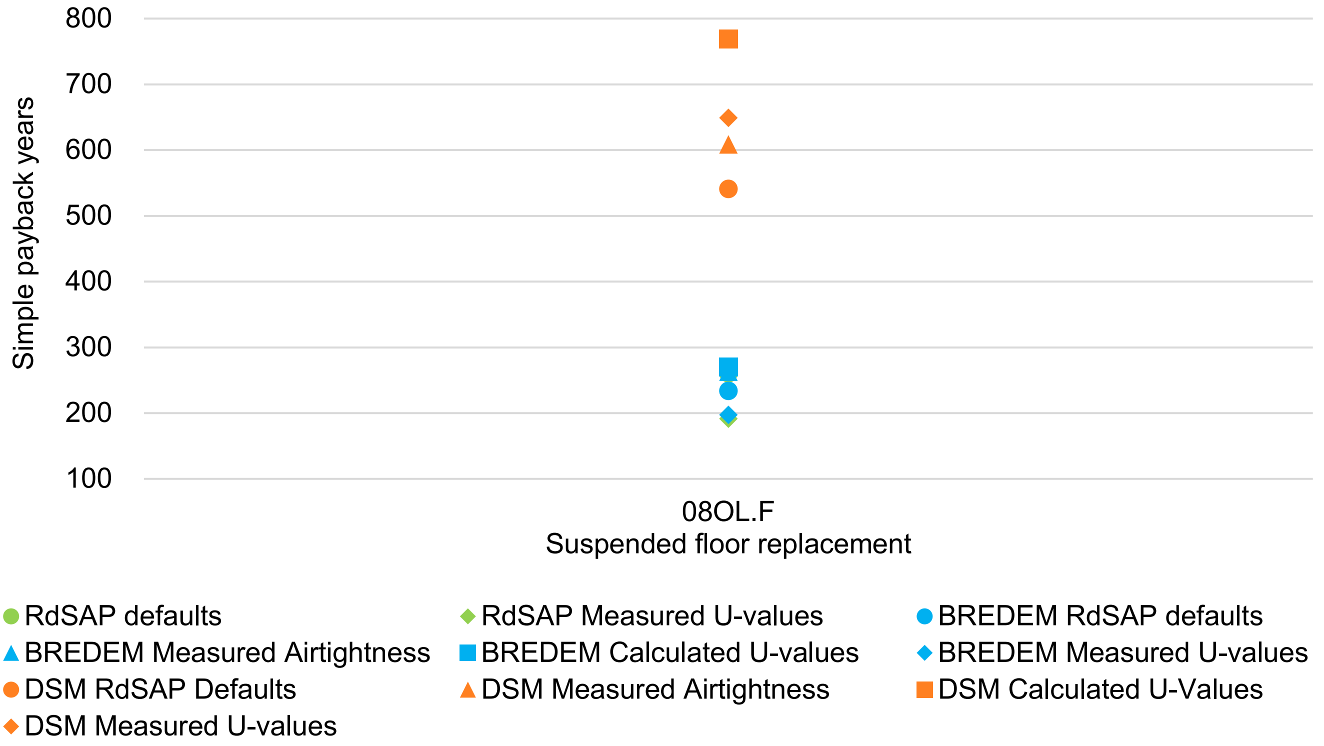

Figure 3-35 Simple retrofit paybacks

Retrofit costs summary

The retrofit cost was substantially higher than benchmark costs for suspended timber ground floor retrofits, since it involved the replacement of the living room ground floor, which may yield other durability benefits.

The savings predicted for household fuel bills were very small in comparison to the retrofit costs, resulting in unfavourable payback periods.

There is a large discrepancy in the predicted savings from the DSM and steady-state models because of the different space heating demands predicted by each. This highlights the risk that EPCs may overpredict retrofit savings achievable by households, since they do not account for all the useful gains and impacts on space heating that can be considered in DSM.

4 Conclusions

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

Suspended ground floor retrofit performance
The suspended timber ground floor replacement reduced the whole house HTC marginally from (167 ± 9) W/K to (148 ± 10) W/K, representing a reduction of (19 ±13) W/K, or (11 ± 8) %. Most of this was due to fabric reductions, though around 3 W/K may have been due to reduced air leakage and a maximum estimate of 6 W/K to reductions in thermal bridging.

The retrofit is not anticipated to improve the EPC rating of the home, which was already predicted to be EPC band D using steady-state models. However, DSM predicts a much lower space heating requirement, and when used in the EPC calculation results in the home being assessed as band C. In all models, the ground floor replacement has little impact on the SAP score or fuel bills, with a maximum saving of £31 (5 %) and a minimum of £8 (3 %) being predicted, depending on which model is used. Similarly, only a 2 % to 7 % reduction in annual CO_2 emissions is predicted for the retrofit.

The cost of the retrofit was substantially higher than conventional ground floor retrofits, since the entire living room floor was replaced. Coupled with the marginal fuel bill savings, this means the payback rates are not financially viable. However, these assessments were undertaken based on out-of-date fuel cost figures, so new assessments using more up-to-date fuel prices are needed. Replacing the suspended ground floor may have additional maintenance benefits for homeowners, for example it may improve the durability and longevity of the floor.

The results suggest that, although some savings are possible from retrofitting suspended timber floors, they unlikely to make a meaningful contribution to EPC, fuel bill reduction or carbon reduction.

Impact of wind washing on the coheating test
The initial coheating tests undertaken on the dwellings suggest that unreasonably high retrofit savings may have been achieved by the application of the ground floor retrofit. However, the observations using thermography suggest that the dwellings are likely to be highly susceptible to the effects of wind washing. Consequently, it is thought that the initial coheating tests resulted in elevated heat losses being sustained in the home, and an HTC of (208 ± 19) W/K was calculated. When wind washing was accounted for in the coheating test analysis, the HTC of the house pre-retrofit reduced by around 41 W/K.

Air leakage in steel-frame homes
The Dennis-Wild steel-framed case study home had numerous problematic direct and indirect air leakage pathways, owing to the lack of a principal and continuous air barrier. As a consequence, it had a mean air permeability of 16.6 $m^3/(h \cdot m^2)$ @ 50Pa, according to the blower door test. As a number of the air leakage pathways observed were indirect, rectifying these pathways would be particularly challenging, especially those related to cavities within the fabric, which caused air exchange between the floor voids, walls and ceilings.

Thus, the new suspended ground floor retrofit, only reduced the whole house infiltration rate to 15.3 $m^3/(h \cdot m^2)$ @ 50Pa (9 %), i.e., within the error of the test (±10 %). However, thermography showed that air leakage pathways associated with the suspended ground floor were substantially reduced.

Inter-dwelling air exchange
As in other DEEP case studies, inter-dwelling air exchange was measured using a co-pressurisation test. In this case, the blower door test predicted the air leakage rates to be 14 % lower when air exchange between the neighbours was eliminated, i.e. greater than the reduction in air leakage measured by installing a new suspended ground floor retrofit.

External wall in-situ U-value uncertainty
The U-values derived from the HFPs installed on the external walls yielded unexpected results. The first floor wall was anticipated to have similar in-situ measured U-values as the downstairs wall. However, it was measured to be substantially lower. The first floor had an in-situ U-value of (0.68 ± 0.02) $W/(m^2 \cdot K)$, while the ground floor U-value was measured to be (1.15 ± 0.4) $W/(m^2 \cdot K)$.

Thermography undertaken during the tests suggests that warm air from inside the home was entering at low levels and moving vertically up within the cavity walls, gaining heat as it moved. It is suggested that this air movement is likely to have affected the internally measured heat flux density values in the upstairs rooms, making them appear lower and under-reporting the amount of heat loss taking place through the first floor external walls in the home.

Improving model inputs
In this case study, the steady-state models predicted substantially more heat loss than measured by the coheating test. In part, this was due to the default wall U-values being higher than measured (the default and measured infiltration rates were, by chance, almost identical and so had almost no impact on the predictions). However, even when the defaults were replaced with measured U-values, the predicted HTC was still much higher than measured. The DSM model also predicted a much higher HTC than the coheating tests when the default model inputs were used. However, when these were replaced with measured inputs, the DSM predictions became much more aligned with the measured coheating test values.

Overheating
As found in other DEEP case studies, the pre-retrofit home was at risk of overheating. Following the suspended ground floor retrofit, the overheating risk increased and became more pronounced. This is thought to be attributable to the sub-floor void being cooler than the internal dwelling air temperature in the summer, thus providing some limited cooling. This mechanism was inhibited post-retrofit by the addition of the new suspended insulated ground floor. It is important to note that the overheating assessment assumed a worst-case scenario, without any solar shading or other mitigation measures.

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