Department for Energy Security & Net Zero

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DEEP Report 2.08

Case Study 52NP & 54NP

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Prepared for DESNZ by

Professor David Glew, Leeds Beckett University (LBU)

LBU contributing authors (alphabetically):

Mark Collett
Dr Martin Fletcher
Dr Adam Hardy
Beth Jones
Dominic Miles-Shenton
Dr Kate Morland
Dr Jim Parker
Dr Kambiz Rakhshanbabanari
Dr Felix Thomas
Dr Christopher Tsang

Any enquiries regarding this publication should be sent to us at: EnergyResearch@energysecurity.gov.uk

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Executive summary

52NP and 54NP are two of fourteen case study homes retrofitted in the DEEP project. The case studies were used to identify the performance of, and risks associated with, retrofitting solid walled homes. The data from the case studies were also used to evaluate modelled predictions of retrofit performance and risk.

In these case studies airtightness improvements and ground floor retrofits were undertaken, which reduced air leakage in both homes by around 41 % and floor U-values by over 70 %. Cumulatively these retrofits were observed to reduce the home's heat transfer coefficient (HTC) by (28 ± 22) % in 52NP and (27 ± 12) % in 54NP according to coheating tests. *Closing-the-loop* analysis suggests the airtightness improvements were responsible for around 60 % of this improvement, while the floor retrofit achieved the remaining 40 %. These homes already had external wall insulation (EWI), and thus had relatively low starting HTC, meaning that, despite large percentage reductions, the absolute savings were relatively small, around 39 W/K, representing annual fuel bill reductions of between £23 and £76.

The HTC reduction predicted by an energy performance certificate (EPC) was 9 %, which was lower than measured, since the reduced data Standard Assessment Procedure (RdSAP) only assumes infiltration rates and cannot account for reductions in air leakage achieved. This has consequences for motivations around undertaking airtightness retrofits, and the appropriateness of RdSAP for promoting whole house retrofits.

The airtightness retrofits themselves were not all successful, only the installation of floor coverings reduced air leakage in the home. More research is needed to understand the implications of floor coverings as an energy saving measure and the implications for blower door tests being undertaken in homes without floor coverings.

When the EPC default assumptions around airtightness and U-values were replaced with measured and calculated values, the predicted reduction in HTC increased to between 17 % and 22 %, depending on the model and data used. This resulted in improvements of between 1 and 3 SAP points, meaning the homes did not improve on their baseline EPC ratings of band C. This is partially due to the homes already having EWI, thus, it appears that installing floor insulation and airtightness improvements in addition to EWI may not be sufficient to achieve EPC ratings of band B in mid-terrace solid walled homes.

The case study found that dynamic energy modelling (DSM) predicted closer HTC values to measured results than steady-state models. It also confirmed previous findings that replacing defaults with measured data to improve the accuracy of EPCs is less important in energy efficient homes. Replacing default U-values and airtightness with measured and calculated values reduced the HTC between 10 % and 15 %, i.e., a similar impact to the retrofits.

Inter-dwelling air exchange was observed during the blower door test between the case study homes. When co-pressurisation tests were undertaken to remove air transfer across the party walls, the infiltration rate was determined to be between 11 % and 18 % lower. This has implications beyond the case study homes. For instance, homes with adjacent dwellings that are naturally ventilated, may be more airtight than tests suggest. i.e., some naturally ventilated homes may need mechanical ventilation to ensure adequate fresh air is being provided. More research is needed to understand the implications of this for the UK housing stock, Building Regulations, retrofit policy and regulations, indoor air quality, and the blower door industry.

1 Introduction to 52NP and 54NP

Case studies 52NP and 54NP are both four-bedroom, pre-war, solid walled dwellings, and are adjacent terraces sharing a party wall. Their interesting features include having a room-in-roof, basement, and a large amount of party wall. Being neighbours, these case studies provided an opportunity to investigate solid party wall air and heat transfer. A suspended timber ground floor retrofit was undertaken in each house, then incremental improvements in airtightness were made to explore the contribution of each air leakage pathway to whole house air leakage heat losses and quantify the benefit of removing specific infiltration routes.

1.1 DEEP field trial objectives

52NP and 54NP are two of fourteen DEEP case studies which, collectively, investigate the research objectives listed in Table 1-1. Not all the objectives are addressed by each case study.

Table 1-1 DEEP research objectives

Objective	Rationale
Model input accuracy	Policy relies on models with known limitations, exploring inputs and model robustness improves policy advice.
Unintended consequence	More retrofit scenarios need modelling to confirm condensation, underperformance, air quality and comfort risks.
Cumulative impact	Piecemeal retrofits are common, clarity is needed on impact of 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 Case study research questions

Over the course of the three-year project and following advice from the Department for Energy Security and Net Zero (DESNZ), the wider DEEP steering group, and expert QA panel, questions and objectives have been refined into the seven discreet research questions listed below which are used to discuss the findings.

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

Data collected from case studies 52NP and 54NP do not answer all these research questions but 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

52NP and 54NP, shown in Figure 1-1, are two four-bedroom properties in Leeds, West Yorkshire, built around 1900. They are two neighbouring mid-terrace houses, made of solid nine-inch brick. Each has two external walls (front and rear). The houses share a party wall, and both share a party wall with their other neighbour (52NP with 50NP, and 54NP with 56NP). Both houses have their own chimney stack, a room-in-roof (comprising two bedrooms), a basement, and a suspended timber ground floor.

This is a typical construction for the area, though less so nationally. There are over 1.4m homes in England and Wales built between 1900 and 1918 [1] and four-bed terraced houses make up around 2 % of all homes [2]. Thus there may be around 28,000 homes similar to 52NP and 54NP, although many may not have basements. While it is unlikely that the results from 52NP and 54NP are directly transferrable across all terraced properties in general, the features of the case study do enable a deeper understanding of airtightness and heat loss across party walls. This may provide insight into the issues faced by terraced properties where the floor joists from two homes sit adjacent to each other at regular intervals within a party wall.

Figure 1-1 Case study houses 54NP (left) and 52NP (right)

Figure 1-2 Case study houses site location plan

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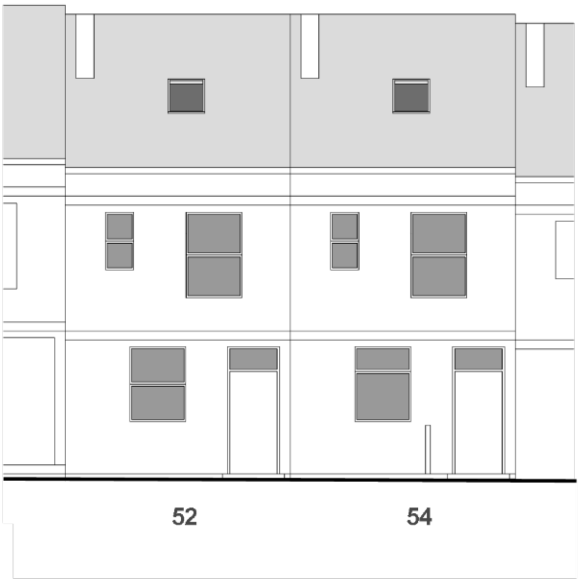
Floor plans, elevations and sections are shown in Figure 1-3, Figure 1-4, and Figure 1-5.

Figure 1-3 House floor plans

Front (south east) elevation



Rear (north west) elevation

Figure 1-4 House elevations

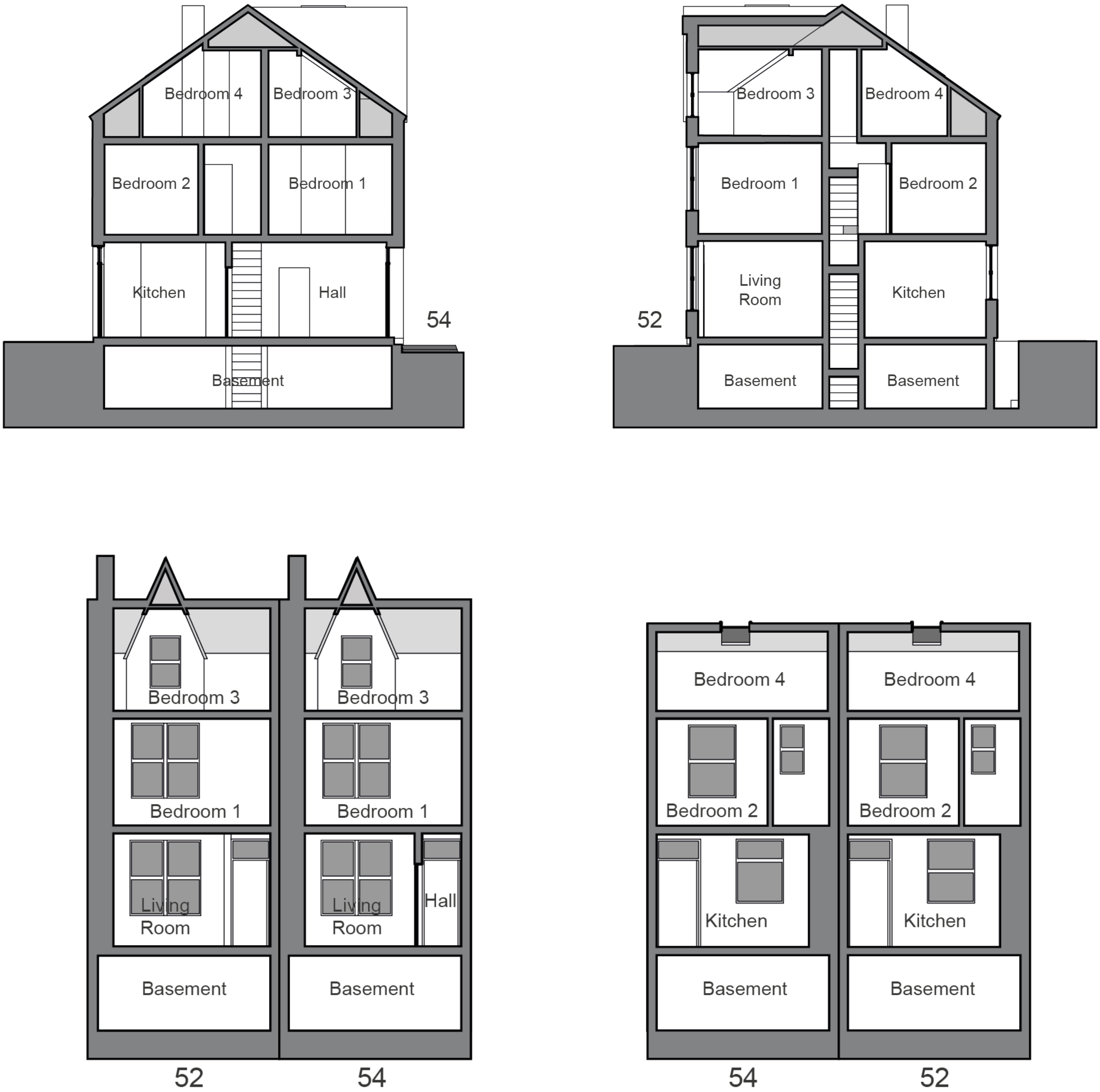


Figure 1-5 House sections

The dimensions of each element in the homes are listed in Table 1-2 and were used to allocate heat losses as well as generate thermal models in RdSAP, the Building Research Establishment Domestic Energy Model (BREDEM) and DSM. The only difference in the layout is that there is a large living room in 54NP since it has absorbed the hall, which impacts the energy calculations in the models.

Table 1-2 House dimensions

Detail	Measurement
Volume	*251.05 m^3*
Total floor area	*93.82 m²*
Total heat loss area	*135.34 m²*
Ground floor	32.40 m²
Front external wall	18.40 m²
Rear external wall	15.60 m²
Windows	13.19 m²
Door	4.25 m²
Sloping ceiling	13.74 m²
Loft	11.52 m²
Party walls	130.41 m²
Dormer sloped ceiling	4.50 m^2
Dormer flat ceiling	2.13 m²
Knee wall	12.77 m²
Ceiling to eaves	6.84 m²

The construction details are summarised in Table 1-3. Features to note are that brick effect render EWI (≈ 100 mm) was already installed on the front external walls of both properties, and painted pebble dash render EWI (≈ 105 mm) was applied to the rear elevations. Insulation was also present in the room-in-roof in the flat ceiling above Bedrooms 3 and 4, and in the stud walls of Bedroom 4. There was some insulation in the sloping ceilings for both room-in-roof bedrooms.

The suspended timber ground floors of each house were found to be insulated with mineral wool and underdrawn with pink (fire resistant) plasterboard. However, there was evidence of condensation trapped between the floorboards and plasterboard. Further investigation revealed that some of the floor joists were rotting. Therefore, the insulation and plasterboard were removed from both properties prior to starting the baseline tests.

The windows were double glazed timber units and often in a poor state of repair, particularly in the Living Room and Bedroom 1 as the stone mullion separating each set of windows was degrading.

1.4 Retrofit approach

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

Table 1-3 Construction and retrofit summary

Detail	Baseline construction	Retrofit[1]
Airtightness	8.52 $m^3/(h{\cdot}m^2)$@50Pa (52NP) 9.85 $m^3/(h{\cdot}m^2)$@50Pa (54NP)	General sealing of waste pipes and windows
Floor	Uninsulated suspended timber	Mineral wool between joists 200 mm x 0.044 W/(m·K) Target U-value: • 0.18 $W/(m^2{\cdot}K)$ (Kitchen) • 0.17 $W/(m^2{\cdot}K)$ (Living room)
Intermediate floor	Timber intermediate floor	Sealing of intermediate floor voids, joists, and floorboards.
External wall	Solid brick with external wall insulation	N/A
Rear knee wall	Timber studs with 75mm rigid insulation in between	N/A
Front knee wall	Uninsulated timber stud wall	N/A
Exposed intermediate ceiling (first floor)	Ceiling to eaves void (timber intermediate floor)	N/A
Loft	Ceiling joist with mineral wool in between	N/A
Pitched roof	Rafter with 50mm rigid insulation	N/A
Dormer sloped ceiling	Rafter with 50mm rigid insulation	N/A
Dormer flat ceiling	Ceiling joist with mineral wool between	N/A
Windows	uPVC double glazed	N/A
Door	Composite	N/A

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

Figure 1-6 identifies where insulation was found in the homes before any retrofits were carried out. The sequence of the staged retrofit approach is illustrated in Figure 1-7 to Figure 1-10. Building performance evaluation (BPE) tests, and whole house energy modelling were conducted at each stage of the retrofit to quantify the performance changes associated with each separate intervention. The specific methodologies for these are described in the DEEP Methods 2.01 Report.

The codes in Table 1-4 and Table 1-5 are shorthand to identify each retrofit stage to aid the discussion. As can be seen, retrofit stages 2 and 3 were installed in the reverse order in the homes, owing to logistical constraints of the contractor, while stages 4 and 5 were identical in both homes.

Table 1-4 Phased retrofit stages for 52NP

	Retrofit stage	Code	Retrofit date
1	Baseline	52NP.B	January / February 2021
2	Suspended timber ground floor insulation	52NP.F	February 2021
3	Airtightness improvement 1 Intermediate floor joists sealed	52NP.FA1	February 2021
4	Airtightness improvement 2 General sealing of waste pipes, windows and doors	52NP.FA2	March 2021
5	Airtightness improvement 3 New carpets and vinyl flooring fitted	52NP.FA3	March 2021

Table 1-5 Phased retrofit stages for 54NP

	Retrofit stage	Code	Retrofit date
1	Baseline	54NP.B	January / February 2021
2	Airtightness improvement 1 Intermediate floor joists sealed	54NP.A1	February 2021
3	Suspended timber ground floor insulation	54NP.FA1	February 2021
4	Airtightness improvement 2 General sealing of waste pipes, windows and doors	54NP.FA2	March 2021
5	Airtightness improvement 3 New carpets and vinyl flooring fitted	54NP.FA3	March 2021

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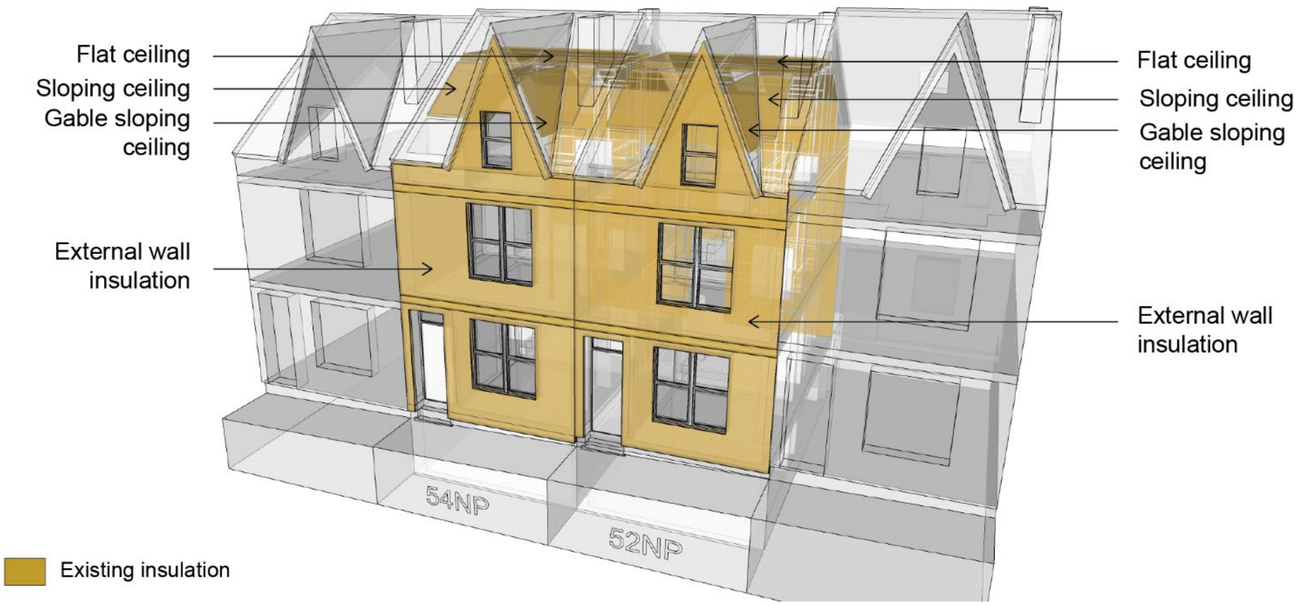

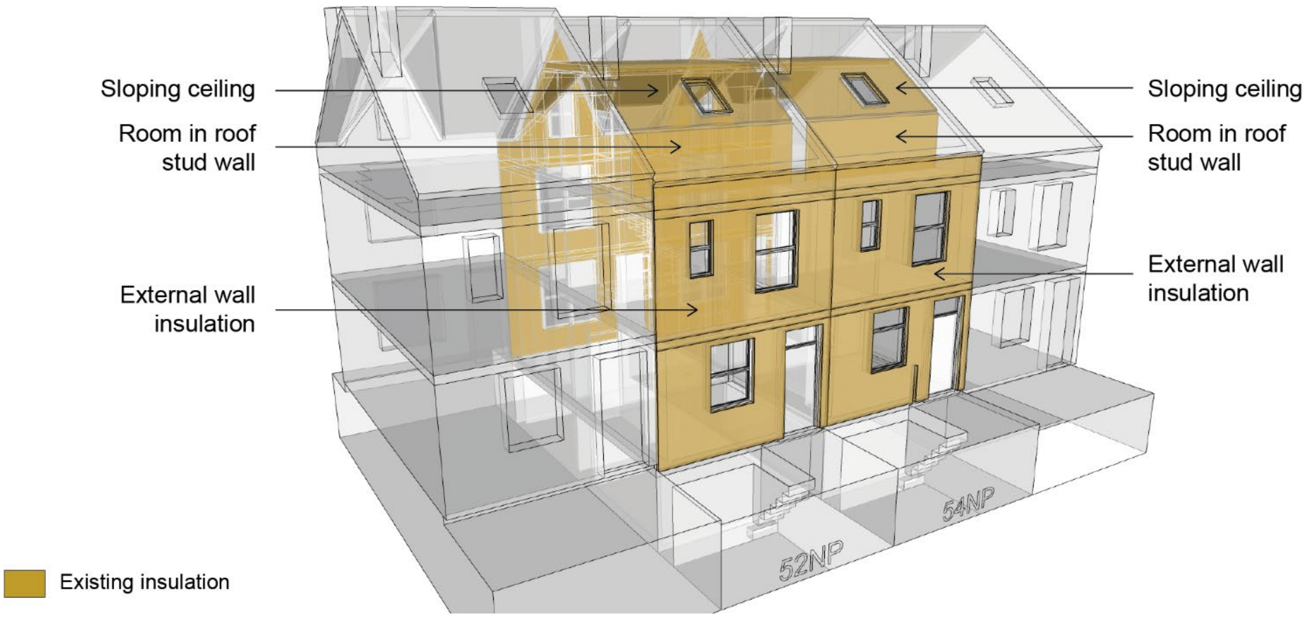

Figure 1-6 Stage 1: Insulation already in the property prior to the retrofits (52NP.B and 54NP.B), front and rear elevations

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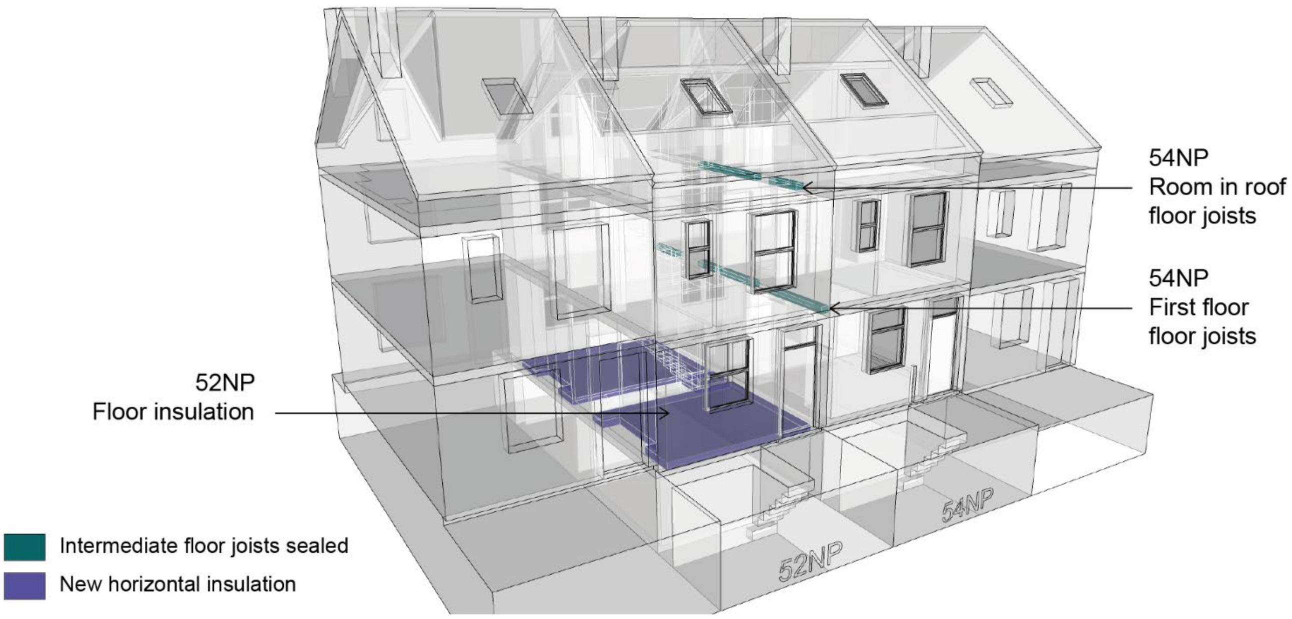
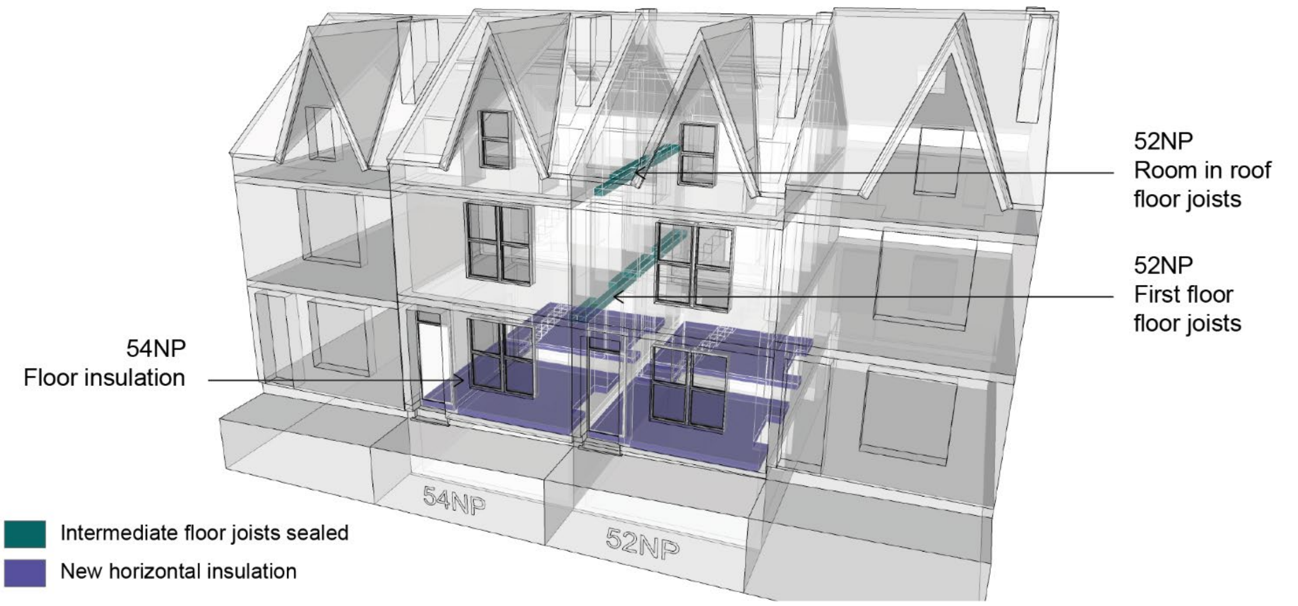


Figure 1-7 Stage 2: Ground floor retrofit to 52NP (52NP.F) and airtightness retrofit (sealing intermediate floor joists) at 54NP (54NP.A1)[2], front and rear elevations

[2] Existing insulation removed from the graphic for clarity



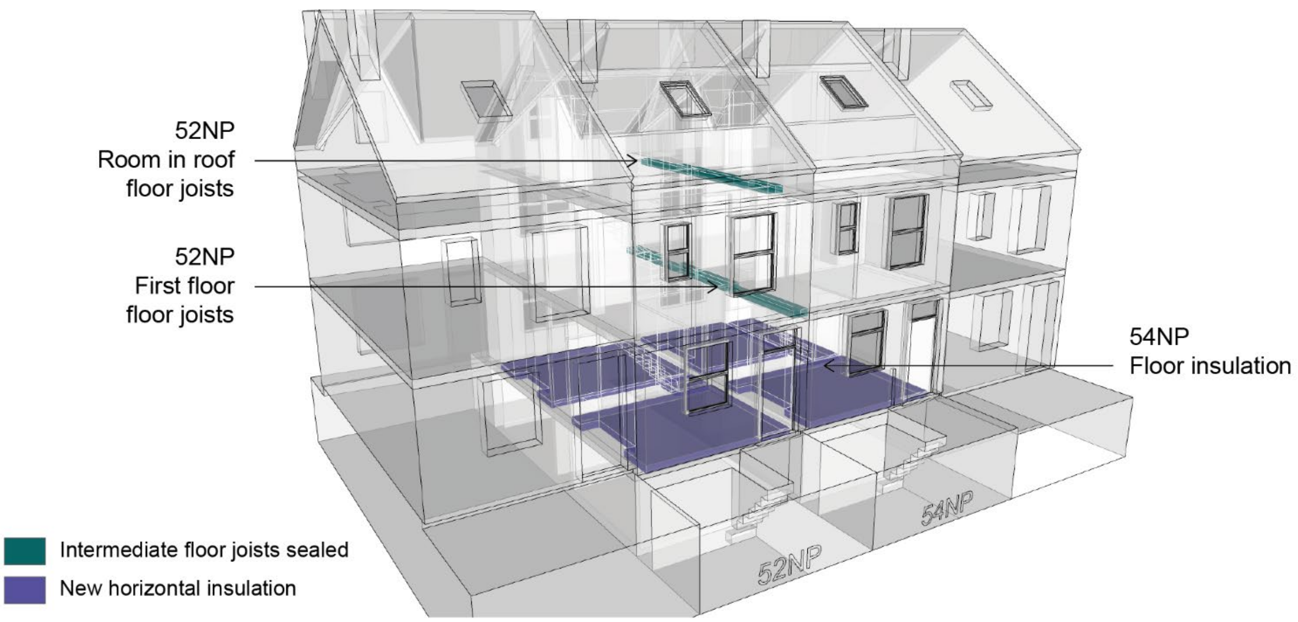
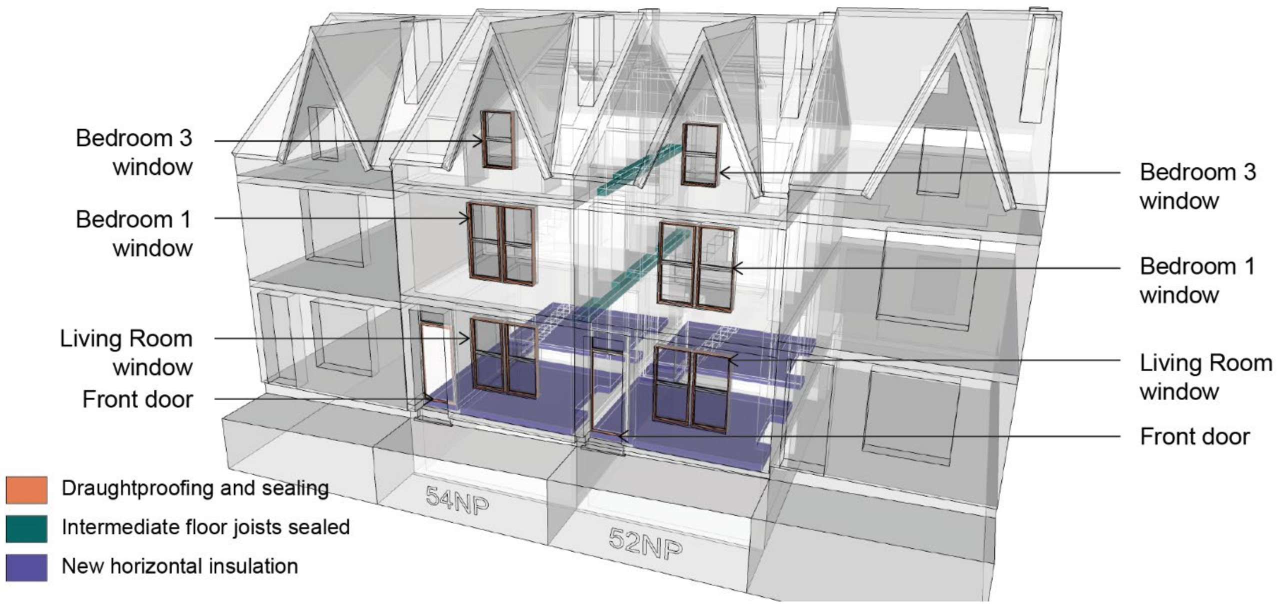


Figure 1-8 Stage 3: Airtightness retrofit (sealing intermediate floor joists) at 52NP (52NP.FA1) and ground floor retrofit 54NP (54NP.FA1)[3], front and rear elevations

[3] Existing insulation removed from the graphic for clarity



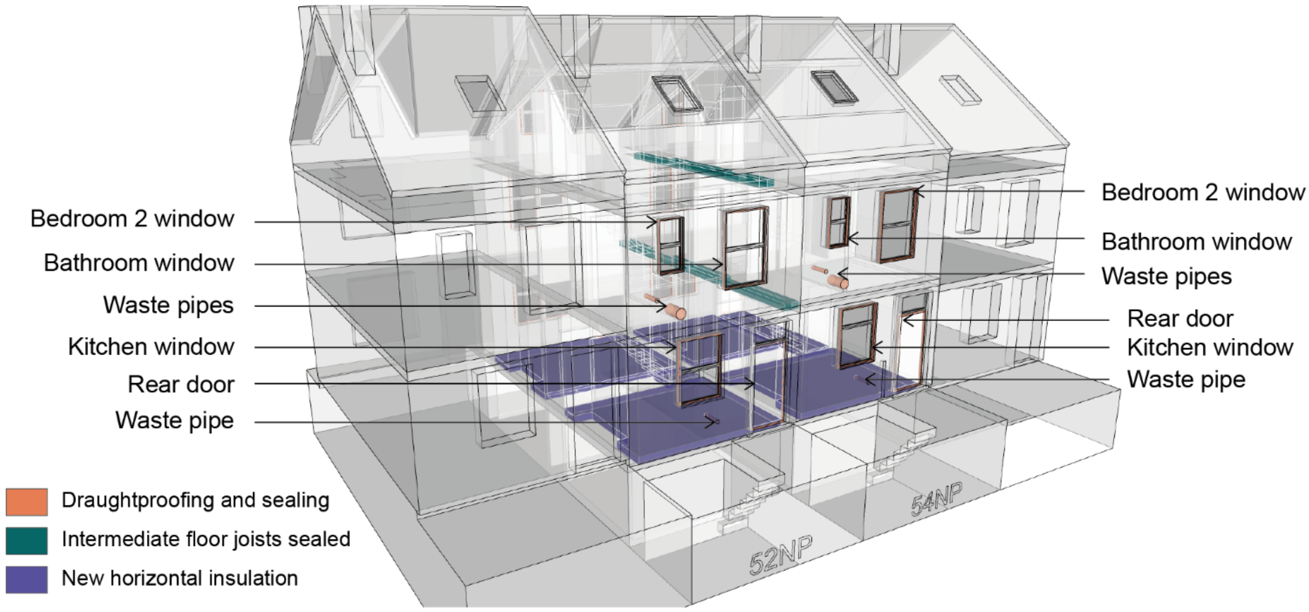


Figure 1-9 Stage 4: Airtightness retrofit (general sealing of waste pipes, windows and doors) to both 52NP (52NP.FA2) and 54NP (54NP.FA2)[4], front and rear elevations

[4] Existing insulation removed from the graphic for clarity

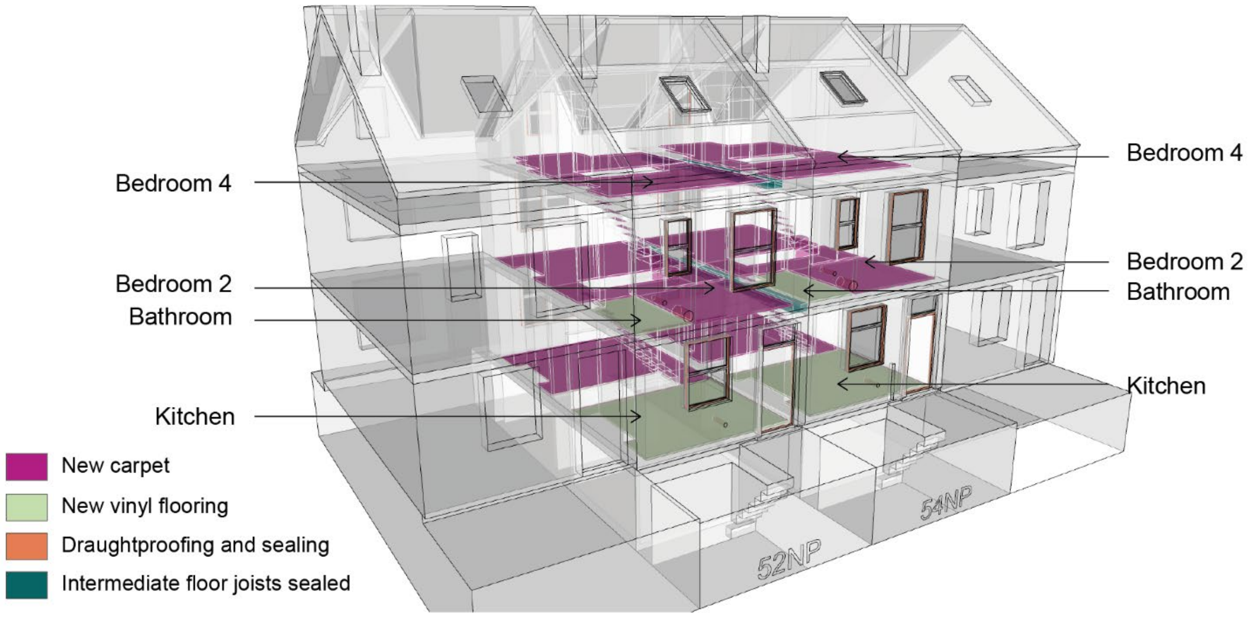


Figure 1-10 Stage 5: Airtightness retrofit (carpets fitted) to both 52NP (52NP.FA3) and 54NP (54NP.FA3)[5], front and rear elevations

[5] Existing insulation removed from the graphic for clarity

1.4.1 Condition of existing external wall insulation

Both 52NP and 54NP had EWI installed in the early 2010s. For the most part, this EWI was still in reasonable condition. However, there were some areas of significant concern in terms of damage to the insulation materials that may lead to deterioration in performance or, more significantly, damp.

For instance, Figure 1-11 shows contrasting EWI joins between the neighbours to the case study homes. As can be seen from the images, which provide a view up the party walls, the expansion joint between the two homes in the left-hand image appears to have been omitted in the right-hand image. This resulted in weathering and consequently caused cracking in the joint between the two homes. Water penetration behind the insulation now occurs and propagates damage, underperformance of the insulation, and moisture build-up.

It is not known when this cracking first occurred, but the problem appears to be maturely manifest in the years since installation. It is not known if the landlord has to pay to rectify the defect given workmanship warranties tend to be restricted to 1 year, while product guarantees can be 25 years if installed according to their BBA certificate, which is not the case here.

This indicates likely instances where defects have been previously unchecked and allowed to propagate in funded insulation policies such as the Energy Company Obligation (ECO). This sort of issue may be less likely to occur in the future under schemes covered by PAS2035, which requires best practice detailing. But the extent to which these issues exist nationwide is not known. A national survey of the quality of historic EWI would be required to investigate this.

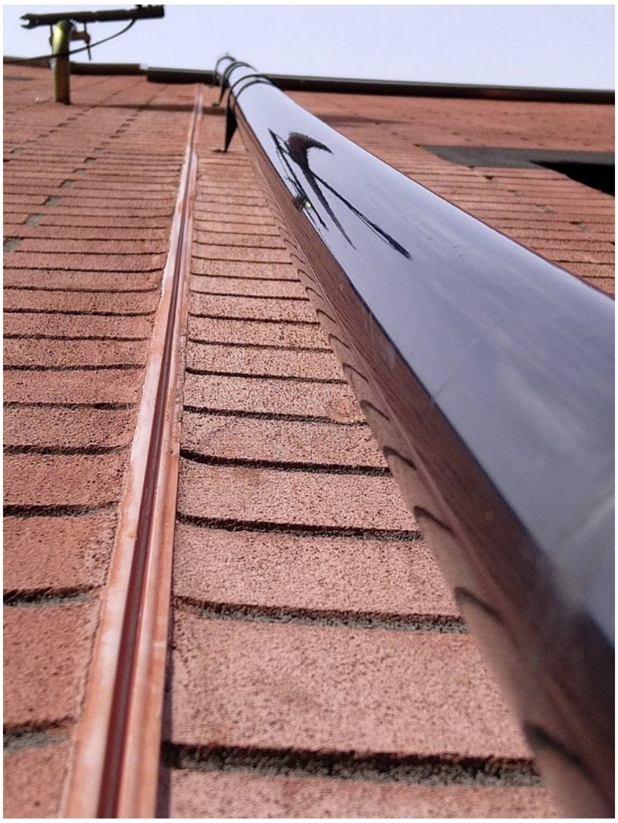


Figure 1-11 Expansion joint installed between 54NP and 52NP (left), but not installed between 52NP and 50NP (right), and the resulting damage

1.4.2 Condition of existing suspended timber ground floor insulation

One of the most important considerations when installing insulation is the risk of moisture build up and condensation. In both case study buildings there was some suspended timber floor insulation installed from the basement and covered by an unsealed and un-plastered plasterboard ceiling. On closer inspection, the boards and insulation showed signs of damp.

This damp was likely caused by a combination of two factors. Firstly, the basement ventilation had been covered, leading to high relative humidity levels. Secondly, some weeping radiator pipework was found, and water from the leak was dripping down onto the floor timbers. Moist air from the basement could also penetrate the plasterboard ceiling and become trapped, then condense on the cold surfaces of the plasterboard, insulation, and timbers.

To remedy this, ventilation was reinstated, the plasterboard ceiling and insulation were removed, and the timber floor joists were left to dry to below 20 % wood moisture equivalent. Following the installation of new insulation, no replacement plasterboard ceiling was installed. Instead, a breathable membrane was used to help secure the insulation in place so moisture passing through the floor from the rooms above would not be trapped but could escape into the ventilated basement.

Case study and retrofit summary

52NP and 54NP already had new double glazing and external wall insulation. Thus, this case study looks at the benefit of installing additional retrofit measures in homes, which may be considered part of a whole house retrofit, namely floors and airtightness improvements.

In addition, 52NP and 54NP provided an opportunity to investigate the variability in retrofit savings by installing identical floor and airtightness retrofits in neighbouring properties to compare performance.

The case studies provided evidence of the benefits of various airtightness improvements to quantify the contribution of each stage to the overall reduction in air leakage, rather than providing a simple aggregated benefit.

Finally, these homes provided the potential to investigate the way in which air and heat transfer occurred across solid party walls, and how this was affected by addressing air leakage pathways.

2 Fieldwork and modelling methods

BPE tests and modelling were undertaken on 52NP and 54NP at each retrofit stage, in accordance with the methodologies listed in the DEEP Methods 2.01 Report. This section outlines the implementation of these methods at 52NP and 54NP, including any variations and additions.

2.1 Environmental data collection

Internal environmental data logging equipment is described in detail in the DEEP Methods 2.01 Report. The internal environmental data collected at 52NP and 54NP included air temperature, relative humidity (RH), and CO_2 levels. External environmental data were collected via a weather station located on the Leeds Beckett University Rose Bowl building, located approximately 2 miles from 52NP and 54NP. These included vertical solar irradiance, air temperature and wind speed. This was supplemented by an external air temperature sensor positioned outside 52NP and 54NP.

2.2 Measured survey

A detailed survey of the building was undertaken, a digital version of the house was developed using SketchUp, which was used to calculate the dimensions of each element and draw up the plans shown in the previous section. Plans, sections, and elevations were directly exported to DSM. The construction makeup of the existing building was assessed where access could be gained to observe the material makeup.

2.3 Airtightness and thermography

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

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

2.4 Heat flux density measurement and U-values

32 Hukseflux HFP01 heat flux plates (HFPs) were installed on various elements in 52NP, and 31 in 54NP. These were installed to measure the baseline and improvements to U-values achieved by the fabric upgrades, as well as to quantify the party wall heat exchange measured during the coheating test. 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. Where possible, multiple locations for each element were measured. Heat flux from individual HFPs along with internal and external temperature data were used to calculate U-values for each element. Where more than one HFP was located on a single element a simple average was used. Where a repeated thermal bridge was measured, or an area of non-representative heat flux was observed, a weighted average was calculated to provide the whole element U-value estimates. These U-values were used to calibrate energy and thermal models, estimate the heat loss due to the fabric (HTC_f), and compare this with the whole house HTC and disaggregation techniques. U-values for the windows had to be assumed and, therefore, represent an area of uncertainty when considering calibrating energy models.

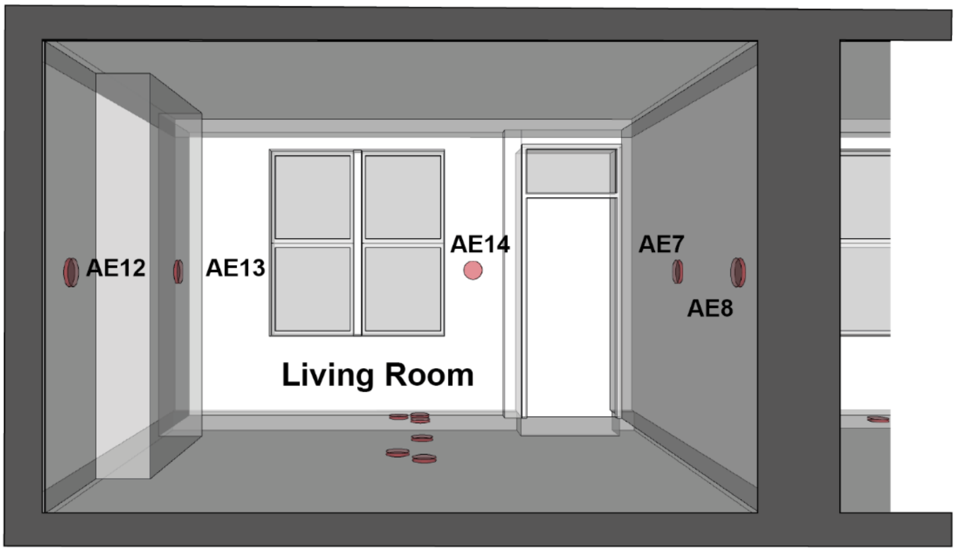
Table 2-1 HFP locations

HFP	Element	Room
G1	Party wall to 56NP	54NP Rear Room-in-roof
G2	Knee wall	54NP Rear Room-in-roof
G3	Sloped ceiling	54NP Rear Room-in-roof
G4	Party wall to 52NP	54NP Landing
G5	Flat ceiling	54NP Front Room-in-roof
J1	Party wall to 56NP	54NP Back Bedroom
J2	Rear external wall	54NP Back Bedroom
J3	Rear external wall	54NP Back Bedroom
J4	Party wall to 52NP	54NP Bathroom
J5	Party wall to 52NP	54NP Landing
I1	Dorma cheek	54NP Front Room-in-roof
I2	Dorma slope	54NP Front Room-in-roof
I3	Dorma flat ceiling	54NP Front Room-in-roof
I4	Dorma face	54NP Front Room-in-roof
I5	Party wall to 56NP	54NP Front Room-in-roof
AD1	Floor	54NP Living Room
AD2	Floor	54NP Living Room

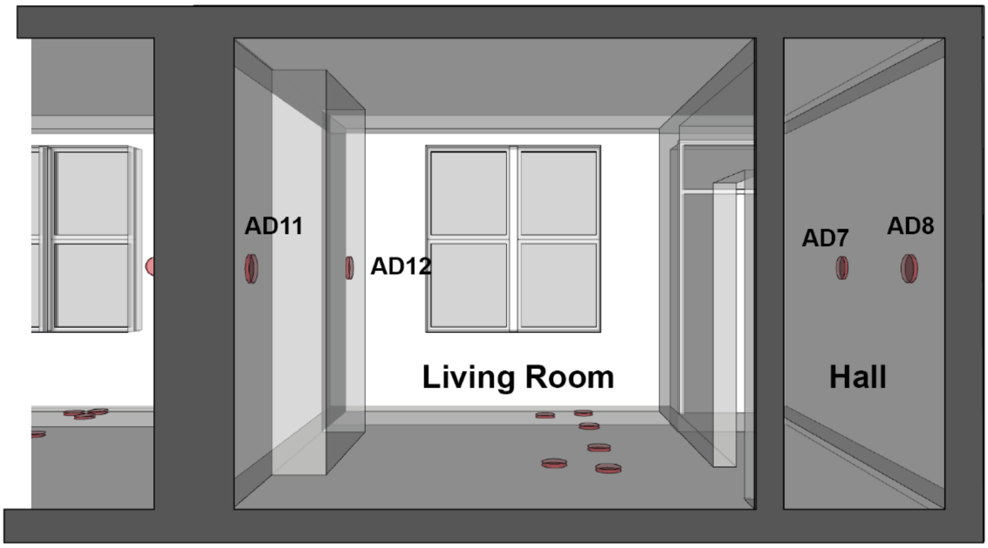
AD3	Floor	54NP Living Room
AD4	Floor	54NP Living Room
AD5	Floor joist	54NP Living Room
AD6	Floor joist	54NP Living Room
AD7	Party wall to 56NP	54NP Hall
AD8	Party wall to 56NP	54NP Hall
AD9	Party wall to 56NP	54NP Kitchen
AD10	Party wall to 52NP (chimney)	54NP Kitchen
AD11	Party wall to 52NP	54NP Living Room
AD12	Party wall to 52NP (chimney)	54NP Living Room
AD13	Party wall to 52NP (chimney)	54NP Front Bedroom
AD14	Party wall to 52NP	54NP Front Bedroom
AD15	Party wall to 56NP	54NP Front Bedroom
AD16	Party wall to 56NP	54NP Front Bedroom

HFP	Element	Room
AE1	Floor	52NP Living Room
AE2	Floor	52NP Living Room
AE3	Floor	52NP Living Room
AE4	Floor	52NP Living Room
AE5	Floor	52NP Living Room
AE6	Floor	52NP Living Room
AE7	Party wall to 54NP	52NP Living Room
AE8	Party wall to 54NP	52NP Living Room
AE9	Party wall to 54NP	52NP Hall
AE10	Rear external wall	52NP Kitchen
AE11	Party wall to 50NP (chimney)	52NP Kitchen
AE12	Party wall to 50NP	52NP Living Room
AE13	Party wall to 50NP (chimney)	52NP Living Room
AE14	Front external wall	52NP Living Room

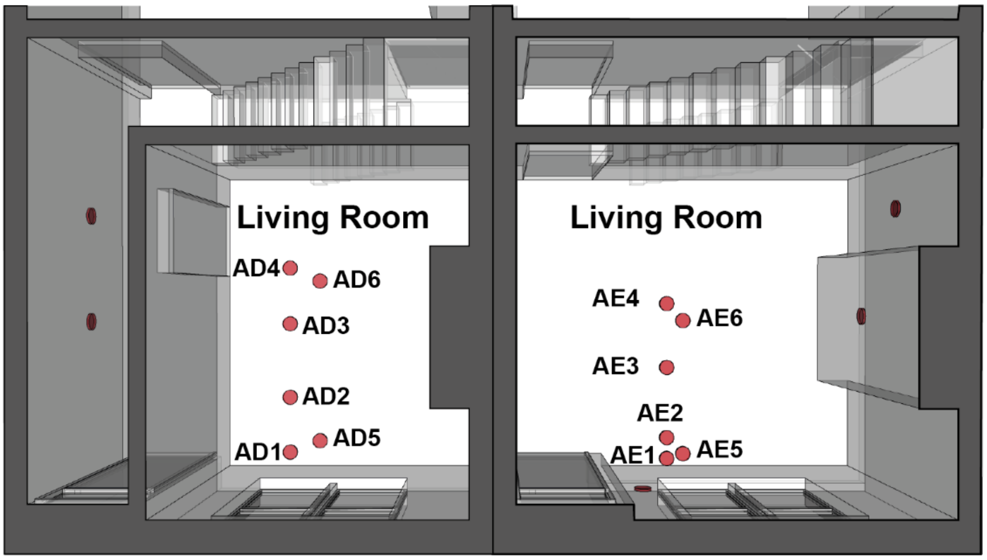
AE15	Party wall to 50NP	52NP Front Bedroom
AE16	Party wall to 54NP	52NP Front Bedroom
AF1	Knee wall	52NP Back Room-in-roof
AF2	Sloped ceiling	52NP Back Room-in-roof
AF3	Party wall to 50NP	52NP Back Room-in-roof
AF4	Party wall to 50NP	52NP Room-in-roof Landing
AF5	Party wall to 50NP	52NP Front Room-in-roof
AF6	Dorma cheek	52NP Front Room-in-roof
AF7	Dorma face	52NP Front Room-in-roof
AF8	Dorma sloped ceiling	52NP Front Room-in-roof
AF9	Dorma flat roof	52NP Front Room-in-roof
AF10	Flat ceiling	52NP Front Room-in-roof
AF11	Party wall to 54NP	52NP Front Room-in-roof
AF12	Party wall to 54NP	52NP Back Room-in-roof
AF13	Party wall to 50NP	52NP Bathroom
AF14	Party wall to 50NP	52NP First Floor landing
AF15	Party wall to 50NP (chimney)	52NP Front Bedroom
AF16	Party wall to 54NP	52NP Rear Bedroom


AE12
AE13
AE14
AE7
AE8
Living Room

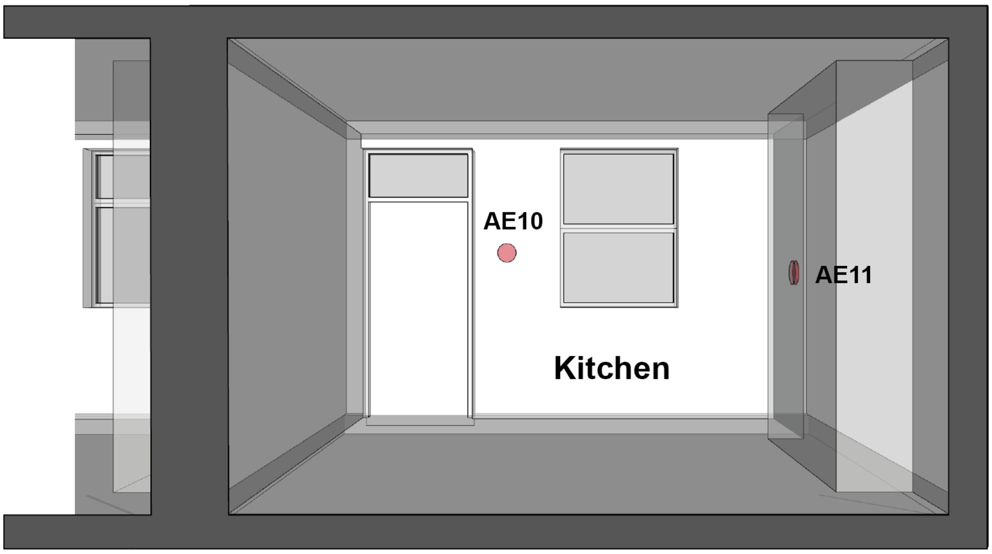
52NP


AD11
AD12
AD7
AD8
Living Room
Hall

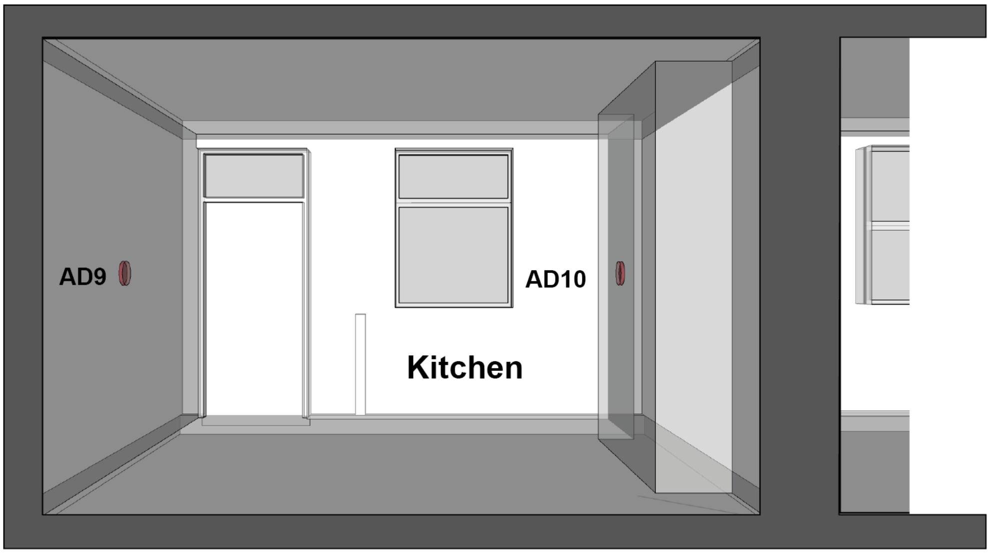
54NP



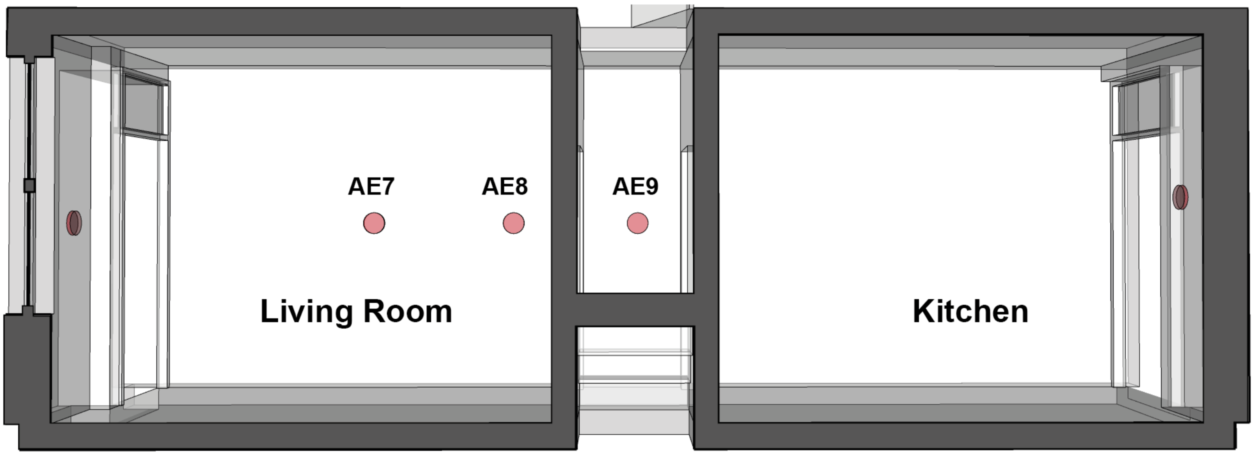
54NP 52NP



52NP



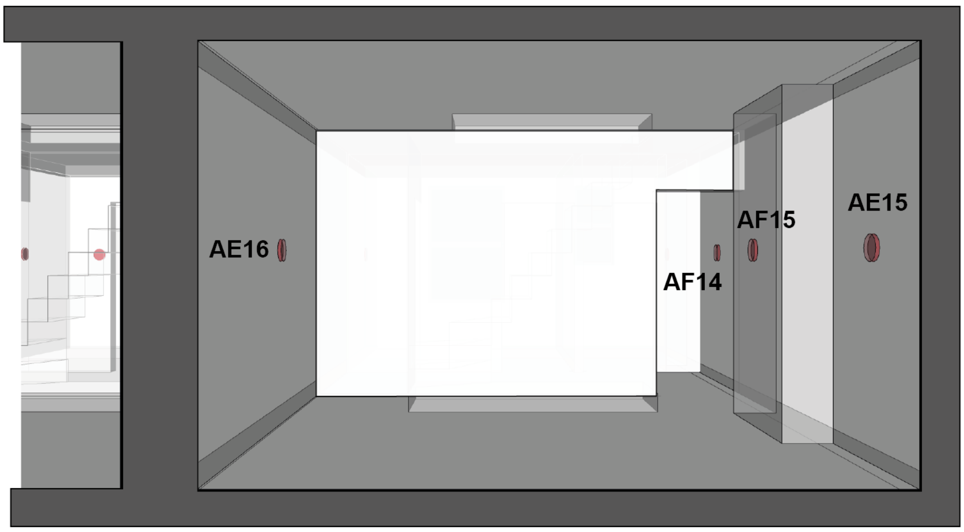
54NP



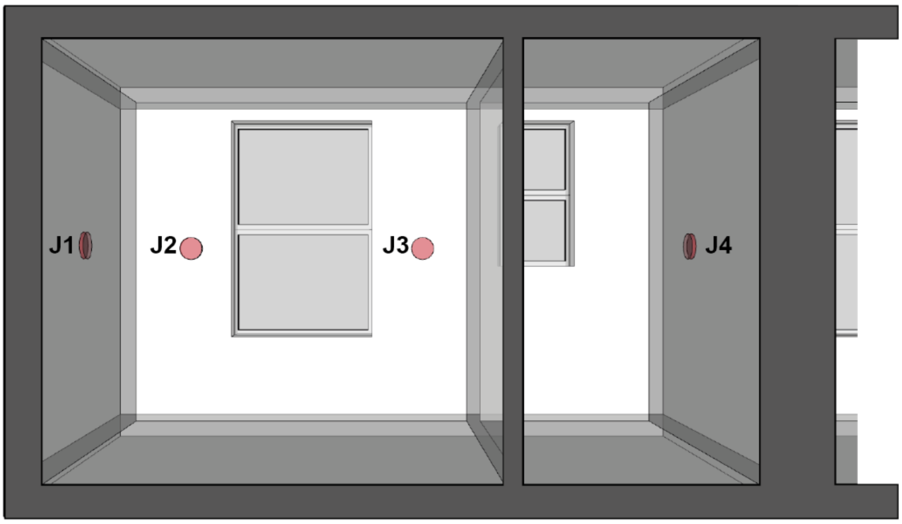
52NP

Figure 2-1 Ground floor HFP locations

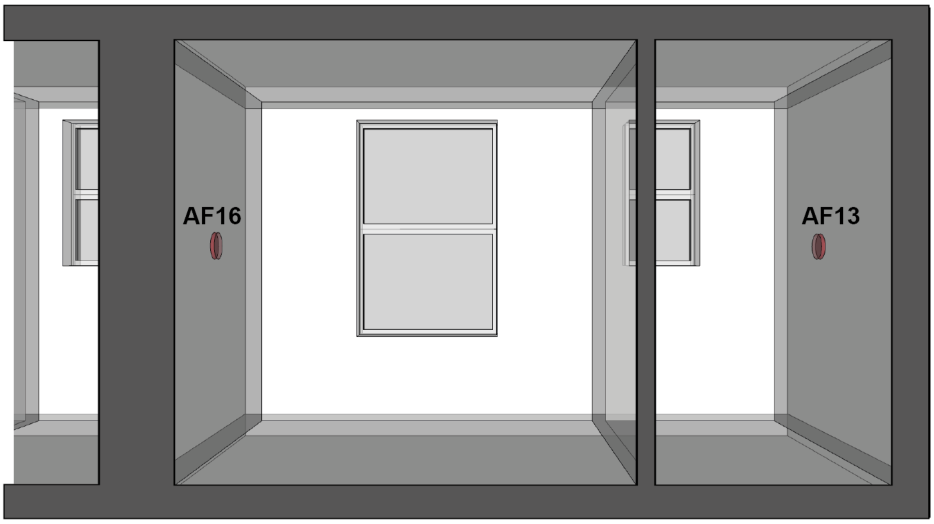
54NP



52NP

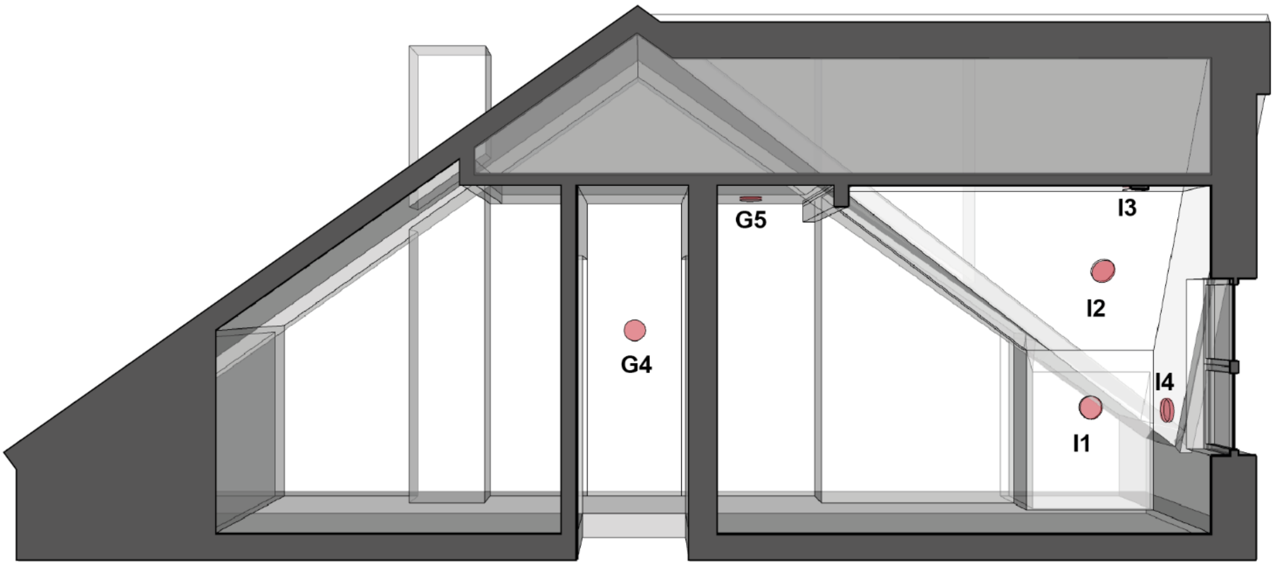


54NP

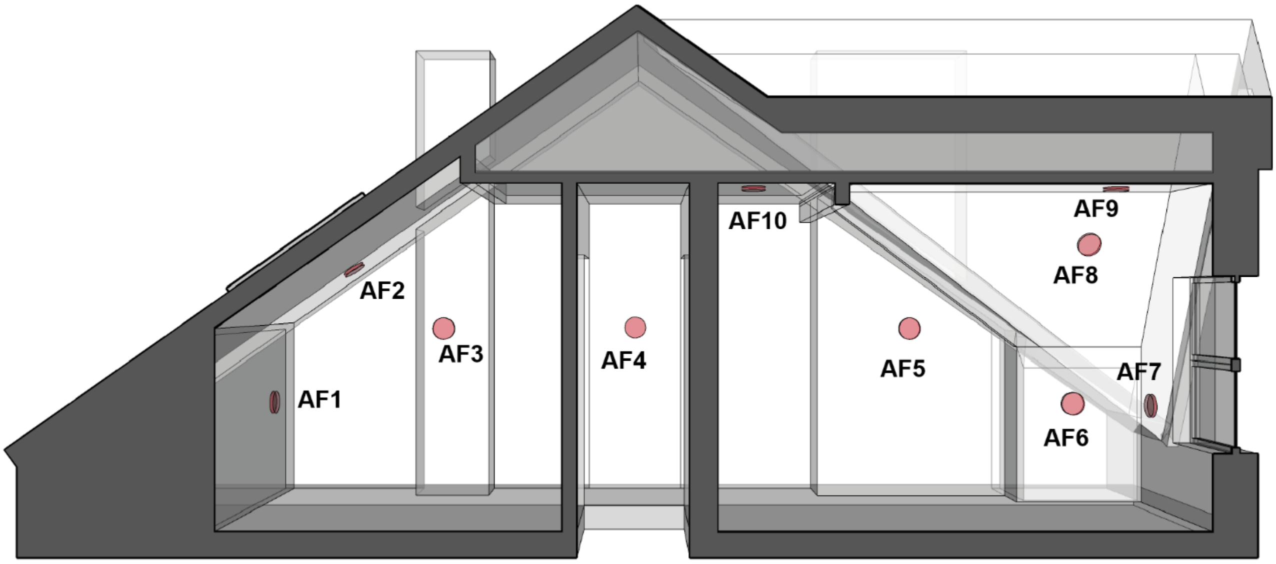


52NP

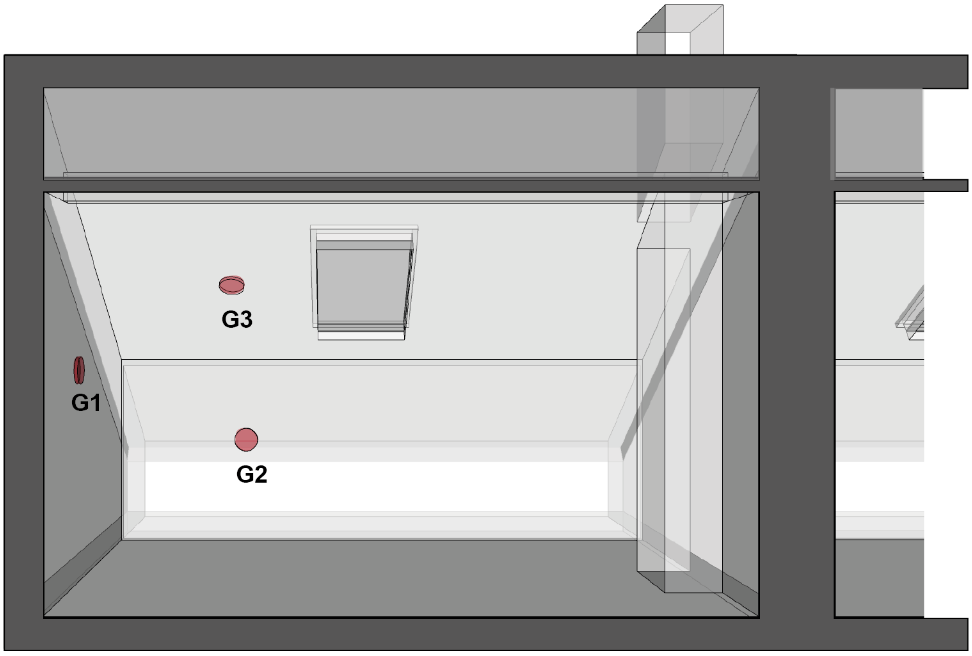
Figure 2-2 First floor HFP locations



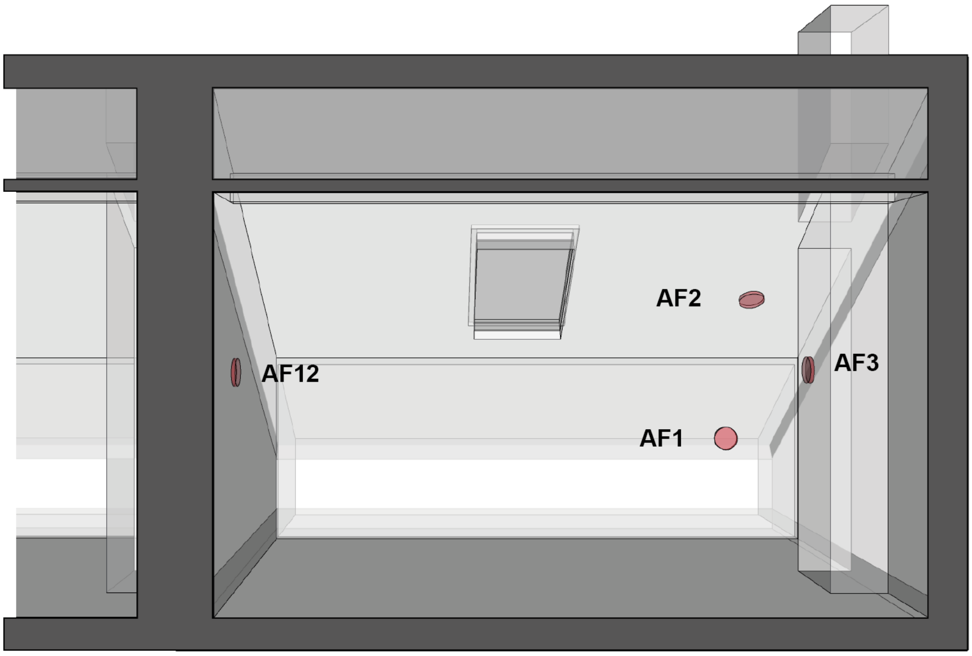
54NP



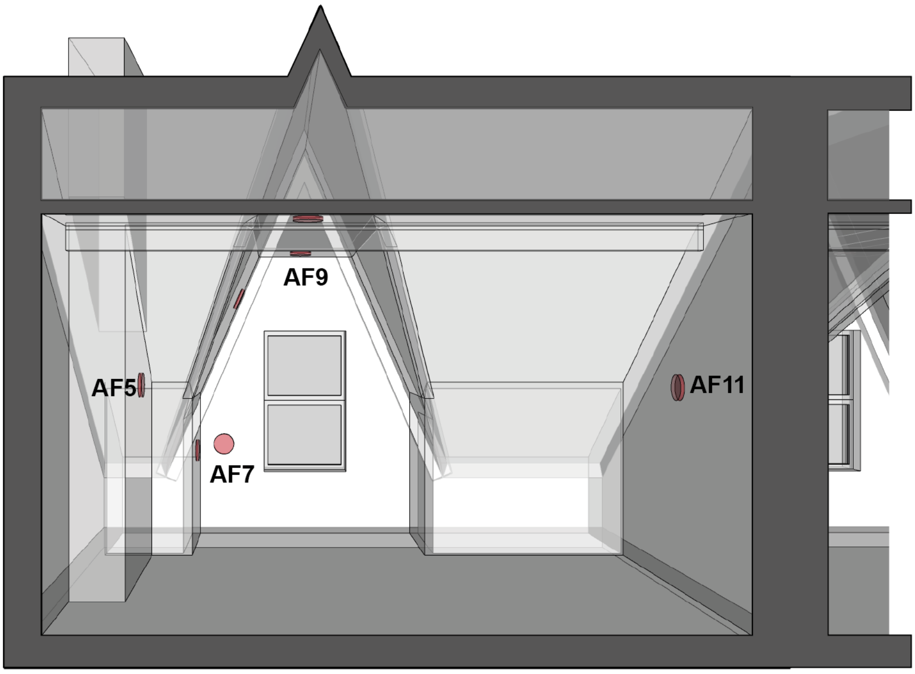
52NP



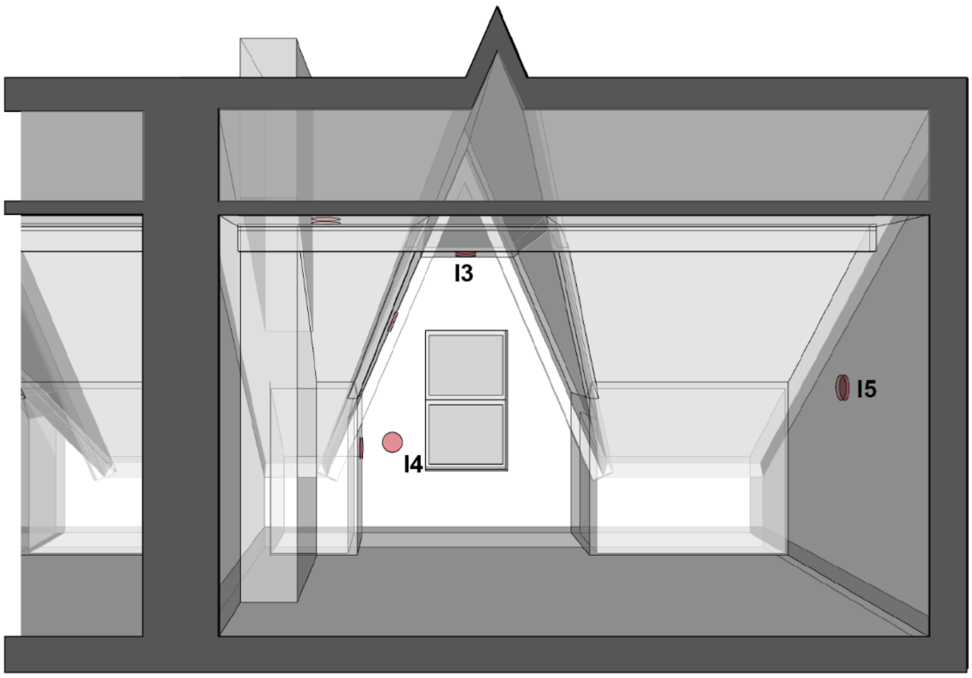
54NP



52NP



52NP



54NP

Figure 2-3 Room-in-roof HFP locations

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. However, 52NP presented a unique challenge, as the HFPs used in this property to measure the party wall and floor heat flux had a fault which led to an overestimation of heat flux. The amount of this overestimation was unknown, precluding any correction of data. This meant that a standard party wall correction could not be applied. Instead, an alternative approach was taken, as described below.

There are three party walls which could experience heat loss of interest to this study. These are 52NP-50NP, 52NP-54NP and 54NP-56NP. Both 52NP and 54NP where coheated to the same temperature and, barring any bypasses, no appreciable heat flux would be expected through this wall.

This was confirmed via the reliable HFPs on this party wall, and 52NP-54NP exchanges where therefore not considered. The 54NP-56NP party wall was measured with reliable HFPs and these data do suggest a small heat flow into 56NP. This would be expected due to the elevated and consistent temperatures of the coheating test.

The party wall heat loss through the 54NP-56NP wall was assumed to be representative and used to approximate the 52NP-50NP party wall heat loss. Because 52NP and 54NP share a similar construction and were heated to the same internal set point, this assumption is likely to hold, providing the neighbours' temperatures were relatively similar (e.g., if one neighbour was void and the other occupied, this assumption would not be valid).

To test this assumption thermal images were assessed for each party wall, which showed relatively similar temperatures and thus similar heat loss. Furthermore, analysis of the faulty HFP data was conducted. It was known that this faulty HFP data was an overestimate of the true values. Thus, analysis of these data gave an upper limit on the party wall heat loss for 52NP. For both retrofit stages, the heat losses were not excessive, and the measured heat loss to 56NP fell within the upper limit of the 52NP-50NP data. This suggests that both neighbours were heated to similar temperatures and the party walls behaved in similar manners. These values are shown in Table 2-2.

Table 2-2 Estimation of party wall heat losses

Retrofit stage	Overestimated 52NP-50NP party wall heat loss (W/K)	True 54NP-56NP party wall heat loss (W/K)
Baseline	42 ± 6	29 ± 13
Post-retrofit	26 ± 18	11 ± 22

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

Table 2-3 Modelling stages

Calibration step	Infiltration	U-values	Thermal bridging
1	Default[6]	Default[6]	Default[7]
2	Measured[8]	Default[6]	Default[7]
3	Measured[8]	Calculated[9]	Default[7]
4	Measured[8]	Measured[10]	Default[7]

Additionally, the models predict annual energy demand, annual heating cost, carbon dioxide emissions, SAP score and EPC band. The success of the retrofits against these criteria can therefore be evaluated and, along with the retrofit install costs, simple payback periods for each retrofit can be calculated. By learning about the variability of the models and how they compare to measured data in real cases, recommendations may be possible for improvements to both the models and the ways they are used. Improving understanding of modelling uncertainty may lead to more informed retrofit decision making at individual dwelling and national policy levels.

Case study method summary

A deep dive into the 52NP and 54NP retrofit case study was undertaken. This involved coheating tests, blower door tests, and 63 heat flux density measurements of fabric elements, taken before and after each of the floor and airtightness retrofits.

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

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

The findings from these case studies, therefore, can provide useful information on the impact of floor retrofits and reduced infiltration on heat loss, but data on the implication for indoor air quality needs a holistic understanding of the impacts of airtightness retrofits.

[6] Provided by Appendix S RdSAP 2012 version 9.94.
[7] Provided by Appendix K RdSAP 2012 version 9.94.
[8] Derived from blower door test.
[9] Derived from BRE calculator.
[10] Derived from HFP measurements.

3 Results

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

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

3.1 Airtightness improvements

The airtightness of the homes and improvement achieved by each retrofit are shown in Figure 3-1, indicating that a reduction of 41 % in infiltration rates was achieved.

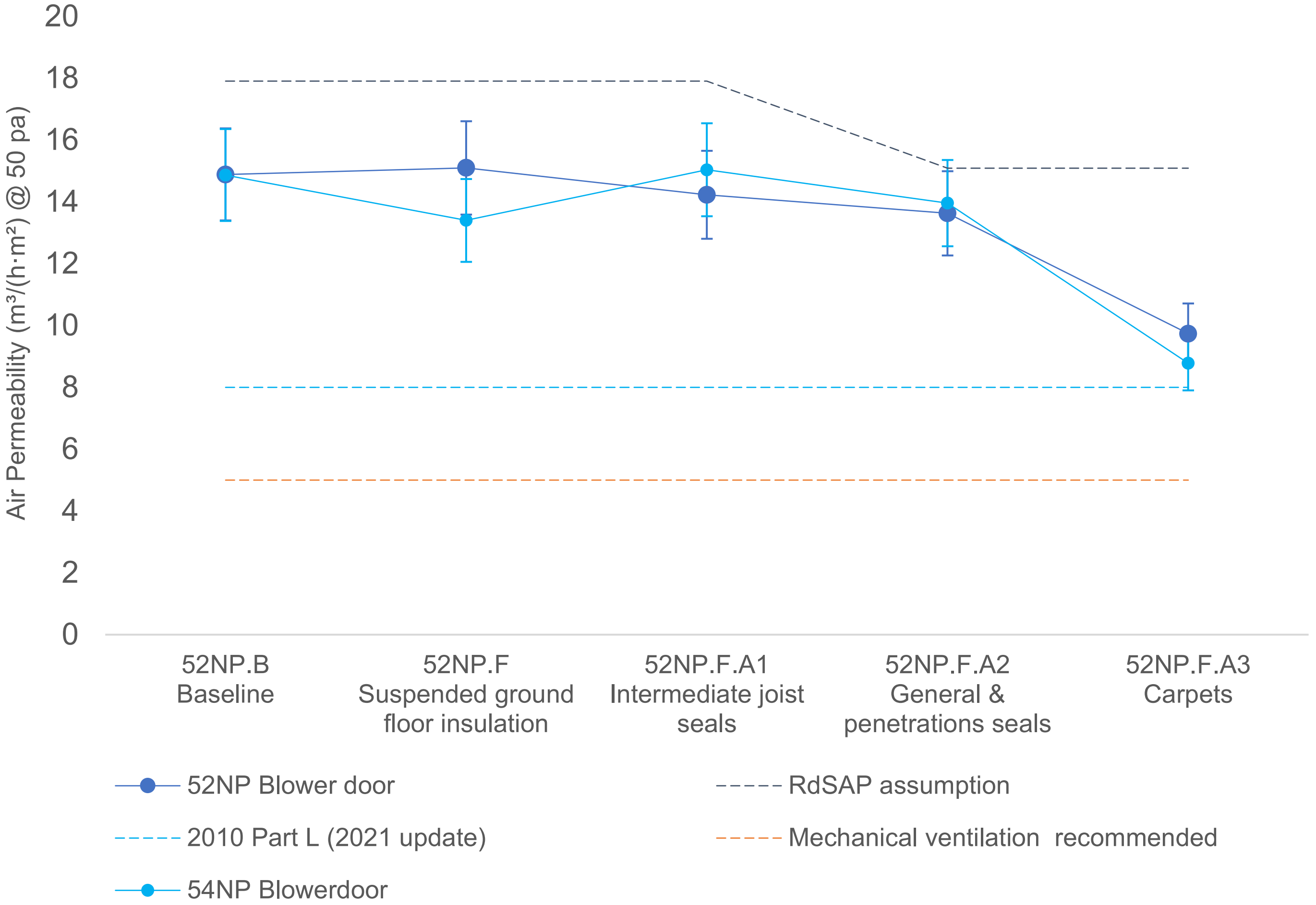


Figure 3-1 Infiltration rate of case study homes pre- and post-airtightness improvements[11]

[11] Note for the suspended floor insulation result that 52NP already had intermediate floor joists sealed

As shown, the specific airtightness measures had a marginal effect, except for installing carpets and new lino in the homes (the baseline home had no floor coverings). This finding has potential implications for airtightness tests performed in homes without floor coverings, as the results may not reflect lived-in infiltration rates. The results further show the potential benefits of floor finishes in reducing heat losses, a factor which should perhaps be recognised in energy models and as a standalone retrofit measure. Additionally, it is worth noting that the measured airtightness of the homes was very similar. Being neighbours with a similar retrofit history, this may have been expected, but it is useful to confirm that homes with similar characteristics can exhibit similar air leakage.

Although the airtightness of these homes was worse than required by new build standards, their performance was substantially better than assumed in RdSAP for these types of houses. If heat losses associated with air leakage are predicted to be higher than in reality, this results in a underprediction of energy efficiency, a lower resulting EPC score, and an overprediction of the benefits of retrofits, especially those associated with reducing infiltration.

3.1.1 Inter-dwelling air exchange

As these case study homes were adjacent properties, this afforded the opportunity to undertake pressurisation tests to quantify the extent of inter-dwelling air exchange taking place. The co-pressurisation test is relatively simple, involving a simultaneous blower door test on both homes. Since both homes are at the same pressure, inter-dwelling air exchange is minimised.

52NP and 54NP are terraced homes. This means there is one other neighbour for 52NP and one for 54NP where the pressure could not be controlled, and so some inter-dwelling air exchange may have occurred between these homes. However, by subtracting the individual pressurisation test results from the co-pressurisation test results, one can quantify the inter-dwelling air exchange associated with the party wall between 52NP and 54NP. The results of this test are shown in Figure 3-2.

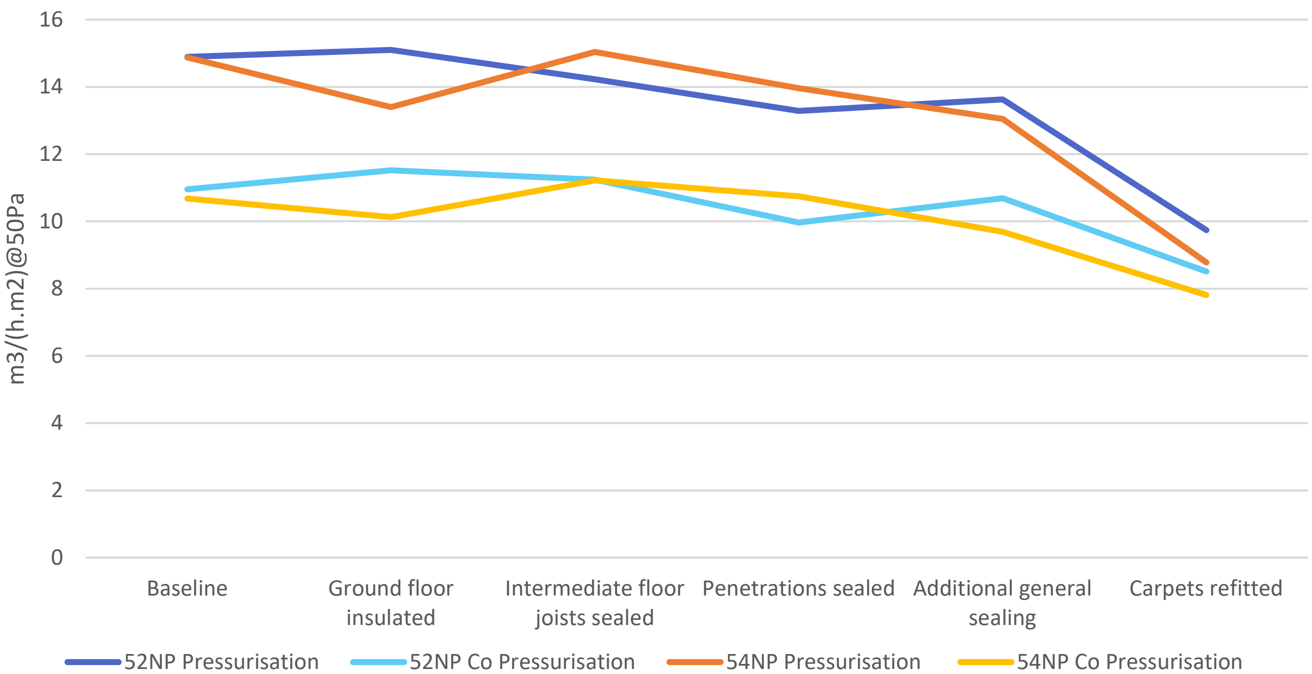


Figure 3-2 Comparison of pressurisation and co-pressurisation results identifying party wall inter-dwelling air exchange taking place during the blower door test

As shown, the results of the co-pressurisation tests are substantially lower, suggesting that air leakage pathways exist between adjoining homes. However, fitting carpets may have reduced inter-dwelling air movement. This suggests that intermediate floors and ground floor voids play an important role in any inter-dwelling air transfer.

The results also show that fitting carpets substantially reduced the whole house air leakage, since they impeded air movement into floor voids, which in turn reduced air movement through the associated leakage pathways to the outside.

The extent to which this has wider implications for occupants is outside the scope of the DEEP project. More research into solid party wall air exchange may be needed to understand the level of impact this has on heat loss, air quality, noise pollution and fire risk in the UK housing stock.

The extent to which inter-dwelling air exchange manifests during normal conditions is not fully understood. The measurements obtained in this case study were under induced high pressure (50pa) environments, which is not representative of normal conditions. Thus, it is not likely that the amount of inter-dwelling air exchange measured here would take place in a lived-in home. The findings are perhaps more significant for historic blower door tests in adjoining properties where measurements are taken under pressurised environments.

Furthermore, most floor coverings are not fixed, meaning it may be difficult to attribute longer term fuel bill savings to them. When tenancies change, the removal of carpets by social landlords as part of decent lettable standards, is relatively common. If doing so increases air leakage this has implications for new tenants. Additionally, blower door tests to inform new build homes are often performed without floor coverings in place.

These are mid-terrace properties, and the co-pressurisation tests only removed the drivers of air movement across one of the party walls. It is likely, however, that some degree of inter-dwelling air exchange took place. Anecdotal observations in the case studies identified that cooking smells from neighbours were noticeable during the tests, for example.

The findings could have implications for historic blower door tests in adjoining properties, with overestimated infiltration rates and ventilation heat loss rates due to the test pressures across party elements. This has implications if the data are used to provide compliance assurance, i.e., adjoined solid walled homes may have less internal to external air exchange than their airtightness test results suggest.

This may have several implications, for instance if homes do not receive enough fresh air, or if homes have lower heat losses linked to air leakage than previously thought. More research is needed to characterise inter-dwelling air exchange in various house types to understand the national importance of this discovery. It is possible that future guidance and technical standards on undertaking blower door tests may need to take account of this phenomenon via updated methodological protocols.

The coheating tests performed in these case studies identified the whole house heat losses of the baseline and fully retrofitted homes, i.e., after carpets were installed. Therefore, the savings identified are cumulative of both the floor insulation and the airtightness improvements, so cannot identify the impact of removing the inter-dwelling air pathway. However, the modelling undertaken at the homes provided an indication of the specific impact on HTC of each individual measure.

3.1.2 Impact of retrofits on airtightness

The order in which the retrofits were carried out was slightly different in each home. However, none of the retrofits (except the final installation of floor coverings) made a measurable difference to the airtightness of the homes since, in all cases, any change recorded was within the error of the test method.

Sealing intermediate floor joists
The aim of sealing the intermediate floor joists was to reduce inter-dwelling air exchange. This is a little-understood phenomenon, but findings from DEEP suggest that air leakage pathways exist between homes. Specifically, this may occur more in homes with solid party walls where there are joists that penetrate the party wall, many of which may not be sealed around.

In this case study, the attempt to seal the intermediate floor joists did not nullify this. This may be because intermediate floors are not usually plastered, and the mortar between bricks can deteriorate forming gaps, as shown in Figure 3-3. This means that a parge coat may be more effective at removing this inter-dwelling air exchange than sealing around joists alone. More research is needed to ascertain whether this approach would be effective in other homes with different sealing approaches. It may also be partly due to the works themselves being disruptive, removing and replacing floorboards, which may have worsened air movement into the intermediate floor void.

Figure 3-3 Mortar gaps and cracks in intermediate floor party wall brickwork

Figure 3-4 shows that, under depressurisation in 54NP, warmer air was drawn into the intermediate floor void from across the party wall.

Figure 3-4 Warm air from neighbouring dwelling entering 54NP via first floor intermediate floor (top) and second floor intermediate floor (bottom)

Ground floor insulation

Mineral wool floor insulation was installed from the basement, which avoided the need to remove the timber flooring. In other DEEP retrofits where floorboards were removed to install insulation, this resulted in boards being damaged and needing replacement. After the insulation was installed, a breathable membrane was installed under the insulation. However, this did not provide an effective air barrier since infiltration was still observed through the floor and perimeter post-retrofit. This confirms findings from other retrofits in DEEP that floor retrofits do not affect airtightness unless membranes are installed, with effective seals.

Sealing and draughtproofing of general penetrations

A common approach to reducing airtightness in homes is to undertake remedial sealing around penetrations, including fenestrations, to seal off air leakage where seals are non-existent or have deteriorated over time. The use of mastic to seal penetrations is widespread, however seals are known to fail over time as the mastic sets and shrinks. Indeed, penetrations may have no seals at all, as was observed for several penetrations in these case study homes, for instance the WC waste pipes shown in Figure 3-5.

Figure 3-5 Unsealed WC waste pipe (left) and boxed-in pipework requiring destructive investigation to facilitate sealing (right)

Accessing penetrations to undertake sealing is often problematic, as they tend to be located around kitchen and bathroom appliances that are boxed in, as shown in Figure 3-5. Where the penetrations are inaccessible or not visible, they can go unobserved or require substantial work to access, such as removing bath panels or kitchen units.

Other common leakage pathways that can be more easily sealed include around electrical services and penetrations. Despite sealing being performed on multiple penetrations in both homes, no measurable reduction in air leakage was observed.

Floor finishes

As stated, investigation found that these case study solid walled homes had more air leakage than current new build standards, which may affect the occupants' thermal comfort and air quality. However, the findings from this case study suggest that when the homes are carpeted or when new floor finishes are fitted, the lived-in air leakage for these types of homes is reduced.

The floor finishes achieved a significant reduction in infiltration in the home, reducing air exchange between the living space and ventilated floor void, or in the ventilated basements of these homes.

This is an important finding for the blower door testing industry, since blower door tests are routinely performed on homes before floor finishes are installed, due to construction scheduling. Therefore, if these blower door tests are used to achieve compliance, inform designs of ventilation systems, or inform EPCs, they may overestimate the amount of heat loss associated with air leakage and may need to be updated once the floor finishes are installed.

This finding also implies that carpets or floor finishes themselves may be a useful energy retrofit for homes with exposed, suspended timber floors. This has implications for decent housing standards in social rented properties, where carpets may be removed at the end of tenancies.

Fitting replacement floor coverings may be the responsibility of new tenants, and if this does not take place the home may have higher heat losses. This implies a conflict between letting standards and drives to reduce fuel poverty, i.e., landlords may be inadvertently reducing the energy efficiency of homes for tenants. It also raises the possibility of floor finishes being incorporated into broader domestic energy efficiency policy and standards.

Figure 3-6 52NP Living Room showing limited air infiltration through the ground floor with carpets (top), and greater infiltration after carpets were removed (bottom) during depressurisation

It is possible that the addition of a vapour-permeable air barrier to the suspended floor may have had the same impact on airtightness as the carpets and linoleum flooring. More research may be able to identify whether just installing an air barrier to the ground floor, therefore, has potential as an energy saving measure.

The coheating tests performed in these case studies identified the whole house heat losses of the baseline and fully retrofitted homes, i.e., after carpets were installed. Thus, the savings identified were achieved with both the floor insulation and the airtightness improvements, so the impact of removing the inter-dwelling air pathway cannot be identified uniquely.

While small savings may have been achieved by each of these approaches, they are too small to identify in a single or pair of homes. A larger sample would be needed to robustly measure the benefit of undertaking sealing. As an alternative, in DEEP, energy modelling has been undertaken for 52NP and 54NP to estimate the impact of each airtightness measure.

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

Low pressure Pulse tests were undertaken, though only 2 tests yielded valid results, perhaps due to the large building and complex air leakage pathways present in the home. This meant no conclusions could be drawn from the blower door comparisons.

CO_2 tracer gas decay analysis was undertaken during both coheating phases. Firstly, with the houses in the original condition but with carpets and the kitchen vinyl floor coverings removed, and secondly following the airtightness retrofits with carpets and vinyl floor coverings re-fitted.

In 52NP, the timed CO_2 releases during the first coheating phase showed a large discrepancy between the indicated ventilation rates on the ground and second floors. The ground floor ventilation rate was measured at 3.24 and 3.18 h^{-1}, while the second floor ventilation rate was 1.11 and 1.27 h^{-1}. During the second coheating phase, CO_2 decay analysis was performed following a period where the research team's presence in the house had raised the CO_2 concentration high enough above background levels. This showed a significant reduction in ventilation rates, to 0.69 h^{-1} on the ground floor and 0.45 h^{-1} on the second floor.

54NP showed similar results. Analysis of the decay following timed CO_2 releases during the first coheating phase showed a similarly large discrepancy between the indicated ventilation rates on the ground and second floors. The ground floor ventilation rate was measured at 3.64 and 3.80 h^{-1}, while the second floor ventilation rate was 1.27 and 1.41 h^{-1}. Unfortunately, none of the CO_2 decay periods in the second coheating phase were suitable for analysis.

Timed CO_2 release mechanisms were positioned on the ground floor. It is suspected that the size of the houses (each >250m^3), and the directions of the circulation fans inside (installed to create isothermal conditions for coheating) meant that the CO_2 decay rates on the ground floor included a degree of dispersal throughout the buildings, rather than being representative of the whole house ventilation rate. In both houses the time between maximum CO_2 concentration occurring on the ground floor and maximum concentration on the second floor was between 70 and 90 minutes, regardless of retrofit stage.

This shows the uncertainty around using CO_2 decay measurements in homes like 52NP and 54NP, via field trials with standard CO_2 decay test equipment, over short time periods. More research is needed to explore how useful tracer gas decay measurements can be in determining air infiltration rates when either longitudinal or using different test equipment or tracer gasses.

Airtightness improvement summary

The airtightness retrofit was successful in reducing the air leakage by around 40 % from over 15 $m^3/h·m^2$ to around 9 $m^3/h·m^2$, on a par with new home standards.

Most of this saving was achieved by installing carpets and lino flooring, while insulating the floor (from the basement), and sealing around service penetrations and joists in intermediate floor voids was ineffective.

Additionally, it was found that up to 15 % of the measured infiltration rate may be due to inter-dwelling air movement. The impact of this on the accuracy of blower door tests in adjoining dwellings, energy predictions used in models, and air quality needs further investigation.

3.2 U-value improvements

Three methods were adopted for deriving U-values:

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

All three are used in DEEP for comparison and this section reports on the differences between them. The report considers the implications of the methods for accuracy of energy and heat loss prediction and the contribution of fabric elements to HTC, as well as the predicted benefits achieved by retrofits.

3.2.1 Failure of heat flux density measurements

The heat flux density measurements in 52NP were compromised by a technical fault in the updated Datataker DT85. A ground loop was present, causing an additional unquantified current in the measurement devices, meaning these values cannot be relied on.

Thus, in some instances it was necessary to use the U-values derived from 54NP for both houses, where data were recorded with older models of the Datataker, DT80, which had no ground loop problems. Additionally, some of the 54NP data also suffered from ground loop problems, and where this occurred the calculated values were used.

A summary of the pre- and post-retrofit U-values for the suspended timber floor is presented in Table 3-1. The lack of measured heat flux data is a limitation in the case study, specifically around the ground floor heat losses after retrofit, but also for the calibration of energy model data inputs using measured U-values.

Table 3-1 RdSAP default, calculated and measured U-values (W/(m²·K))[12]

	Pre-retrofit			Post-retrofit		
	RdSAP default	Calculated	Measured	RdSAP default	Calculated	Measured
52NP						
Floor (Living Room)	0.50	0.59	n/a	0.16	0.17	n/a
Floor (Kitchen)	0.50	0.70	n/a	0.16	0.18	n/a
54NP						
Floor (Living Room)	0.50	0.57	n/a	0.16	0.17	n/a
Floor (Kitchen)	0.50	0.68	n/a	0.16	0.18	n/a
54NP (data also used for 52NP)						
Front external wall	0.32	0.35	0.36 ± 0.04	-	-	-
Rear external wall	0.32	0.35	0.35 ± 0.04	-	-	-
Knee wall (Room-in-roof rear bedroom)	0.59	0.44	0.30 ± 0.02	-	-	-
Knee wall (Room-in-roof front bedroom)	2.30	1.33	0.12 ± 0.01	-	-	-
Ceiling to eaves void	2.30	0.94	n/a	-	-	-
Loft	0.33	0.28	0.20 ± 0.02	-	-	-
Pitched roof	0.77	1.02	0.34 ± 0.01	-	-	-
Dormer sloped ceiling	0.77	1.02	0.36 ± 0.05	-	-	-
Dormer flat ceiling	0.50	0.54	1.00 ± 0.06	-	-	-

The reductions in U-values achieved for the suspended timber floor according to each approach to acquiring U-values were around 70 %, and are listed in Table 3-2. Again, there were no “measured” values as the heat flux data was subject to ground loop issues.

[12] n/a represents measurements that suffered from ground loop issues resulting in unreliable values

Table 3-2 also shows the potential performance gap and prediction gaps when using RdSAP that occur in the fabric retrofits. Since there are no reliable measured floor U-values, no performance gap can be calculated, so only the RdSAP prediction gap is shown. The RdSAP defaults prediction gap is the difference between the RdSAP default predicted reduction for post-retrofit U-values and the calculated predicted reduction.

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

Element	RdSAP default predicted reduction	Calculated predicted reduction	Measured reduction	RdSAP defaults prediction gap	"As-built" performance gap
Floor (Living Room)	0.34	0.42	n/a	-19%	n/a
Floor (Kitchen)	0.34	0.52	n/a	-35%	n/a

The table above shows that the RdSAP predictions made for reductions in U-values using the age-based default assumptions are slightly lower than would be expected for these particular homes. This could result in underprediction of EPC scores, CO2 emissions and fuel bill savings.

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

Table 3-5 shows what impact the improvement in U-values had on fabric heat loss. This considers the U-values, coupled with the relative size of heat loss area of each element, to illustrate the implications of using default RdSAP, calculated or measured U-value inputs.

- The heat losses for 52NP are very similar to 54NP, which is not surprising as they are neighbouring homes with assumed similar construction and geometries.
- The calculated heat losses for each fabric element are marginally smaller than those assumed by the RdSAP default U-values.
- The floor retrofit is predicted to reduce HTC_f by 11 W/K in RdSAP and 14 W/K according to the calculated U-values.
- The homes were already fitted with EWI, and so the relative importance of the remaining elements to HTC_f was greatly magnified. The uninsulated roof was the greatest area of heat loss, followed by the walls and windows.

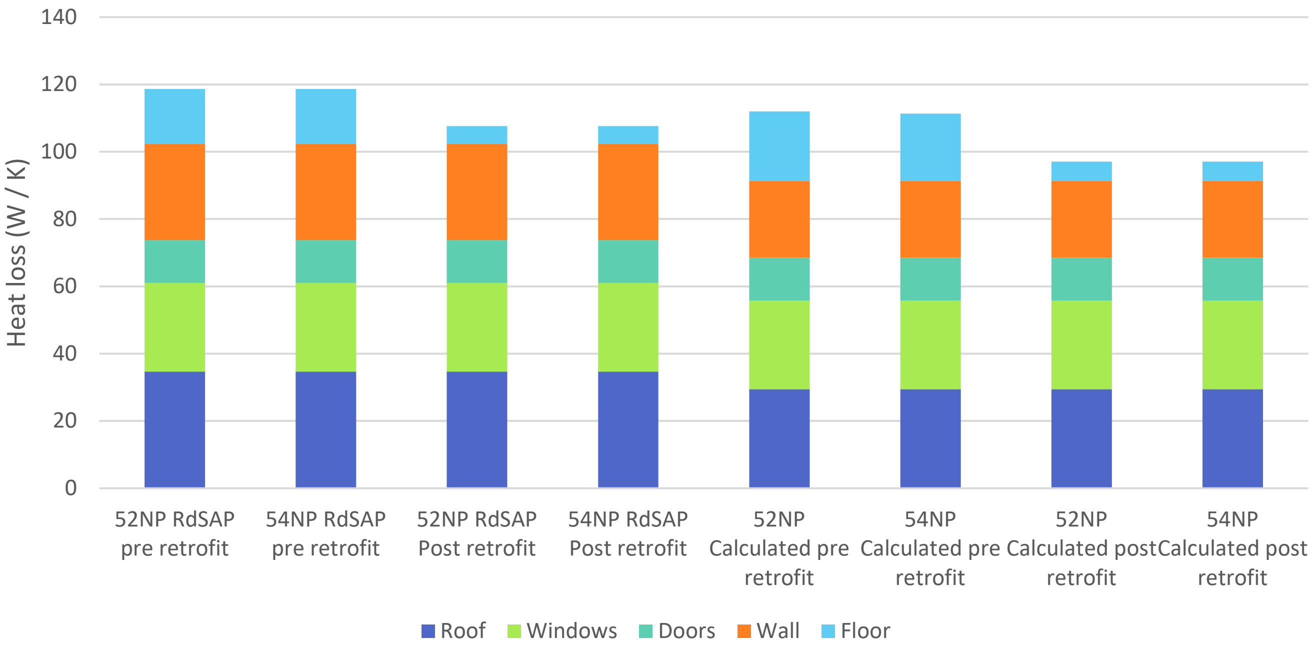


Figure 3-7 Heat loss of fabric elements pre- and post-retrofit, as recorded by heat flux density measurements

U-value improvement summary

The Datataker DT85 ground loop issues resulted in unreliable U-values being measured in 52NP, so 54NP data was used in its place.

This resulted in floor U-value measurements in both 52NP and 54NP being unreliable. Calculated floor U-values, however, showed an improvement of over 70 % post insulation.

Floors were a relatively small proportion of whole house heat loss, while the uninsulated roof and old double glazing were responsible for over 50 % of HTC_f. Despite this, the floor retrofit was assessed as being responsible for an 8 % to 13 % reduction in HTC_f.

3.3 Whole house heat loss (HTC) improvement

As shown in Figure 3-8, there is a similarity in the measured baseline HTC for each house. This is not surprising since they are neighbouring properties with similar dimensions and building characteristics, and both have previously undergone an EWI retrofit and have new glazing. Indeed, the slight difference apparent in the HTC of each home is not statistically significant.

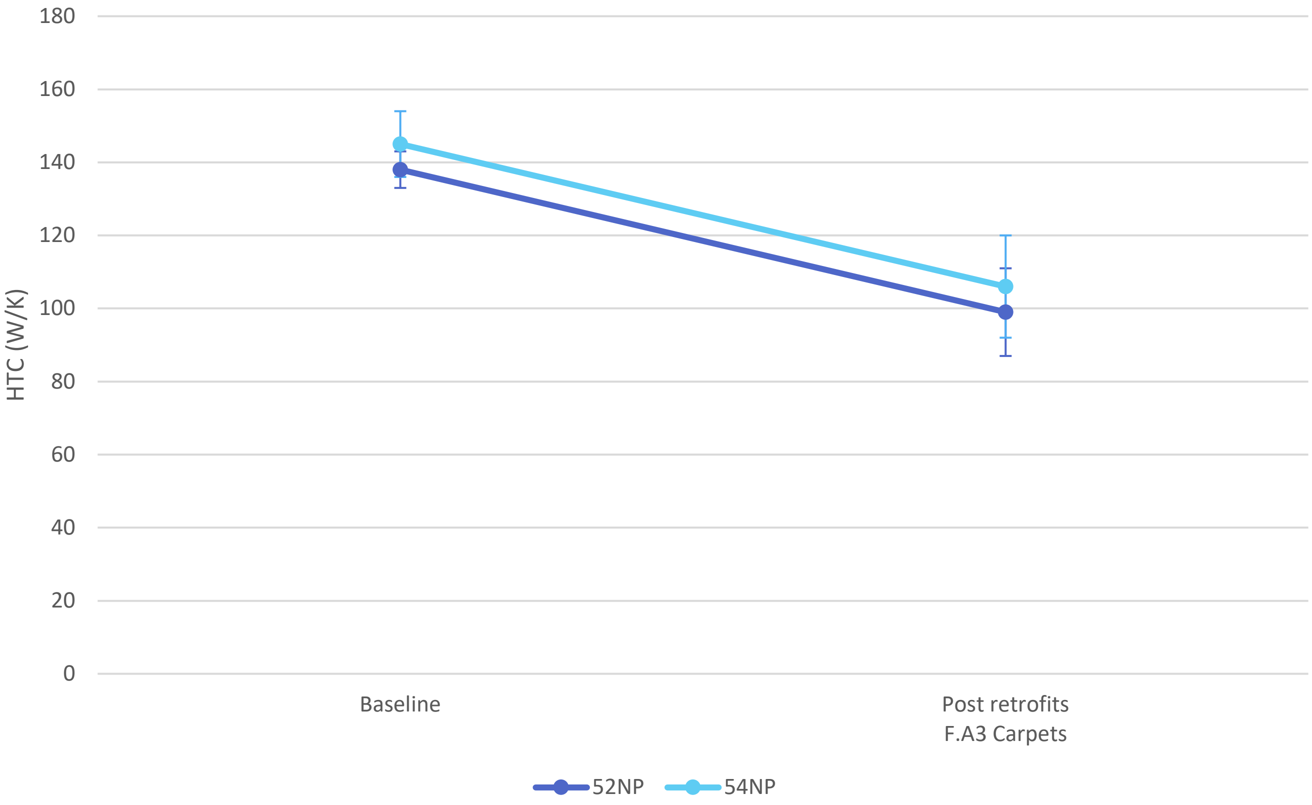


Figure 3-8 Coheating HTC at each retrofit stage

The total measured heat loss for the dwelling at each stage is shown in Table 3-3 and Table 3-4. As shown, the retrofits appear to have a similar impact on HTC, both reducing the overall HTC by the same absolute value, (39 ± 31) W/K for 52NP and (39 ± 17) W/K for 54NP.

Since the previous section identifies that the floor retrofits were likely to only be responsible for a reduction of (11 – 14) W/K, this overall saving indicates that the reduction in heat loss attributable to the reduction in infiltration was relatively substantial.

Table 3-3 52NP HTC after each retrofit stage

Retrofit stage	HTC (W/K)	HTC uncertainty	HTC reduction (W/K)	Percentage reduction
52NP.B Baseline	138 ± 14	10 %	n/a	n/a
52NP.FA3 Floor insulation and all airtightness improvements	99 ± 27	27 %	39 ± 31	(28 ± 22) %

Table 3-4 54NP HTC after each retrofit stage

Retrofit stage	HTC (W/K)	HTC uncertainty	HTC reduction (W/K)	Percentage reduction
54NP.B Baseline	145 ± 9	6 %	n/a	n/a
54NP.FA3 Floor insulation and all airtightness improvements	106 ± 14	13 %	39 ± 17	(27 ± 12) %

3.3.1 Infiltration heat loss (HTC_v) compared to ground floor heat loss reduction

This section explores how air leakage reductions relate to reductions in whole house HTC based on Equation 1.

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

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

According to this method, the 41 % reduction in infiltration rate achieved by the retrofit in each home may have reduced the HTC saving by around 22 W/K. If this is the case, it would make the airtightness retrofit responsible for just over half the HTC reduction overall, with the rest being a result of the floor retrofit.

However, since there was only a single post-retrofit coheating test to capture the cumulative benefit of the retrofits, this cannot be corroborated by measured values. What is clear, however, is that almost all the air leakage savings came from the installation of the carpets.

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

3.3.2 QUB and coheating test HTC results

An alternative method of measuring the HTC, QUB, as described in the methods chapter of DEEP 2.0, was undertaken in the homes at various retrofit stages to compare against the coheating test. In total, 21 QUB tests were performed on both 52NP (10) and 54NP (11). This was done to investigate the reliability and accuracy of the QUB test. The tests were completed in December 2020 (baseline), February 2021 (airtightness stage 1 and floor Insulation), March 2021 (airtightness stage 2) and April 2021 (airtightness stage 3).

Of the 21 tests completed, 4 were discounted based on the test α value (a ratio of power input, temperature difference and HTC of the property) being outside recommended limits. The results of the remaining 17 tests are shown in Figure 3-9, compared against the upper and lower uncertainty limits of the measured coheating HTC (with no adjustments made for party wall losses) which are represented by grey dashes for the two retrofit stages where these were completed. Despite the homes being mid-terrace, no heat flux density measurements were taken throughout the QUB tests, so comparison against HTC adjusted for party wall losses cannot be made.

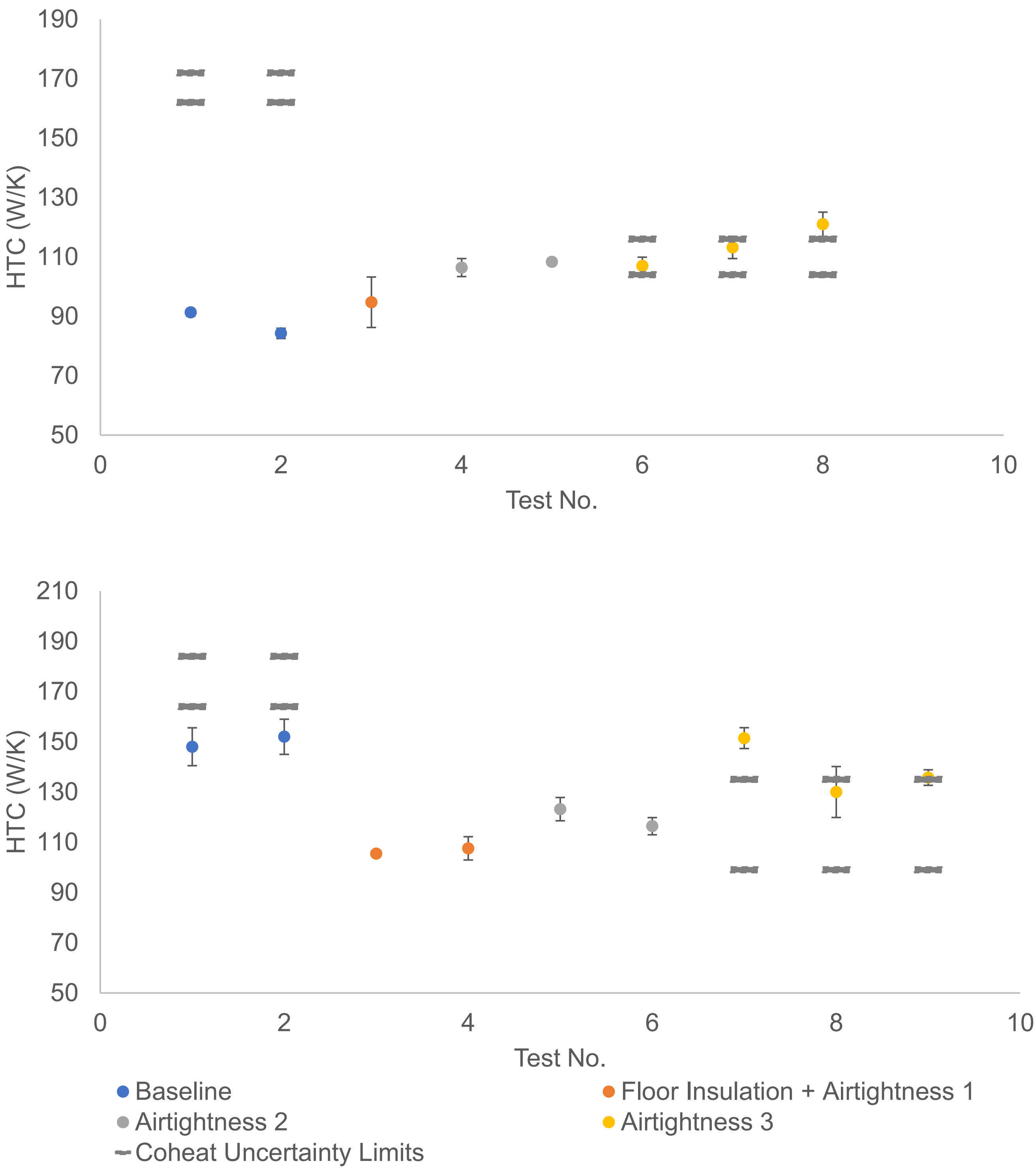


Figure 3-9 Individual QUB HTC measurements against coheating, 52NP (top) and 54NP (bottom)

For either house, the trend of the QUB measurements does not follow the expected correlation of HTC lowering and performance improving with the iterative retrofits. The two measurements are most aligned for the final retrofit stage, with differences of 1 % (52NP) and 14 % (54NP) between the coheating and average QUB measurements. The largest difference observed is for the baseline stage of 52NP, where the average QUB measurement is 47 % less than the coheating measurement. There is no indication in the test data that these tests would not be reliable. The results relative to the mean measurement for each retrofit stage range from 2 % to 16 %.

The cause of the discrepancy between the two measurements is not determined. Possible reasons for the differences could be differing heat flow patterns through elements that do not face the external environment, such as party walls and basements, for the two measurement procedures. Heat flows to such spaces contribute to the HTC, but the temperatures in these spaces and the associated heat flux densities were not monitored throughout the QUB tests so cannot be analysed in detail.

Additionally, the larger temperature difference present in the coheating test may have resulted in larger infiltration losses. The dispersion of individual measurements could be attributed to varying boundary and environmental conditions such as wind speed, internal/external temperature difference, and solar radiation incident during the day prior to the QUB test. These variables can impact heat transfer in the property through varying infiltration rates and solar contributions stored within the fabric.

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

Whole house heat loss improvement summary

This section shows that the HTC of the building was reduced substantially by the retrofits, by around (28 ± 22) % in 52NP and (27 ± 12) % in 54NP.

The airtightness retrofit is estimated to have been responsible for over half the HTC reduction according to the n/20 method, with almost all this saving coming from fitting carpets and lino on the bare floorboards in the homes. Only marginal HTC reductions were achieved by the other activities to improve airtightness.

More investigation is required to explore the benefits of floor insulation as a retrofit for HTC reduction, as well as broader benefits linked to thermal comfort. Additionally, more information is required to understand the issues of reducing infiltration rates in homes on internal air quality, moisture management, and damp in homes.

The QUB method was able to approximate similar HTC values as the coheating test following completion of the retrofits. Large differences between the measurements were observed for the baseline tests, and more investigation is needed as to why this was the case.

3.4 Measured vs. modelled retrofit performance

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

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

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

HTC_b (non-repeating thermal bridging heat losses), calculated by modelling each junction in thermal bridging software; though it is erroneously often assumed to be the remainder once HTC_v and HTC_f are subtracted from the whole house measured HTC.

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

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

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

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

3.4.1 Measured HTC: Aggregated vs. disaggregated approaches

The measured aggregate HTC from the coheating test and the disaggregated HTC calculated from summing HTC_v, HTC_f and HTC_b are presented in Figure 3-10. Comparing these two approaches to derive the whole house HTC is often termed *closing-the-loop* analysis. It is useful in both exploring where heat losses occur and as a reference point for the whole house HTC measured by the coheating test. HTC_f is derived by multiplying the area (m²) of each fabric element by its U-value (W/(m²·K)) and summing these individual elements. HTC_v is calculated from Equation 1, and the HTC_b shown is estimated in the RdSAP model for the houses.

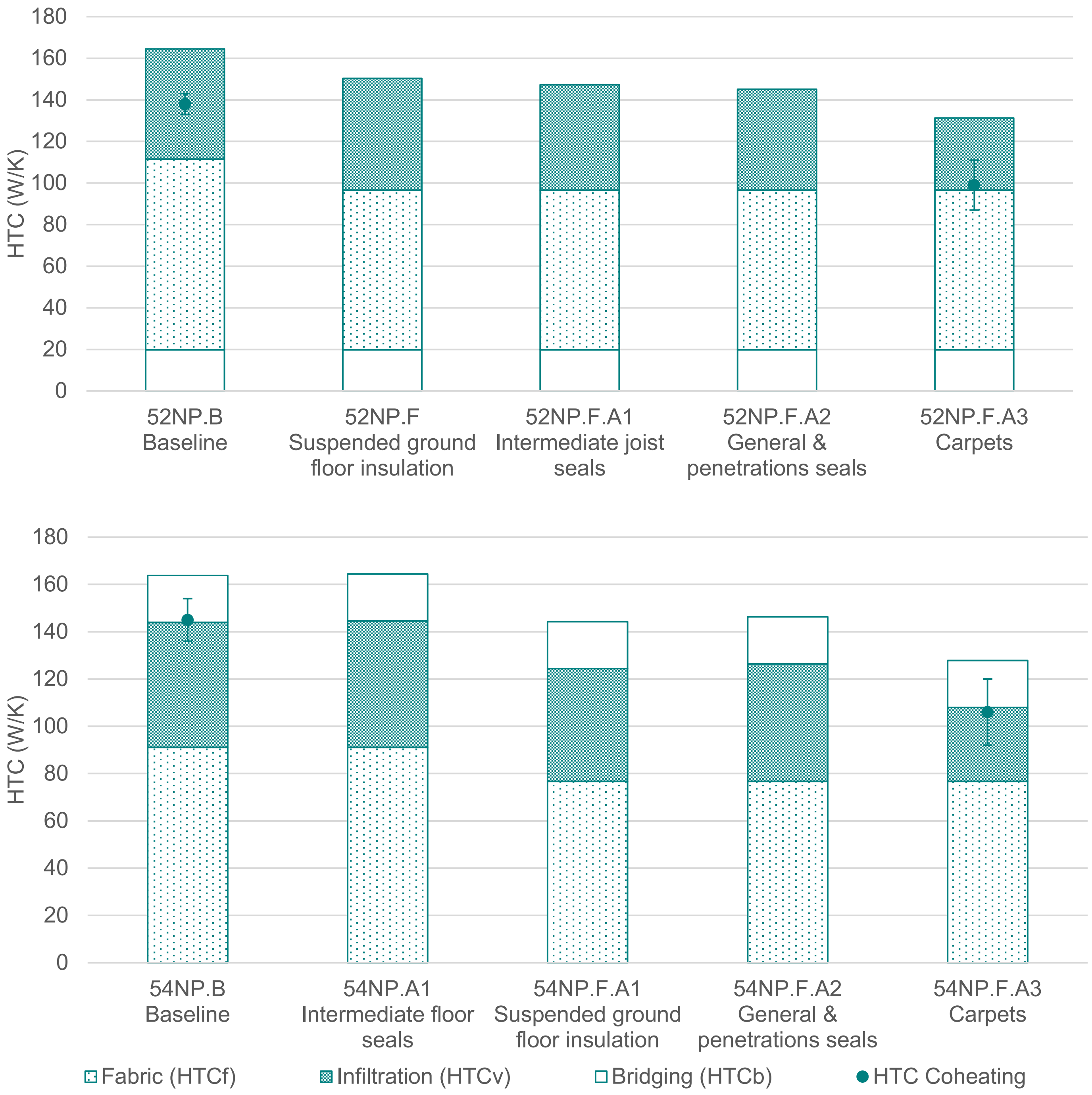


Figure 3-10 52NP (top) and 54NP (bottom) coheating vs. disaggregated measured HTC

The HTC measured by the coheating test is shown to be similar to the sum of HTC_f, HTC_v and HTC_b, though it is outside the uncertainty limits of the coheating test because:

- Assumed thermal bridging in the RdSAP model may not be representative.
- The n/20 method of deriving HTC_v may not be appropriate for these house types.
- The U-value measurements were incomplete so calculated U-values had to be used.
- The U-values that were successful may still not capture the heterogeneity of heat flow through different fabric elements.

However, the relative change in HTC because of the cumulative retrofits is similar according to both methods; around 39 % for both the coheating measurement and the disaggregated approach. Of this reduction, the disaggregated analysis suggests that the floor retrofit produced around 14 W/K savings, while installing carpets achieved a 22 W/K reduction. Therefore around 60 % of the saving was due to carpets.

Table 3-5 52NP Whole house heat loss via disaggregated methods

Retrofit stage	HTC_f W/K	HTC_v W/K	HTC_b W/K
54NP.B Baseline	92 (56%)	53 (32%)	20 (12%)
54NP.A1 Intermediate floor seals	77 (51%)	54 (36%)	20 (13%)
54NP.F.A1 Suspended ground floor insulation	77 (52%)	51 (34%)	20 (13%)
54NP.F.A2 General and penetrations seals	77 (53%)	48 (33%)	20 (14%)
54NP.F.A3 Carpets	77 (58%)	35 (26%)	20 (15%)

Table 3-6 54NP Whole house heat loss via disaggregated methods

Retrofit stage	HTC_f W/K	HTC_v W/K	HTC_b W/K
54NP.B Baseline	92 (56%)	53 (32%)	20 (12%)
54NP.A1 Intermediate floor seals	92 (55%)	53 (33%)	20 (12%)
54NP.F.A1 Suspended ground floor insulation	77 (53%)	48 (33%)	20 (14%)
54NP.F.A2 General and penetrations seals	77 (52%)	50 (34%)	20 (14%)
54NP.F.A3 Carpets	77 (60%)	31 (24%)	20 (16%)

These findings suggest that when solid walls are insulated, the heat loss from ventilation and bridging becomes relatively more important. For instance, air leakage was estimated to be responsible for around a third of whole house heat loss in the baseline home.

The study also suggests that installing carpets reduced the contribution of air leakage to the whole house heat loss to around a quarter. This is a sizable reduction, and it is worth investigating the potential impact of carpets on HTC_v estimates and the representativeness of airtightness tests. The timing of when these are undertaken in the home's lifecycle also warrants further investigation, i.e. lived-in airtightness (with carpets) may be substantially higher than at the construction stage (without carpets).

The next section discusses how modelling software can estimate the HTC reductions from each retrofit, and how their predictions can be improved via calibration.

3.4.2 Measured vs. modelled HTC calibration step 1

The measured HTC values for each retrofit stage are plotted against the HTC values predicted by the uncalibrated models using default RdSAP input data in Figure 3-11.

- Predicted HTCs from all models overestimate HTC since the default inputs assume higher U-values for the room-in-roof than were measured.
- There is an option for EPC assessors to use a simplified method to account for room-in-roof heat losses in RdSAP and this causes the difference between the BREDEM and RdSAP models.
- DSM predicts lower HTCs due to the dynamic addition of useful internal gains.
- The predicted HTCs for 52NP and 54NP are very similar.
- There is no predicted reduction in HTC following any airtightness retrofit in any of the models since RdSAP infiltration is fixed and based on assumed values, so does not capture the benefits of reducing air leakage in homes.
- A small reduction is observed for the floor retrofit in all the models.

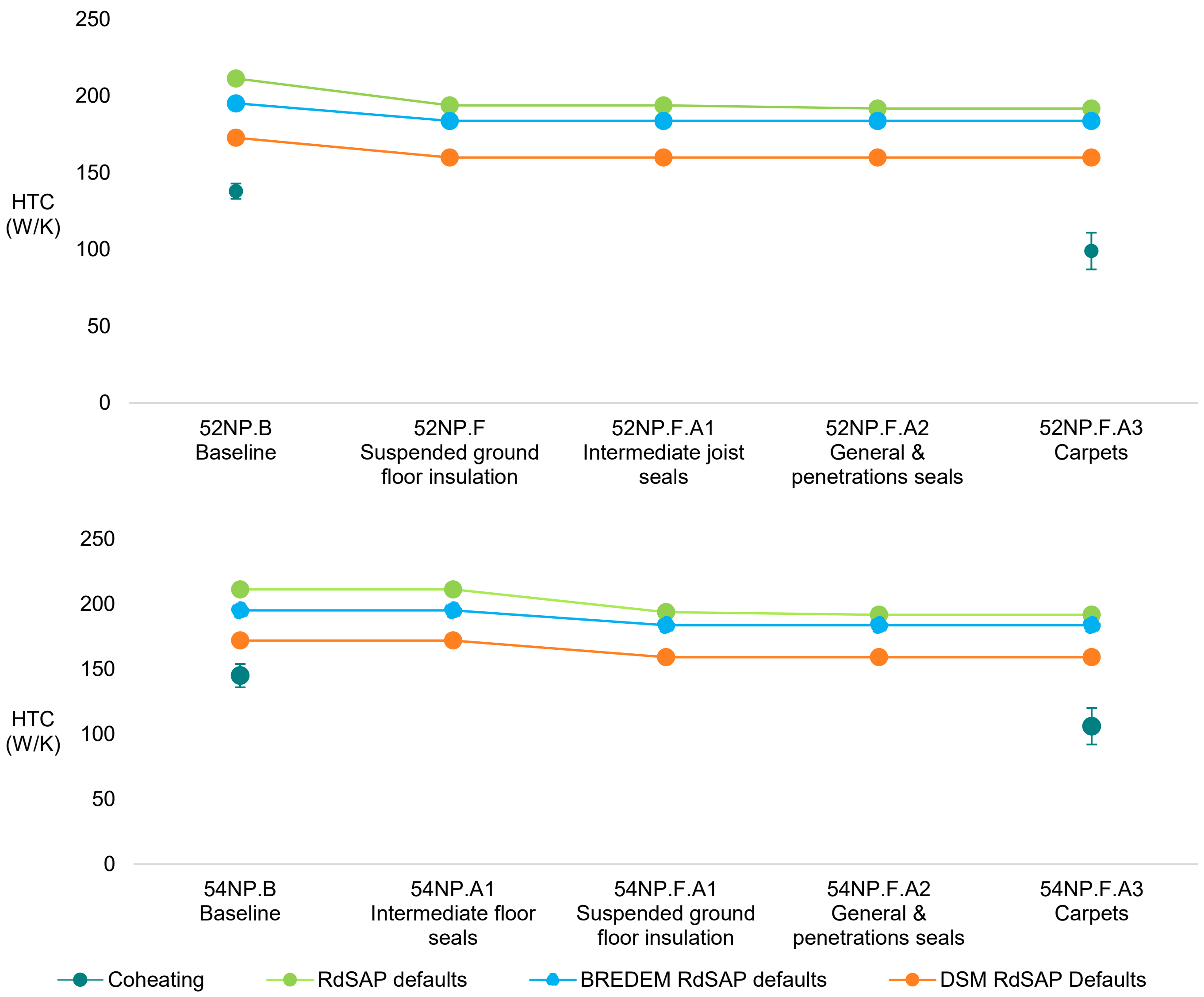


Figure 3-11 52NP (top) and 54NP (bottom) measured vs. modelled HTC calibration step 1: Default data

3.4.3 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 shown in Figure 3-12.

- Including the measured airtightness results brings HTCs closer to the measured value.
- The benefits of reduced air leakage achieved by the carpets can be observed, though the combined airtightness and floor retrofit is less than that measured by the coheating test.
- RdSAP is not included in this calibration step as infiltration cannot be altered in software.

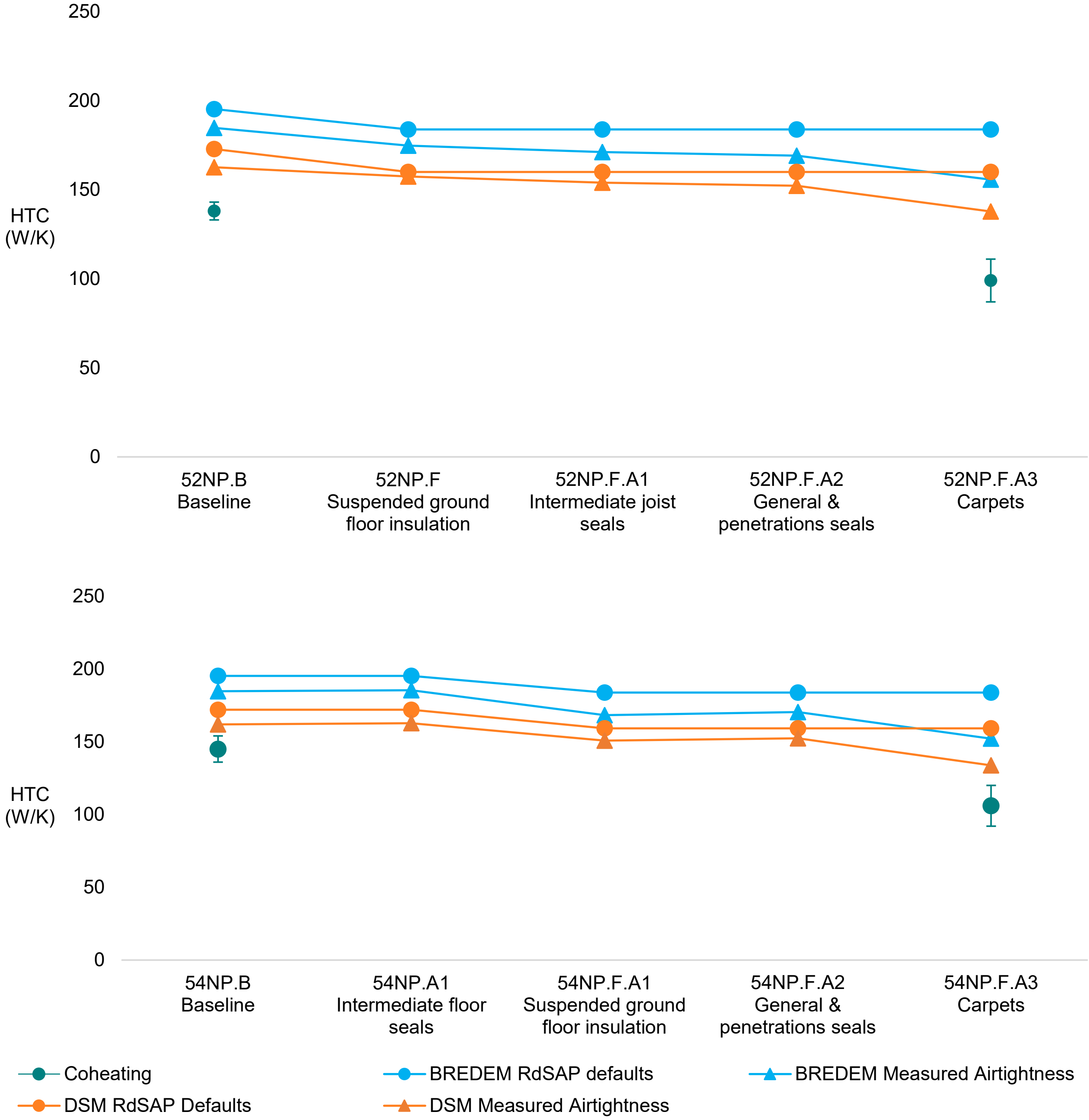


Figure 3-12 52NP (top) and 54NP (bottom) measured vs. modelled HTC calibration step 2: Measured infiltration

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

In this step, the models include U-values defined using the BRE calculator, as shown in Figure 3-13.

- Using calculated U-values further reduces the gap between modelled and measured HTC.
- The change in HTC is small, as there is less variability in the U-values of insulated solid walls, so the calculated values are similar to the default assumptions in RdSAP.
- RdSAP is not included in this calibration step as infiltration cannot be altered in software.

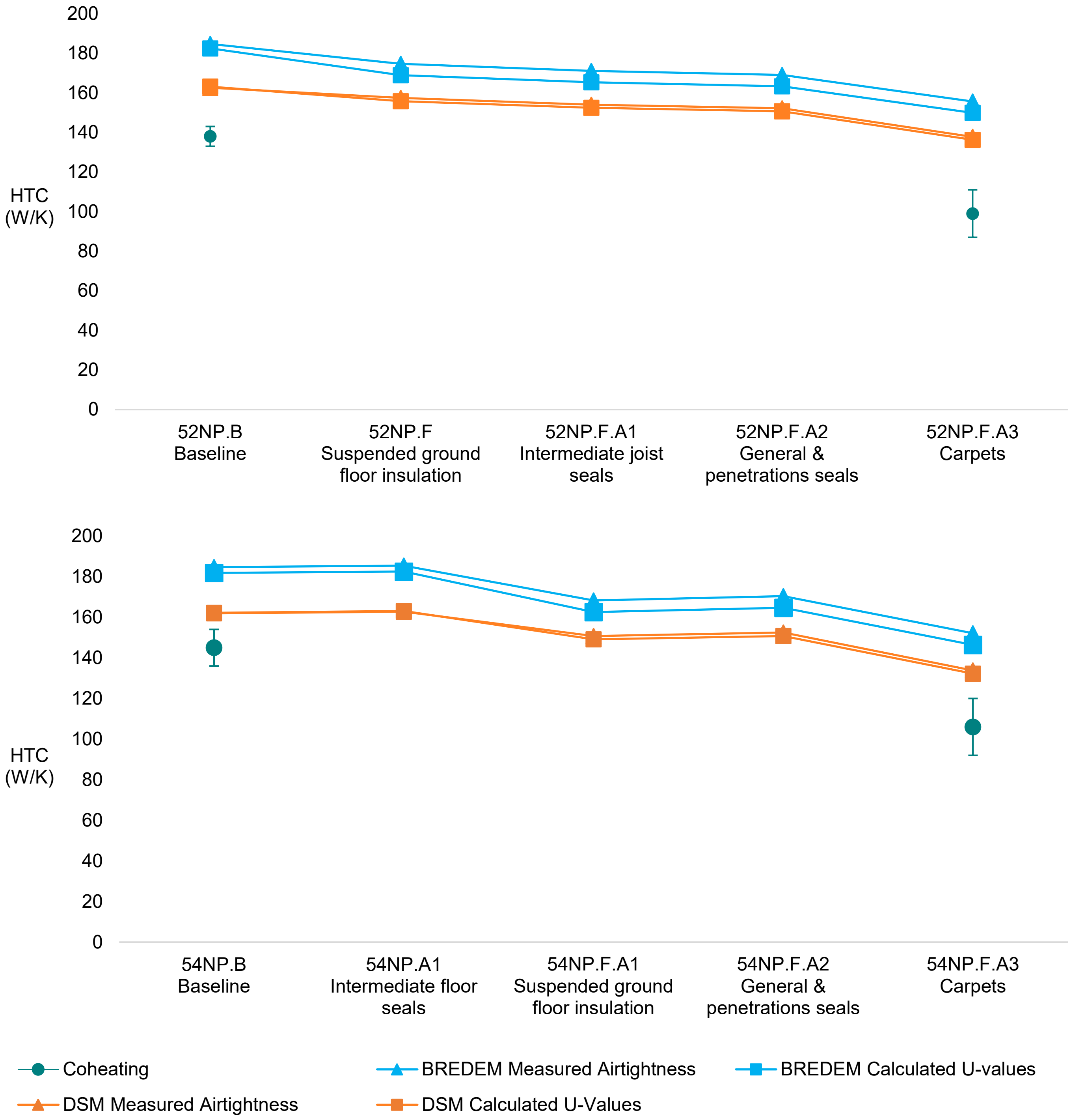


Figure 3-13 52NP (top) and 54NP (bottom) HTC calibration step 3: Calculated U-values

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

In this step, the models 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 3-14.

- Using measured U-values marginally reduces HTC predictions, since they are similar to the calculated values, and no measured values were obtained for the floor or ceiling eaves.
- The RdSAP model is substantially improved by including the measured U-Values, since the default version previously used a simplification of the room-in-roof geometry which has implications for overpredicting room-in-roof heat losses.
- The calibrated models still overpredict the measured HTC, though to a lesser extent.
- The BREDEM and DSM models agree when using measured inputs.

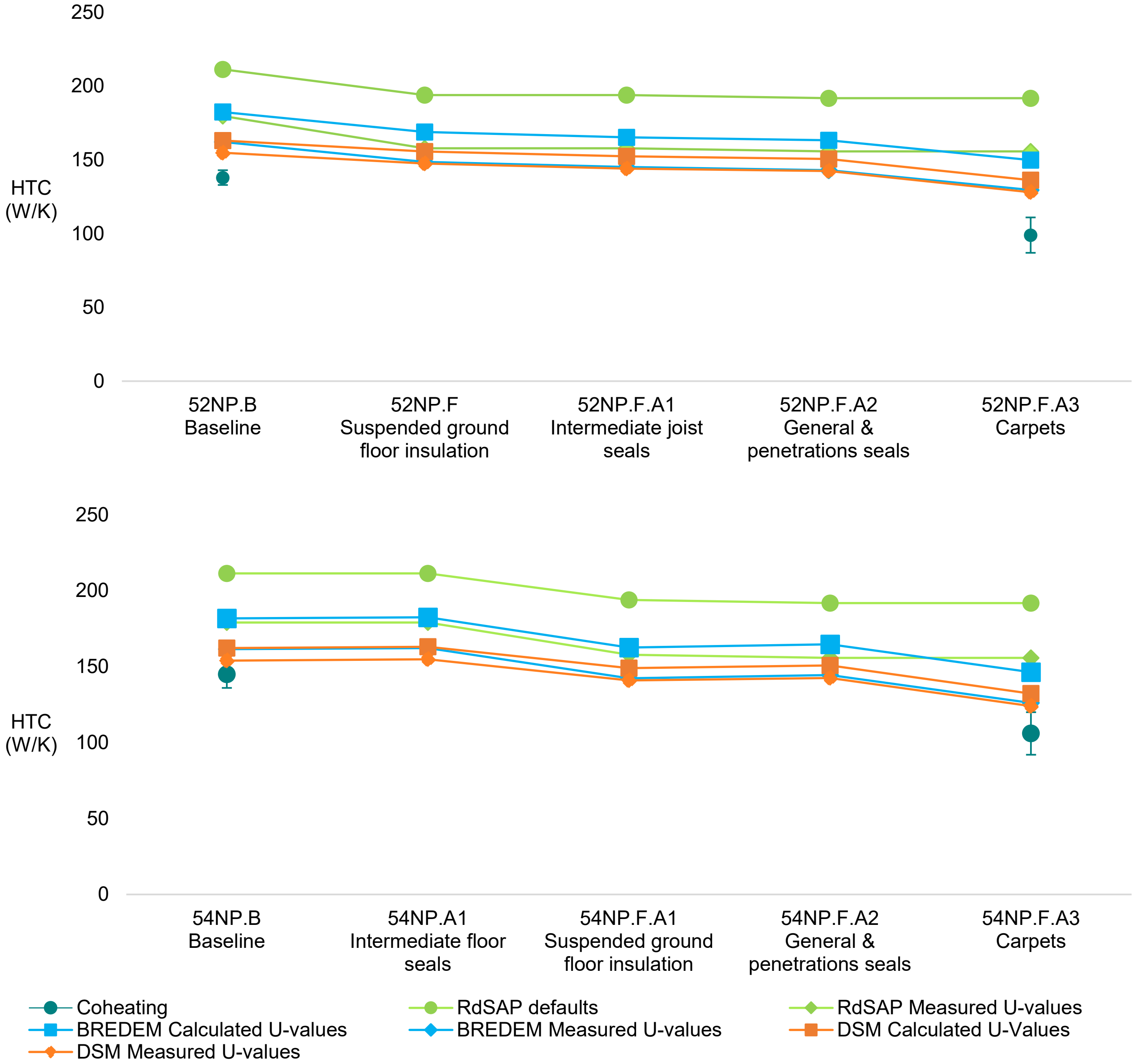


Figure 3-14 52NP (top) and 54NP (bottom) HTC calibration step 4: Measured U-values

3.4.6 Accounting for inter-dwelling air movement: HTC using the co-pressurisation infiltration rate

This report discusses the impact of inter-dwelling air exchange taking place during the high pressure blower door test, which may not translate to real world heat loss at normal pressures. Figure 3-15 shows that removing inter-dwelling air exchange by using the co-pressurisation infiltration rate, reduces the DSM HTC prediction.

As shown, this results in a reduction in HTC, which brings the prediction more in line with the measured HTC. More investigation into how inter-dwelling air exchange can cause overprediction of HTC, and consequently EPCs, is needed. It may be useful to understand whether this trend can be observed in other archetypes, or if there are implications for the UK airtightness testing industry.

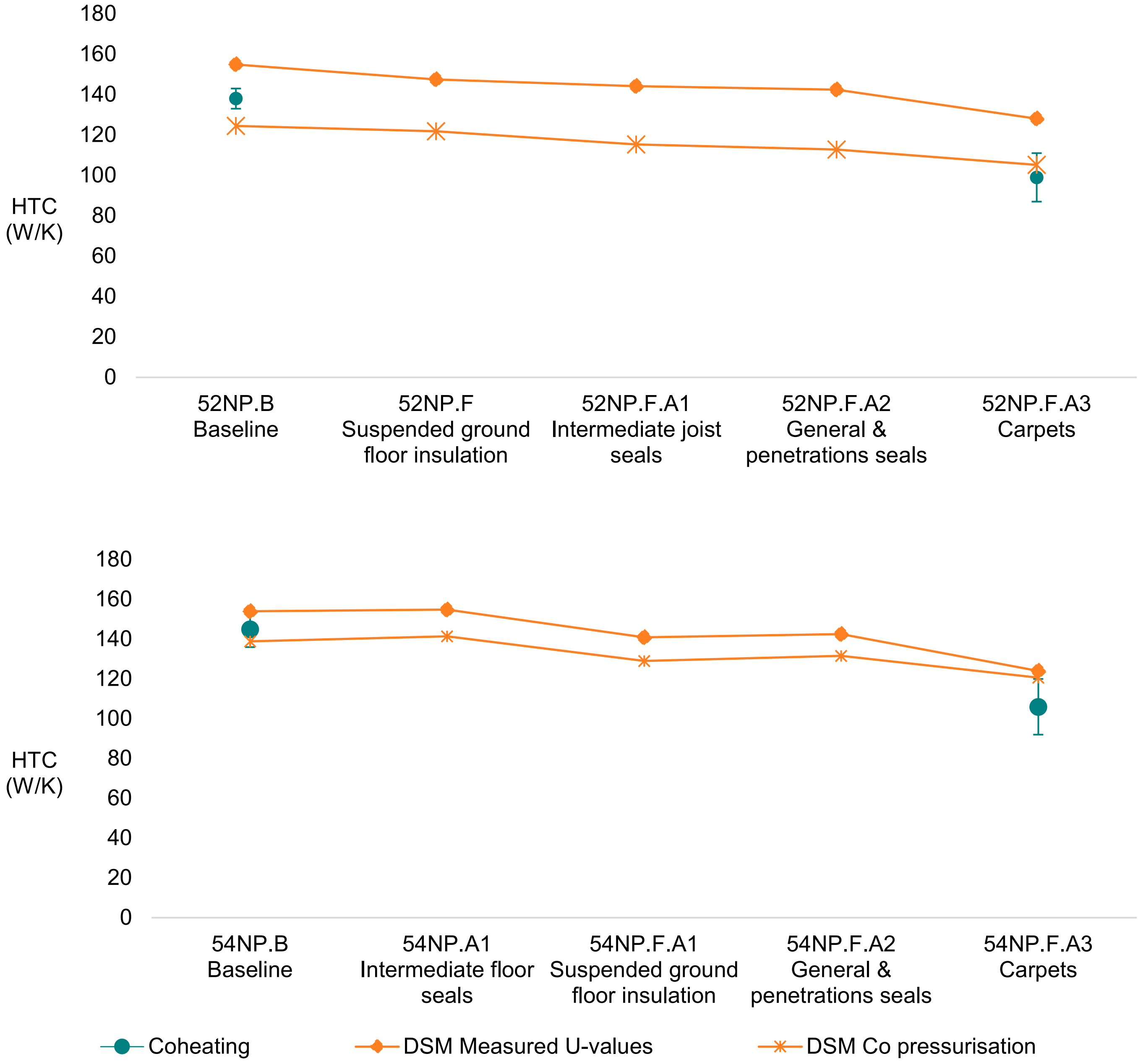


Figure 3-15 52NP (top) and 54NP (bottom) HTC using co-pressurisation results in DSM

Measured versus modelled HTC summary

The estimated HTC from closing-the-loop analysis shows relatively good agreement with the coheating result. This may be because the case study homes already had EWI, and insulated solid walls often have more homogenous heat losses than uninsulated walls. The analysis also shows a similar reduction from the cumulative retrofits.

Both the steady-state and DSM models predict higher HTCs than when the default data for U-values and airtightness are used. However, the addition of measured data for these parameters results in much better agreement. This finding suggests that allowing assessors to use known airtightness values for existing homes would improve the accuracy of EPCs.

When using the RdSAP defaults, models are unable to estimate any benefits from the installation of carpets, which the coheating test measured as relatively large. This is because assessors cannot adjust the airtightness in EPCs for existing buildings, though these results suggest this is something that could be changed in future RdSAP revisions to improve the accuracy of EPCs.

When the pressurisation results are used as the infiltration rates in the models, the agreement of the DSM model with the coheating test is excellent. It is not certain if this is a chance occurrence, or if the co-pressurisation result is more appropriate since it results in no inter-dwelling air exchange. More work is needed to understand the impact of this discovery in other house types.

The DSM model predicts lower HTC than the steady-state models, which is a common pattern across all the DEEP case study homes under investigation. This is due to differences in how internal and solar gains are applied. In these homes it also means that DSM has a closer agreement with HTC, though this is not always the case in the DEEP case studies.

3.5 Predicting EPC band, annual space heating and carbon emissions

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

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

Dynamic and steady-state models are fundamentally different in that DSM calculates heat balances and demand at an hourly timestep, whereas 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 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. RdSAP age band default data were found to underestimate baseline EPC scores, and thus overestimate retrofit savings.

3.5.1 Impact of retrofits on EPC bands

Several policy mechanisms set EPC targets, and the Government has an ambition that all homes (where practically possible) will achieve EPC band C by 2035 [5]. The impact of the retrofits on EPC in this case study as predicted by each model at each calibration stage is shown in Figure 3-16.

None of the retrofits make any material changes to the EPC band or SAP score of the homes. The homes already had EWI, which brought them into the EPC band C category. Both homes, since they are near identical neighbours, had roughly the same scores pre- and post-retrofit. No change was registered for the airtightness retrofits due to the airtightness improvements, though when measured airtightness values are input into the models the homes move to the higher end of EPC band C, gaining up to 3 additional SAP points. The floor insulation delivered only 1-2 additional SAP points.

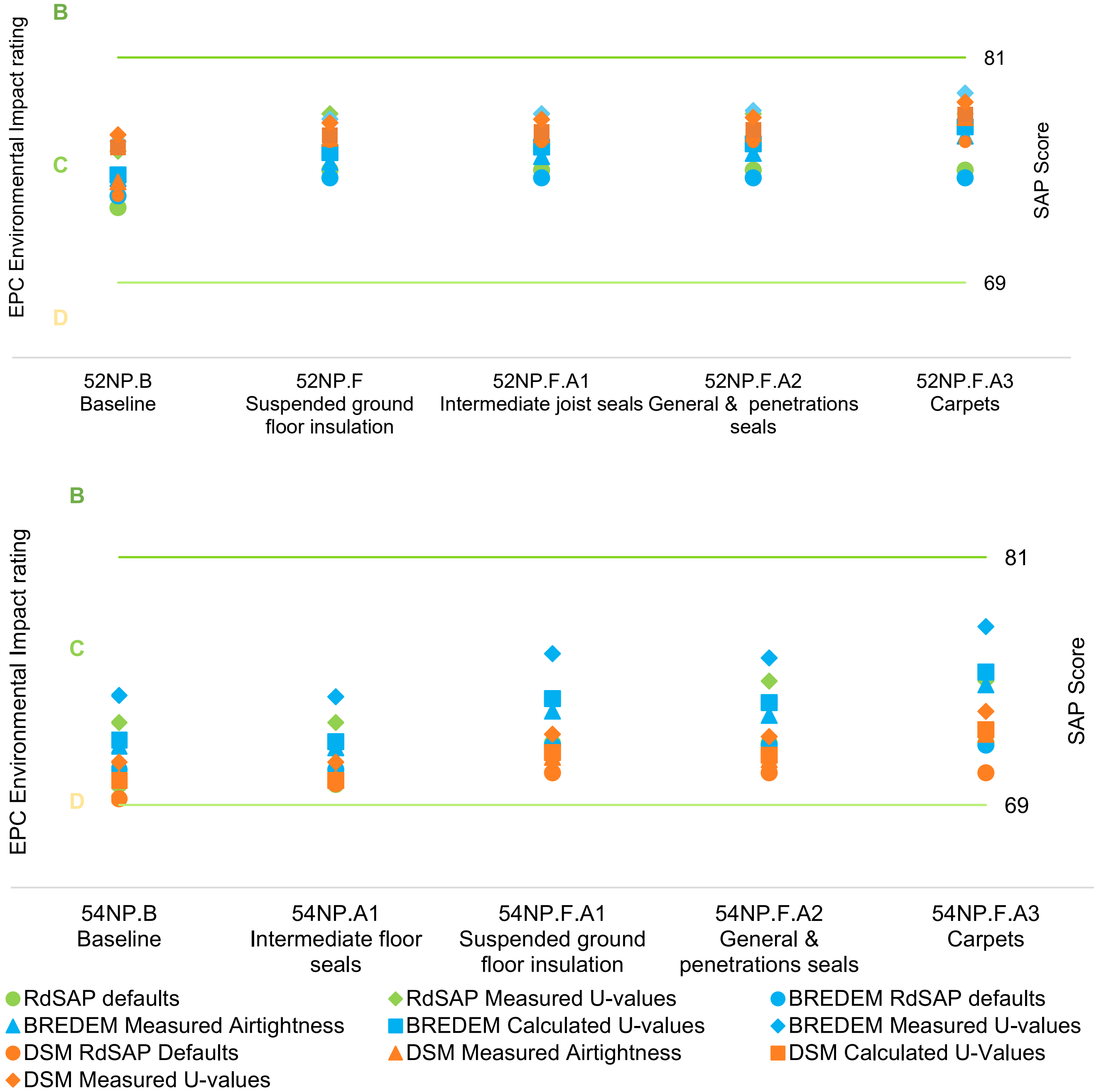


Figure 3-16 Predicted impact of retrofits on EPC band, 52NP (top) and 54NP (bottom)

3.5.2 Impact of retrofits on annual space heating

The Social Housing Decarbonisation Fund (SHDF) Wave 1 evaluates retrofit success by setting a target reduction of 90 kWh per m² for annual space heating for retrofits [6]. The predicted annual space heating demand for the case study retrofits is shown in Figure 3-17.

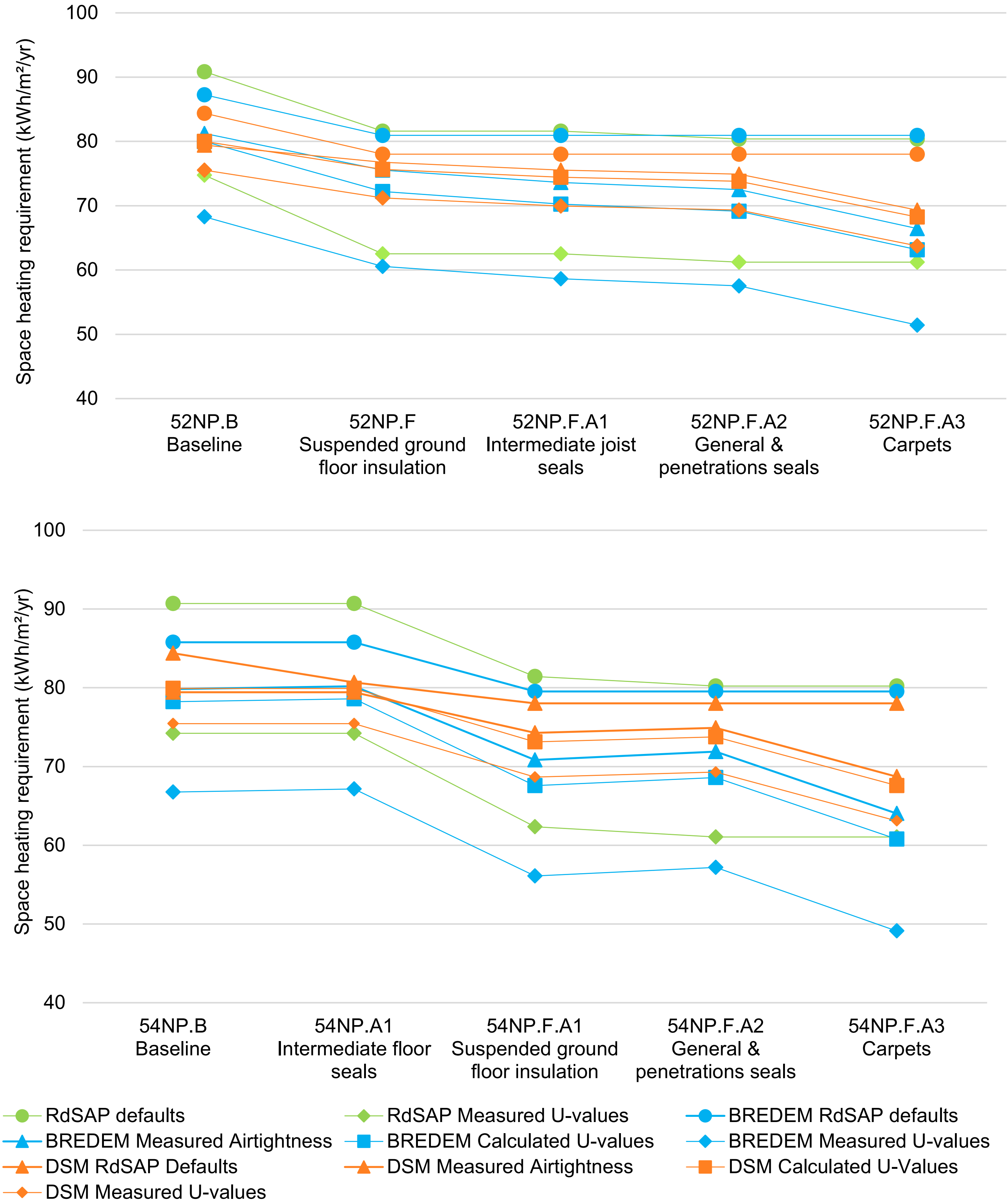


Figure 3-17 Predicted annual space heating demand, 52NP (top) and 54NP (bottom)

The EWI installed at the homes at the baseline means that they were already in line with the SHDF target prior to the retrofits, and well under it if measured airtightness and U-values are considered.

Again, carpets had a substantial impact on reducing the space heating demand in the homes, resulting from the airtightness improvements that this measure achieved. However, when RdSAP default assumptions are used, no savings are predicted from this measure.

Floor retrofits are predicted to reduce space heating demand more than the airtightness retrofits, contrary to the findings from the disaggregated HTC assessment, which suggests airtightness improvements were responsible for more of the savings. More investigation into the comparisons between modelled and disaggregated heat loss measurement is needed to explore this relationship in various house types.

When the co-pressurisation blower door result is used, which removes inter-dwelling air exchange from the energy calculation (as opposed to the blower door test for a single dwelling), the space heating demand drops further. More investigation is required to understand how models apply ground floor and air leakage heat losses and how inter-dwelling air exchange manifests in lived-in homes.

3.5.3 Impact of retrofits on CO_2 emissions

Heating homes is responsible for around 15 % of the UK's CO_2 emissions [7]. The predicted reductions in CO_2 emissions achieved by the case study home retrofits are shown in Figure 3-18.

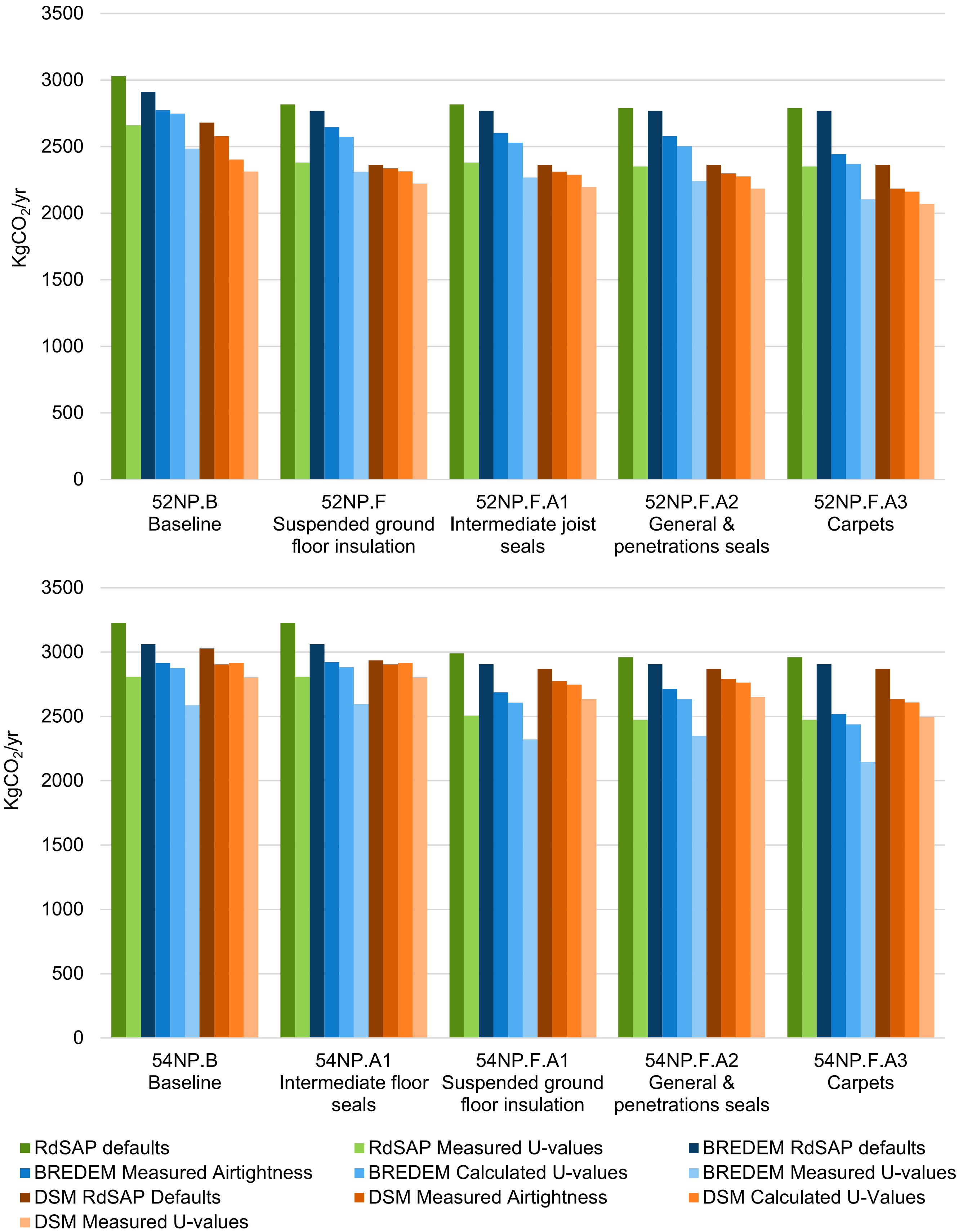


Figure 3-18 52NP (top) and 54NP (bottom) annual CO_2 emissions after retrofits

As shown, the models predict greater savings from the floor insulation than the airtightness improvements, even when the actual measured blower door derived HTC_f is used. This is counter to the findings from the disaggregated HTC analysis, and suggests there is uncertainty in the way models allocate heat losses to air leakage, as well as the utility of the n/20 rule of thumb.

Negative savings, i.e., an increase in CO_2 emissions, are seen for the sealing of the intermediate floor and general penetrations at 54NP. These interventions were ineffective at reducing air leakage, thought the results are within the uncertainty of the test method.

3.5.4 Potential reasons for differences in annual model outputs

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

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

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

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

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

Hourly vs. daily average solar irradiance (external surface temperatures)
External surface temperature is an important part of the dynamic hourly heat loss calculations through all plane elements in DSM. Higher external surface temperatures lead to lower heat loss. 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 that 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 DSM was selected due to the close similarities between monthly average external temperature values (CIBSE Test Reference Year file for Leeds [8]) as discussed in the DEEP Methods 2.01 Report.

Differences specific to 52NP and 54NP
For the baseline scenarios, using measured infiltration rates and U-values, BREDEM predicts a space heating demand that is only 817 kWh/year higher than DSM for 52NP, and 683 kWh for 54NP. In the majority of other DEEP case studies, the HTC value has the greatest influence on the annual space heating demand estimates. BREDEM (and therefore SAP/RdSAP) uses a bottom-up method to calculate the HTC used in the heat balance calculations, based on the thermal transmittance, area of construction, and background infiltration rates.

The DSM models mimic the coheating test conditions and therefore use a top-down method to calculate HTC. Using an unrestricted version of the BREDEM software, it is possible to overwrite HTC with that calculated in the DSM model.

Following this adjustment, the normalised annual space heating demand in BREDEM for 52NP is 4,648 kWh, compared with the DSM estimate of 6,406 kWh, meaning that BREDEM predicts a demand that is lower by 941 kWh. For 54NP, the normalised demand is 4,512 kWh in BREDEM, compared to 5,581 kWh in DSM, meaning BREDEM is 1,069 kWh lower. The BREDEM calculations can be further normalised by using the DSM volume of conditioned space (30.83 m^3 less in both DSM models). Following this final adjustment, the BREDEM estimate for 52NP is 1,497 kWh lower than the DSM output, and 1,608 kWh lower for 54NP. This is perhaps indicative of the these mid-terraces having a small proportion of exposed wall in direct sun, which reduces the impact of external surface temperature differences in DSM.

Predicting EPC band, space heating and carbon reduction summary

This section suggests that although floor insulation and reduced infiltration rates can reduce space heating demand, they result in an improvement of only 1 to 3 SAP points.

The homes had EWI installed prior to the tests commencing and this means that the homes already achieved EPC band C ratings, and the space heating demand was already in line with the SHDF target.

Getting solid walled homes like these case study dwellings to EPC band B may therefore be challenging and require additional disruptive retrofits such as room-in-roof insulation.

Compared to the disaggregated HTC, the modelling results suggest that the benefits of reducing air leakage are underestimated. More work is needed to understand how models account for HTC_f, as well as how appropriate the n/20 rule of thumb is for various dwelling types.

Allowing assessors to replace default infiltration rates with results from blower door tests would improve the accuracy of EPCs and allow them to describe the benefits of SAP score, space heating demand reductions, and CO_2 emissions.

The impact of replacing the blower door test results with the co-pressurisation test results would be to improve the baseline EPC of the homes, but also reduce the effectiveness of the airtightness reductions achieved. More investigation is needed to explore whether this is a more appropriate value to use for dwellings with neighbours and how this would affect their EPCs.

3.6 Overheating risk of retrofitting

The overheating analysis in this section is complementary to this work and uses the overheating assessment method from CIBSE TM59, which is cited in the PAS2035 guidance [9]. Two metrics are used to assess whether the dwelling will overheat. The first is taken from another CIBSE publication, TM52: The limits of thermal comfort: avoiding overheating in European buildings [10]. 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 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 various heatwave intensities. DSY1 represents a moderately warm summer; DSY2 represents a short, intense warm spell; and DSY3 represents a longer, less intense warm spell [8]. 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.

Since the two homes are near identical in building form and construction, 52NP is used to investigate overheating risk for both cases. All internal heat gains and window opening schedules are dictated by the TM59 methodology. The main difference is that 54NP has a smaller openable area of windows in the Living Room. However, following initial analysis of 52NP, the Living Room is shown to be at low risk of overheating.

The results for Criteria A are shown in Figure 3-19. In all weather scenarios, all assessed spaces in 52NP overheat. The floor retrofit makes little difference and the reduction in air leakage marginally increases the overheating risk.

The bedroom spaces in TM59 are also subject to assessment under Criteria B, and the results are given in Figure 3-20. Again, all scenarios fail the overheating assessment, and the retrofits make the situation marginally worse. This indicates that homes with similar building forms and construction may be at risk of overheating. The assessment was not undertaken without EWI installed, and it is not known whether this retrofit increased the risk beyond the threshold, or the uninsulated home was already at risk.

The implication is that these types of homes are likely to overheat under future weather scenarios, with or without retrofits. The room-in-roof bedrooms in these homes particularly suffer from overheating, suggesting that homes with rooms-in-roof may need particular solutions to stay cool. More research is needed to understand the impact of various mitigation measures, such as shutters, blinds and increased ventilation practices, on overheating risk in these sorts of homes.

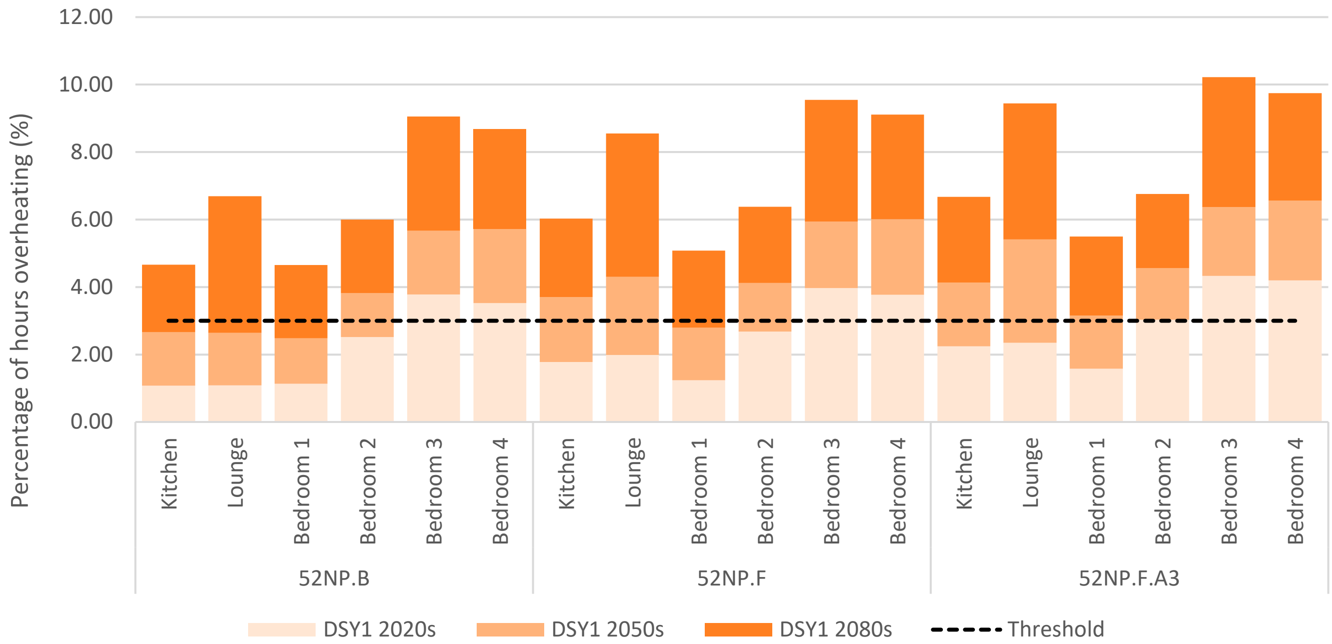


Figure 3-19 Modelled overheating under TM59 Criteria A

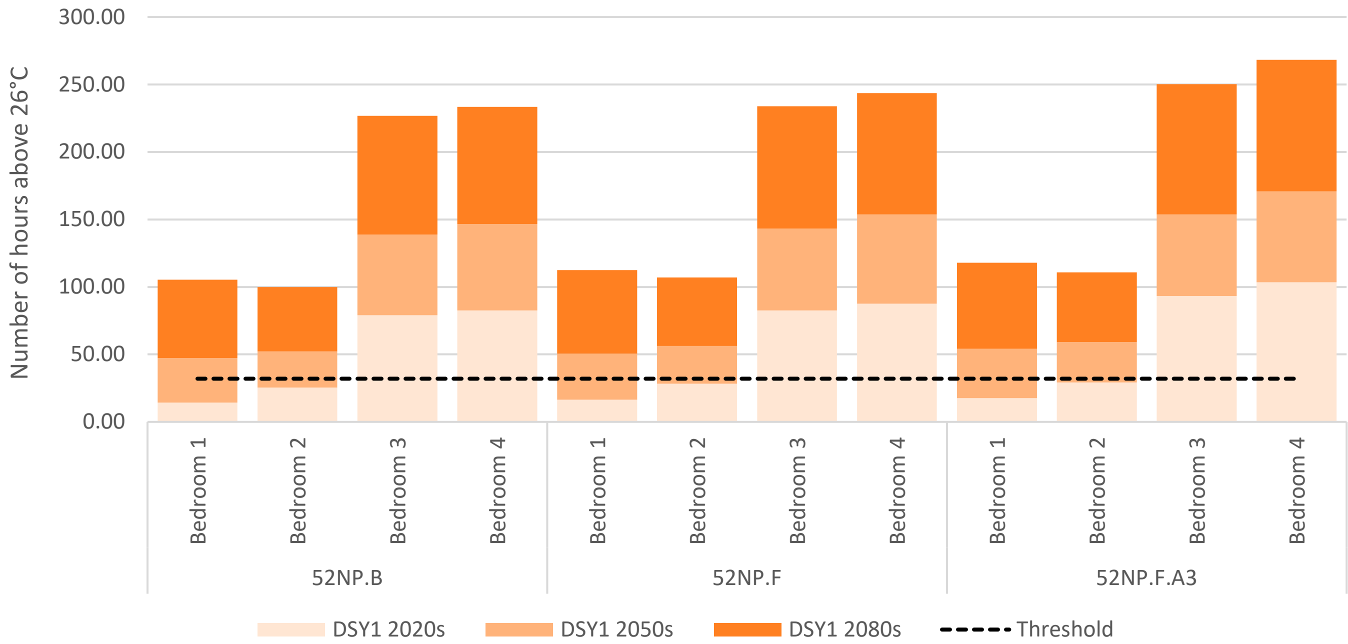


Figure 3-20 Modelled overheating under TM59 Criteria B

Overheating risk of retrofit summary

These case study homes had EWI and were already at risk of overheating. The retrofits marginally worsened the risk. The implication is that as solid walled terrace homes move towards EPC band C, their overheating risks may worsen. This suggests that more effort to balance overheating and heat loss may be needed to avoid future health problems related to overheating in UK homes.

3.7 Retrofit costs and payback

This section looks at the costs of undertaking the retrofit described in this case study. Undertaking work in existing homes can have tremendously variable costs, depending on the specification of the work being undertaken, as well as the condition of the house prior to the retrofit. The cost data presented here may not be representative of the national retrofit market, since retrofits tend to be labour intensive and there are variations across the country based on regional differences in construction labour markets. The data discussed here originate from a single contractor in the North of England and relate to only one house type and a limited range of retrofit specifications.

In this project, the costs of undertaking each retrofit are evaluated as either enabling works to get the house ready for the retrofit (repairs etc.) or the actual costs of the retrofit. Decoration costs are excluded from the costs reported here, since landlords undertake their own decent homes repairs following retrofits and would take on some of the decoration work. Costs associated with decorating are outside the scope of this project. However, these have been found to represent around 14 % of the cost of internal wall insulation [11], though this may be different for EWI, loft, and floor insulation, and new windows and doors. The costs of the 52NP and 54NP retrofits are outlined in Table 3-7. This shows all activities that took place, including those not directly associated with the retrofit itself.

Table 3-7 Cost of retrofits per house

Retrofit	i) Retrofit activity	Retrofit costs	ii) Additional enabling work required	Enabling work costs
Suspended floor insulation	Install 150 mm mineral wool from underneath in the basement with breathable membrane.	£ 3,300	Repair of radiator leaks. Disposal of existing damp mineral wool insulation and plasterboard ceiling to basement.	£ 2,400
Sealing intermediate floor joists	Removal of skirting boards and floorboards to access intermediate floor void. Spray foam around every floor joist.	£ 1,020	Replace broken floorboards and skirting boards.	£ 1,100
General draughtproofing and sealing	Spray foam or sealant applied to penetrations and around fenestrations. Rebuild boxed areas for pipework concealment. Instal draught proofing seals where these are not present.	£ 600	Disposal of old boxing in.	£ 250
Installing floor covering	New underlay, carpets and linoleum flooring throughout. Rehang doors.	£ 1,900	Removal of existing floor coverings and temporary removal of floor mounted bathroom units.	£ 450

Having to make repairs when retrofitting homes can be a barrier to uptake. In this instance a plumber was required to make repairs to radiators, and damp plasterboard and insulation as well as existing floor coverings and boxing in needed removing. In all, these enabling works added another 40 % to the cost of the retrofits.

Table 3-8 shows how the costs of the retrofits were split between labour and materials, which may be useful when considering how to reduce the total costs of retrofits in the future, and where innovations are needed. The major cost of the floor retrofits and airtightness measures was labour, which indicates that time saving innovations for these retrofits may be desirable.

Table 3-8 Breakdown of cost of retrofits per house

Retrofit	Labour	Materials	Total cost	Cost per area (£/m²)	Benchmark (£/m²) [12]
Suspended floor insulation	£ 3,700	£ 2,000	£ 5,700	£ 61	£38 - £92
Sealing intermediate floor joists	£ 1,400	£ 720	£ 2,120	£ 23	n/a
General draughtproofing and sealing	£ 600	£ 250	£ 850	n/a	n/a
Installing floor covering	£ 650	£ 1,700	£ 2,350	£ 25	n/a
Total	£6,350	£4,670	£11,020		

It is useful to consider the HTC savings (W/K) achieved per £ spent. This may provide useful insights for predicting how cost-effective various retrofits are to inform future national retrofit schemes. The cumulative floor retrofit, and airtightness improvements achieved a 39 W/K reduction in HTC, meaning the cost was £283 for every W/K saved. When the costs of the ineffective airtightness measures are excluded and only the costs of the suspended ground floor and installation of new floor coverings are considered, this drops to £206 per W/K.

3.7.1 Predicted fuel bill savings

The impact of the retrofits on household dual fuel bills is shown in Figure 3-21 using SAP fuel prices of 3p per kWh gas and 13p per kWh electricity. These values do not reflect current fuel prices and are shown only as an illustration. The DEEP Synthesis Report discusses how the analysis changes when the October 2022 Ofgem price cap unit prices are considered.

Table 3-9 Annual dual fuel bill estimates for baseline pre-retrofit case study home

Calibration step	RdSAP 52NP	RdSAP 54NP	BREDEM 52NP	BREDEM 54NP	DSM 52NP	DSM 54NP
1. RdSAP defaults	£ 644	£ 723	£ 625	£ 694	£ 588	£ 684
2. Measured airtightness	-	-	£ 603	£ 667	£ 571	£ 662
3. Calculated U-values	-	-	£ 599	£ 660	£ 530	£ 664
4. Measured U-values	£ 585	£ 648	£ 556	£609	£ 516	£ 645

54NP is predicted to have slightly higher annual fuel bills. This may be because it had marginally more air leakage than 52NP, and a different gas boiler with lower efficiency, as well as an electric fire to provide secondary heating.

As default data are swapped for measured and calculated values, the estimated fuel bills for this house fall, indicating that the EPC is overestimating fuel bills by somewhere between £40 and £90. This consequently means any predicted savings from the retrofits may be overestimated.

Figure 3-21 shows that the floor insulation is expected to reduce dual fuel bills by between 3 % and 5 % when measured or calculated U-values are used. However, when using the RdSAP default assumptions for U-values, the saving is predicted to be between 5 % and 11 % - up to £64. This suggests that EPCs are overpredicting the benefits of floor insulation in these homes.

The airtightness improvements achieved by sealing the intermediate floor joists and undertaking general sealing around penetrations are shown to be negligible. They even show a negative saving (i.e., higher fuel bills) for 54NP, due to the blower door test result being higher for these retrofit stages. However, the results are within the error margin of the test, so it is not possible to know if the result did get marginally better or worse. As mentioned, it is possible that removing and replacing floorboards to access the intermediate floor may have itself worsened the airtightness of the homes.

Some savings are shown following the installation of the floor coverings. Fuel bills are predicted to reduce by up to 3 % in 52NP and up to 6 % in 54NP, i.e., up to £36 per annum. However, when using the RdSAP inputs, the models predict no savings because EPCs for existing buildings do not allow assessors to replace the assumed infiltration rates with known values. This means EPCs are overestimating the fuel bills for these homes.

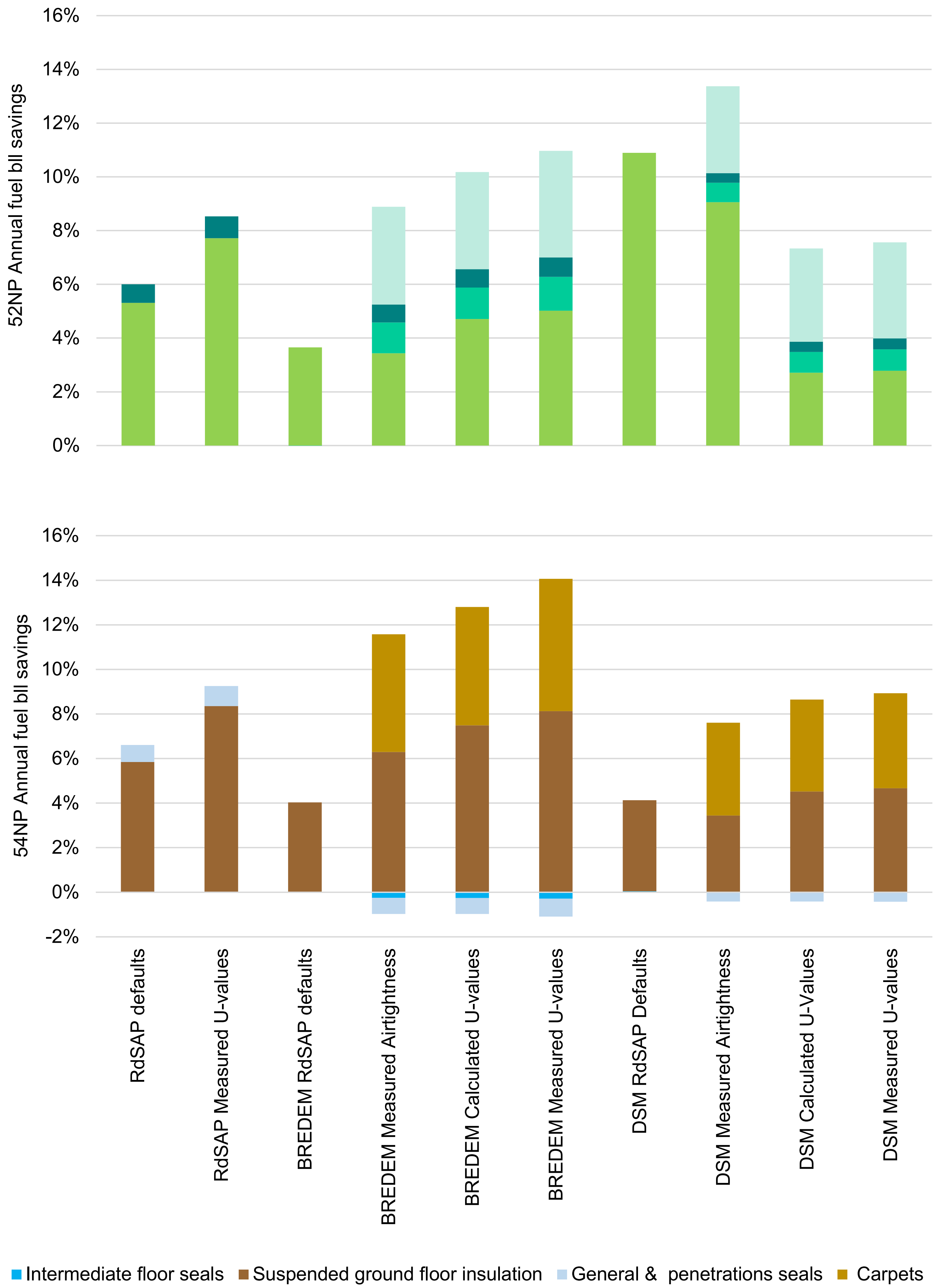

52NP Annual fuel bll savings
16%
14%
12%
10%
8%
6%
4%
2%
0%
54NP Annual fuel bll savings
16%
14%
12%
10%
8%
6%
4%
2%
0%
-2%
RdSAP defaults
RdSAP Measured U-values
BREDEM RdSAP defaults
BREDEM Measured Airtightness
BREDEM Calculated U-values
BREDEM Measured U-values
DSM RdSAP Defaults
DSM Measured Airtightness
DSM Calculated U-Values
DSM Measured U-values
Intermediate floor seals
Suspended ground floor insulation
General & penetrations seals
Carpets

Figure 3-21 52NP (top) and 54NP (bottom) predicted annual fuel bill savings from the retrofits

3.7.2 Predicting simple payback of retrofits

The simple payback time (i.e., not considering fuel price inflation or discount rates) calculated from the retrofit costs and annual fuel bill saving estimates for this case study are shown in Figure 3-22. Recent fuel and retrofit price increases will significantly affect payback rates.

- Installation of carpets shows the lowest payback rates.
- Models using RdSAP default inputs show zero payback years for airtightness measures as it does not predict any savings.
- Payback rates vary enormously depending on which model and input data are used.
- DSM generally has longer payback periods than RdSAP and BREDEM, since it predicts lower space heating demand.

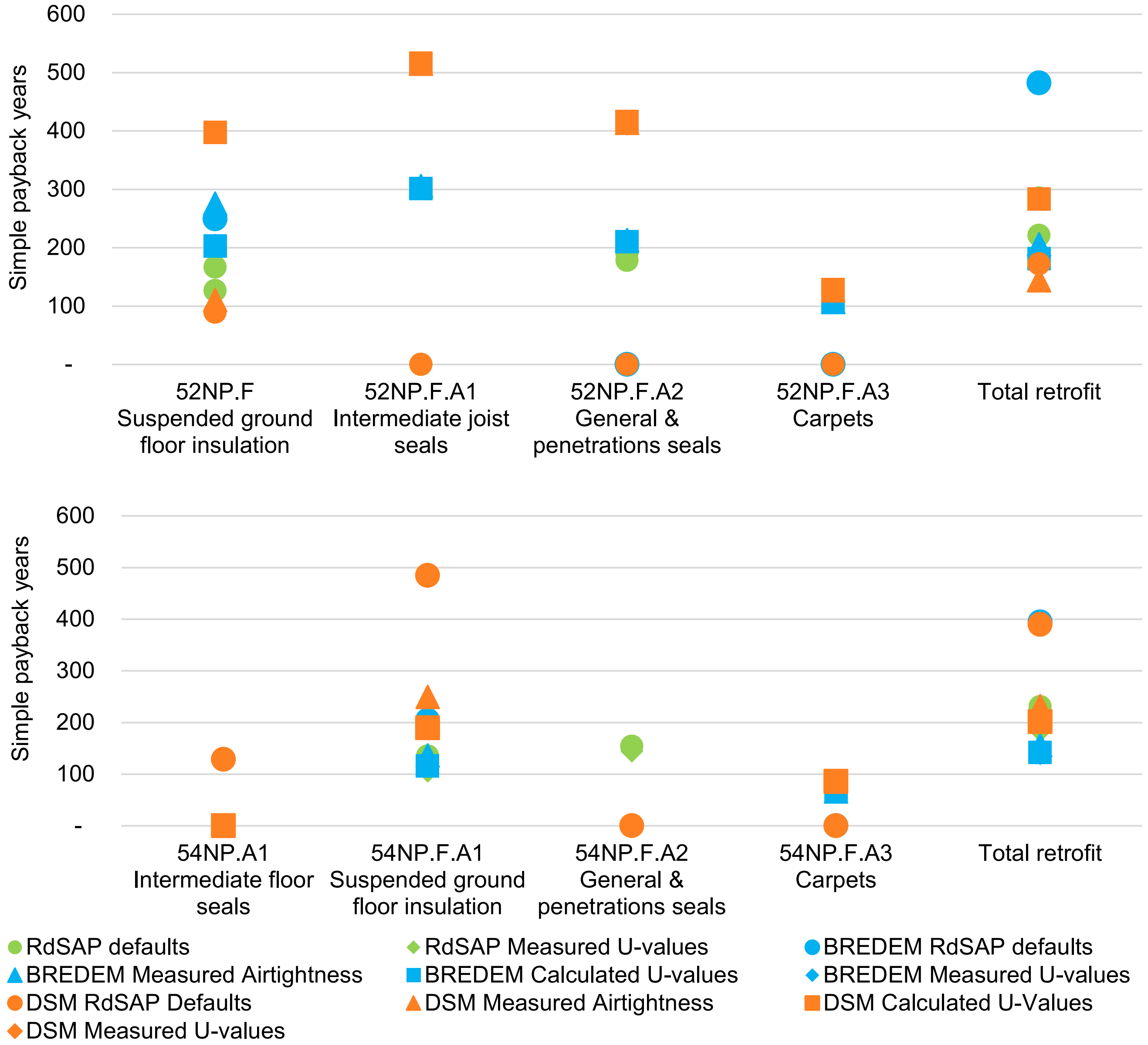


Figure 3-22 Simple retrofit paybacks

Retrofit costs summary

The retrofit costs for these homes were over £11,000 per property, and a cumulative saving of 39 W/K was achieved in each house, resulting in a per W/K saving of around £283. This is higher than the costs of airtightness measures undertaken in other DEEP case studies. The reason for this may be because sealing the penetrations and intermediate floor joists was ineffectual.

The costs were also high due to the large amount of remedial work required, representing 40 % of the total retrofit cost. This proportion of the cost for enabling work is in line with the other DEEP retrofit case studies, which has implications for benchmark cost estimates for retrofit policy.

The findings illustrate the uncertainty of outcomes when undertaking airtightness retrofits. They also highlight that there may be merit in understanding how floor coverings reduce air leakage, since this could have implications for landlords' responsibilities to provide floor coverings, which currently result in the removal of carpets prior to tenancy (without replacement). They also suggest that blower door tests that are undertaken when no floor coverings are present in the homes may overestimate infiltration rates and heat loss.

The retrofits, in general, had very long simple payback periods, however, future price rise estimates and discount rates may alter these estimates.

Reductions in annual fuel bills of between £34 and £64 are predicted from installing the floor insulation, depending on which model is used (RdSAP predicts the highest savings). EPCs do not predict any fuel bill savings resulting from the airtightness improvements, though the other models predict these could result in annual savings of up to £22 in 52NP and £36 in 54NP.

4 Conclusions

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

Airtightness improvements

These case studies provide new information on the impact of improving the airtightness of solid walled homes on whole house heat loss. A 41 % reduction in air leakage meant the house achieved airtightness levels comparable with new build homes and resulted in between 13 % and 15 % reduction in HTC.

These homes already had EWI installed, but had a baseline infiltration rate of around 15 ($m^3/(h{\cdot}m^2)$) @ 50pa, indicating that wall retrofits do not necessarily improve the airtightness of homes. Similarly, the suspended floor retrofit did not lead to a material reduction in air leakage. This case study illustrates the uncertainty of the outcomes of attempts to improve the airtightness of homes. Neither sealing the intermediate floor voids nor sealing penetrations made any change to either home's air leakage rates, yet the installation of carpets had a significant impact and was responsible for almost all the airtightness improvements.

These findings suggest that reductions to infiltration rates to improve the energy efficiency of homes may need addressing as a separate retrofit measure. However, energy efficiency improvements are currently assessed according to EPC bands and SAP scores, which are not able to capture the heat loss reductions of these activities.

The savings measured by the coheating test were inclusive of airtightness and floor retrofit improvements, thus, the disaggregation method, which relies on the n/20 rule of thumb was used to explore how much benefit each retrofit stage achieved. This estimated that 60 % of the HTC reductions were derived from the airtightness reductions. More research is needed to explore heat loss associated with air leakage in homes.

The case studies suggest that airtightness improvements may have a role in future retrofit policy. There is substantial uncertainty of outcomes for airtightness improvements, with some activities not improving airtightness at all. More investigation is needed to explore its impact on space heating, as well as its relationship with ventilation, comfort, damp, and air quality. These are outside the scope of the DEEP case study.

Inter-dwelling air movement

The study provides useful insights into the phenomenon of inter-dwelling air movement. Co-pressurisation tests suggest that around 25 % of the infiltration measured by the blower door test is inter-dwelling air exchange. This drops to only 11 % post the floor covering retrofit, suggesting that a significant proportion of the inter-dwelling air exchange occurs via the intermediate floor voids.

Alternative BPE measurement tools

Attempts to measure airtightness via CO_2 decay and Pulse tests, and to measure HTC via QUB tests, were not particularly successful. This is thought to be due to the homes being very large – four floors including the basement – and having high infiltration rates and large areas of party wall. Specifically for the QUB tests, there was a lack of party wall heat flux data.

Suspended timber floor insulation

The heat flux density measurements for the suspended timber floor were affected by ground loop issues with the DT85 equipment, meaning that measured U-values could not be derived. The calculated U-values, however, showed substantial improvements in heat loss, reducing U-values by over 70 %.

This was estimated to be equivalent to around a 10 % reduction in HTC in both homes, according to the disaggregated method. The models predict the HTC reduction would be between 6 % and 12 %, depending on which model and input data are used.

These houses are mid-terrace homes with four stories including the basement, the ground floors of which make up around 24 % of the heat loss area. They already had EWI retrofits and, therefore, a lower baseline HTC than is typical for this type of house, and were at EPC band C. The floor retrofit was not sufficient to improve this band rating and was only modelled to achieve an improvement of 1 to 2 SAP points. Thus, more research is needed to understand the impact of floor insulation in other house types before generalisations about the benefits of floor insulation on the UK housing stock can be made.

Modelling heat loss and retrofit savings

This case study suggests that HTCs predicted by EPCs can be substantially higher than measured HTCs. The reason for this, in this case study, is mainly due to inbuilt assumptions in RdSAP around room-in-roof geometries, plus overestimates of room-in-roof U-values and whole house ventilation rates. When these are overridden, the predictions are more aligned, though still overpredict heat loss. The refinement of the models by including measured and calculated data was not significant enough to change the EPC, which remained band C. They did, however, gain an additional 3 or 4 SAP points, roughly the same change as that achieved by the combination of the floor and airtightness retrofits.

No savings for the airtightness retrofits were predicted by the models using RdSAP assumptions, since default infiltration rates cannot be replaced with measured data. The air leakage reductions of adding carpets were responsible for around 60 % of the cumulative retrofit savings. There may, therefore, be scope for EPCs to be made more accurate by addressing conventions in the modelling procedure and providing more representative input data. However, comparisons of measured and modelled heat loss in more house types, with differing levels of measured and default input data, is needed to understand how this relationship varies across house archetypes and ages.

Cost effectiveness

Uncertainty around future fuel and retrofit prices makes it difficult to describe the cost effectiveness of retrofits. In this case study, the whole house retrofit costs were £11,020 for each house. These costs were relatively high, with 40 % going to additional enabling work (removing damaged flooring, repairing radiators etc.), and these activities were labour intensive.

The cheapest retrofit was simply the sealing up of penetrations and general draught proofing (£850 per house). However, this did not result in any airtightness improvements. Considering only the retrofits that achieved HTC reductions, the total cost for each home would have been £8,050 to install new floor insulation and floor coverings. Very simple payback assessments of the retrofits show that only the fitting of floor coverings had a payback of below 100 years, and this was only observed for one of the homes. This, however, would be substantially affected by future fuel price variations.

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