Department for Energy Security & Net Zero

LEEDS BECKETT UNIVERSITY
LEEDS SUSTAINABILITY INSTITUTE

DEEP Report 2.07

Case Study 04KG

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Prepared for DESNZ by

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Executive summary

04KG is one of fourteen case study homes being retrofitted in the DEEP project. The case studies are being used to understand the performance of, and risks associated with, retrofitting solid walled homes. The data from the case studies is also being used to evaluate modelled predictions of retrofit performance and risk.

In this case study, the existing double glazing and external doors were upgraded to British Fenestration Rating Council (BFRC) A+ rated replacements, a 20 mm aerogel board was installed on top of the existing uninsulated solid floor slab, and airtightness specialists were engaged to reduce air leakage. Cumulatively these improvements achieved a (30 ± 10) W/K measured reduction in HTC, or (19 ± 6) %. The home's EPC predicted that a 4 % fuel bill saving would be achieved from these retrofits. This is low since RdSAP cannot consider insulation <50 mm, and nor can the assumed infiltration rate be changed. When these are considered, however, models suggest the retrofits could reduce fuel bills by up to 13 %. The home previously had external wall insulation (EWI) fitted, and as a result, was already considered to be an EPC Band C, although a large performance gap was observed for the EWI. The retrofits in this case study added only between 1 and 3 SAP points; not enough to improve the home's EPC band further.

DEEP case studies have shown that modelled predictions of heat loss in insulated homes tend to be more accurate than in uninsulated homes. Despite a performance gap in the EWI, the predicted heat losses in all models, and in the 'closing-the-loop analysis', were relatively close to the measured coheating HTC. Adding the home's actual airtightness further improved modelled predictions. Pre-retrofit, the home was found to be relatively airtight at 9 $m^3/(h·m^2)$ @ 50Pa. The glazing and airtightness retrofits further reduced this to 5.4 $m^3/(h·m^2)$ @ 50Pa; half that assumed in the EPC. It was observed, however, that mastic and tapes failed during coheating testing, and so the air permeability increased to 6.4 $m^3/(h·m^2)$ @ 50Pa. This finding has implications for the use of these temporary strategies in compliance testing for new builds as well as retrofits.

Two additional discoveries were made related to air leakage. Firstly, although they do not have a cavity, no-fines party walls (i.e. concrete walls with only large aggregates) appear to exhibit a party wall thermal bypass heat loss mechanism. Despite not having a clear cavity, air seems to move through connected air pockets in the structure. Secondly, pressure-induced conditions during blower door tests cause inter-dwelling air exchange, which may be overestimating infiltration by around 17 %. This has implications for the perceived air leakage heat losses derived from blower door tests; as well as on fresh air provision in homes, which impacts on health, noise pollution, and fire safety.

After the fabric retrofits, the opportunity to investigate an MVHR retrofit at 04KG emerged. It was observed that the MVHR installation increased air leakage, owing to fabric penetrations being made for ductwork so it is recommended that airtightness tests become an integral part of MVHR commissioning. This meant the models predicted fuel bills would increase post MVHR retrofit as electrical energy use for fans was not offset by heat recovery. However, an analysis showed that if the home's infiltration rate was 3 $m^3/(h·m^2)$ @ 50Pa, and RdSAP default inputs for specific fan power and heat recovery were replaced with actual MVHR specification inputs, space heating demand and CO_2 emissions may reduce. Although running cost and EPC score may not change, additional benefits include improved air quality supplied to all living spaces and constant extraction from wet areas, though measuring the extent of this improvement was beyond the scope of the case study tests.

1 Introduction to 04KG

Case study 04KG was a three-bed, semi-detached, no-fines concrete solid-walled dwelling built in the 1950s. Its interesting features included having a completely solid ground floor slab and that it had already undergone an EWI retrofit several years ago. Staged retrofits were cumulatively installed at the house, including installing new glazing and doors, a non-disruptive approach to solid ground floor insulation, and airtightness improvements. Following the fabric retrofits, the research team was asked to explore the challenges associated with retrofitting a mechanical ventilation with heat recovery (MVHR) into homes. The case study also enabled the exploration of inter-dwelling air exchange.

1.1 DEEP field trial objectives

04KG is one of fourteen DEEP case studies which, collectively, attempt to investigate the research objectives listed in Table 1-1; though not all the objectives are addressed by each case study.

Table 1-1 DEEP Research objectives

Objective	Rationale
Model input accuracy	Policy relies on models with known limitations, exploring inputs and model robustness will improve policy advice.
Unintended consequence	More retrofit scenarios need modelling to confirm condensation, underperformance, air quality, and comfort risks.
Cumulative impact	Piecemeal retrofits are common; clarity is needed on the impact of different options, including achieving EPC band C.
Fabric vs ventilation	Insulation influences fabric & ventilation heat loss yet models currently only attribute savings to U-value changes.
Floor retrofit	80 % of homes have uninsulated floors; clarity on benefits may increase installation from 0.5 % of ECO measures.
Airtightness retrofit	Infiltration undermines retrofits, balancing airtightness and indoor air quality is an unexploited ECO opportunity.
Neighbour risk	Clarity is needed on whether whole house or staged retrofits affect condensation risk for neighbours

1.2 DEEP research questions

Over the course of the three-year project and following advice from DESNZ, the wider DEEP Steering Group, and Expert QA panel, additional questions were proposed. The objectives were refined to develop seven discreet research questions, which are listed below and will be used in discussing the findings:

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

Data collected from case study 04KG contributed to the body of evidence of the DEEP project, that addressed these questions.

1.3 Case study house information

Shown in Figure 1-1, 04KG is a three-bedroom semi-detached property in North Yorkshire. Built in the 1950s, the house is a Wimpey, no-fines concrete property [1]. There are three external walls (front, gable, and rear) and a party wall shared with a neighbour. The external walls have been insulated with 100mm of expanded polystyrene board insulation (EPS) under a render mesh coat, which extends from the damp proof course (DPC) to soffit level at the front and rear, and up to the ridge on the gable wall. According to the landlord, this retrofit took place within the last five years. The house has an accessible loft, which is accessed through a hatch on the landing, and a chimney stack (although the ground floor fireplace, while ventilated at low level, is boarded over).

Around 300,000 homes across the UK were built by Wimpey using no-fines for the external walls [1]. While the construction method was not widely used across the UK for post-war housing, the results from this case study enable the research to explore a deeper understanding of pre- and post-retrofit performance in a non-traditional form of construction.

Two aspects are of particular interest in this case study: firstly, the heat transfer across externally insulated no-fines external walls, and between properties with no-fines party walls; secondly, the impact that external wall insulation has on overall external wall U-values where the external wall insulation finishes below the level of the loft insulation, resulting in a discontinuity in the insulation layer.

Figure 1-1 Case study house

Figure 1-2 Case study house site location plan

2.02 DEEP 04KG

Floor plans, elevations and sections can be seen in Figure 1-3 and Figure 1-4 respectively.

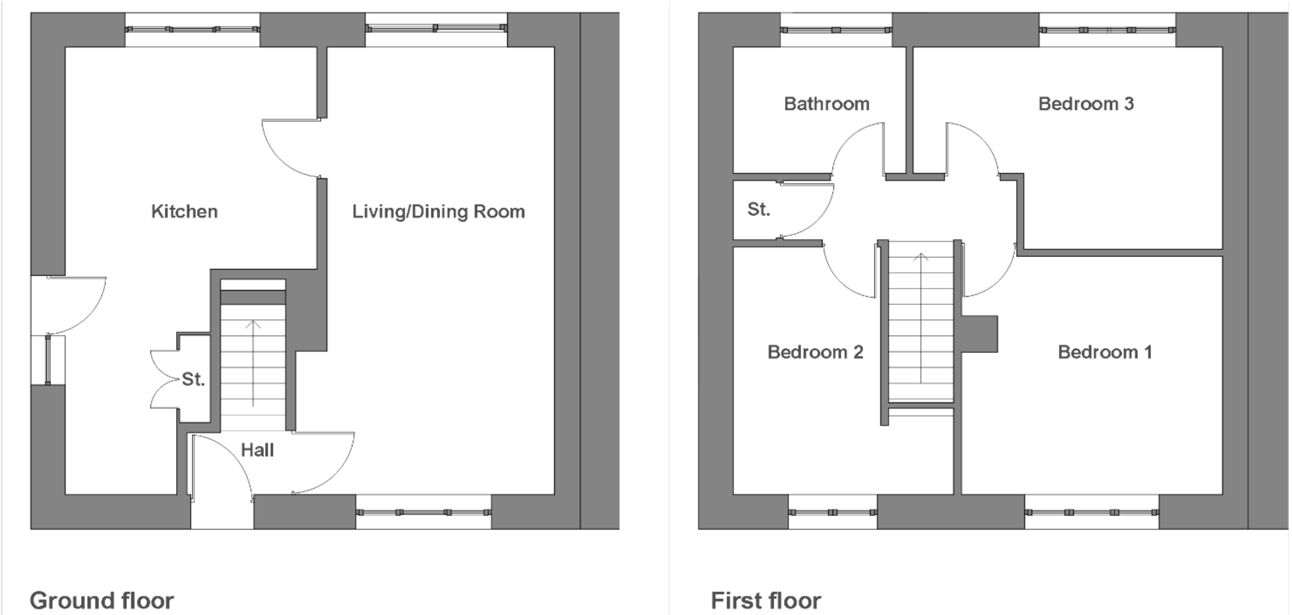

Figure 1-3 House floor plans

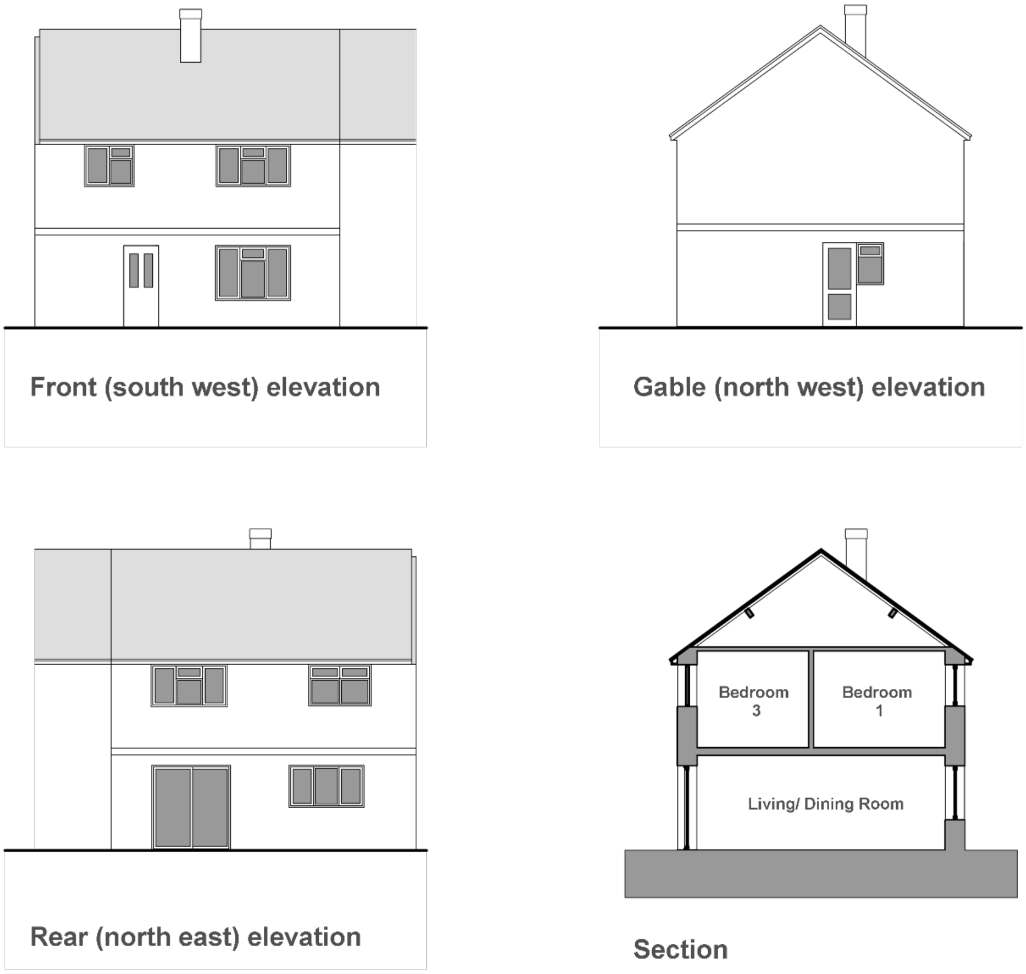

Figure 1-4 Front, rear, gable elevations and section

The dimensions of each element in the home are listed in Table 12 and were used to allocate heat losses as well as generate thermal models in RdSAP, BREDEM, and DSM. These dimensions were obtained via a measured survey of the dwelling.

Table 1-2 House dimensions

Detail	Measurement
Volume	*195 m^3*
Total floor area	*79 m^2*
Total heat loss area	*169 m^2*
Ground floor	40 m^2
Gable external wall	27 m^2
Front and rear external walls (insulated)	40 m^2
Front and rear external walls (uninsulated)	4 m^2
Loft	39 m^2
Windows	16 m^2
Door	2 m^2
Party wall	29 m^2

Construction details are summarised in Table 1-3. There were no obvious defects, however, the windows were in a poor condition and the existing external wall insulation did not fit closely around services and the ground floor perimeter, as shown in Figure 1-5.

Figure 1-5 Thermal images revealed heat loss around the ground floor perimeter and penetrations for the gas supply (top) and boiler flue (bottom)

In addition to the EWI on the gable wall, an additional layer of 20mm polystyrene insulation was found within a timber frame in the kitchen and bedroom 2, shown in Figure 1-6.

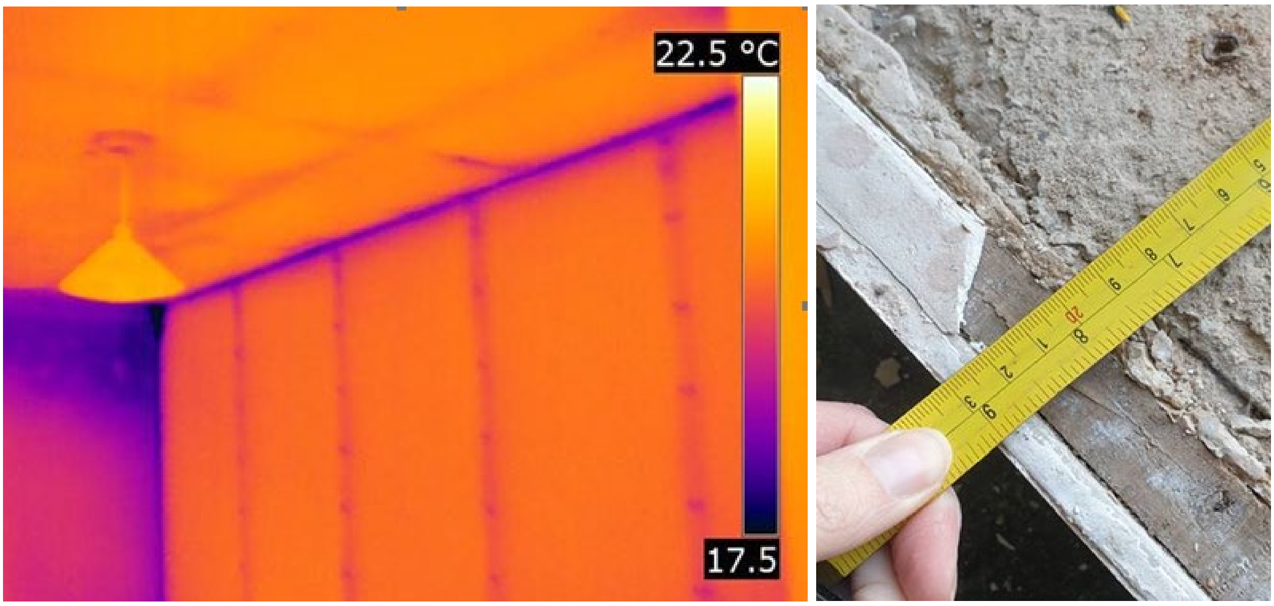

Figure 1-6 TIWI installed on kitchen & bedroom 2 external walls

1.4 Retrofit approach

The retrofit details and U-values for each element are listed in Table 13. The retrofit U-values listed have been calculated by the BRE calculator and are based on the observed materials and thickness of the existing fabric, and knowledge of the insulation being installed. The thermal conductivity of the insulation was provided by the manufacturers. BS EN 12524:2000 [2] was used to determine the thermal conductivity of other construction elements, and the plane element U-values include repeating thermal bridges (e.g. floor joists) in accordance with BR443 [3] and BS EN ISO 6946 [4].

Table 1-3 Construction and retrofit summary

Detail	Original construction	Retrofit[1]
Windows	uPVC Double glazed	uPVC Double glazed U-value: 1.8 $W/(m^2{\cdot}K)$
Doors	Composite	Composite U-value: 1.8 $W/(m^2{\cdot}K)$
Ground floor	Uninsulated solid floor	Aerogel insulation on solid floor 20 mm x 0.015 $W/(m^2{\cdot}K)$ U-value: 0.32 $W/(m^2{\cdot}K)$
Airtightness	9 $m^3/(h{\cdot}m^2)$ @ 50Pa (original condition)	Specialist airtightness contractors were commissioned to reduce the airtightness with a view to allowing effective operation of MVHR
Wall type 1 (Front & Rear)	No-fines concrete with 100 mm EWI	None
Wall type 2 (Front & Rear)	No-fines concrete	None
Gable wall	No-fines concrete with 100 mm EWI and 20 mm IWI	None
Loft	Ceiling joist with 75 mm mineral wool between and 200 mm mineral wool above	None
Ventilation[2]	Natural with mechanical extract fans and trickle vents on windows.	MVHR (efficiency: 83 %)

[1] Target U-values based on assumed construction details and may vary from Approved Document Part L maximums according to manufacturer recommendations or space limitations.
[2] Not part of the original retrofit plan but added at a later stage.

The sequence of the staged whole house retrofit approach is illustrated in Figure 1-8 through to Figure 1-11. Airtightness measures can include a variety of activities. In this case study, specialist airtightness contractors were instructed to achieve an airtightness level commensurate with installing MVHR. Their target was therefore a mean air permeability below 5 $m^3/(h \cdot m^2)$ @50Pa. Their solution was to install a plywood cover over the intermediate floor and seal the floor edges, as well as using mastic to seal accessible penetrations.

Building performance evaluation (BPE) tests, whole house energy modelling and elemental thermal simulations were conducted at each retrofit stage to quantify changes in energy performance and the potential for condensation risk. The specific methodologies for these are described in the DEEP Methods 2.01 Report.

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

Table 1-4 Phased retrofit stages

	Retrofit Stage	Code	Retrofit Dates
1	Baseline	04KG.B	November 2020
2	New windows and doors fitted	04KG.G	December 2020
3	Installation of solid ground floor insulation	04KG.G.F	October 2021
4	Airtightness retrofit	04KG.G.F.A	November 2021
5	MVHR system installed	04KG.G.F.A.M	February 2022

The order in which the retrofits are undertaken is shown in Figure 1-7 to Figure 1-11.

2.02 DEEP 04KG

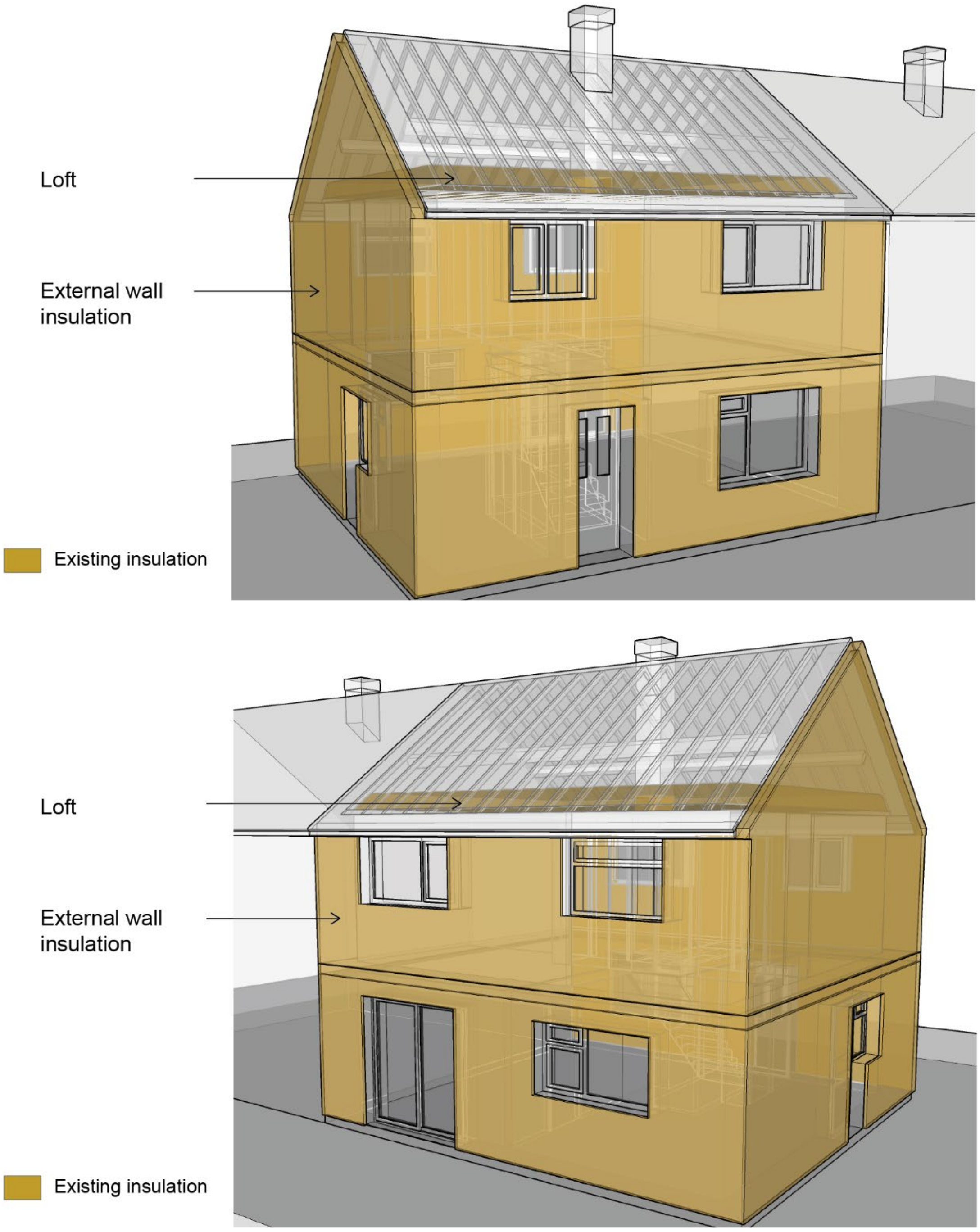

Figure 1-7 Insulation already in the property prior to the retrofits (04KG.B)

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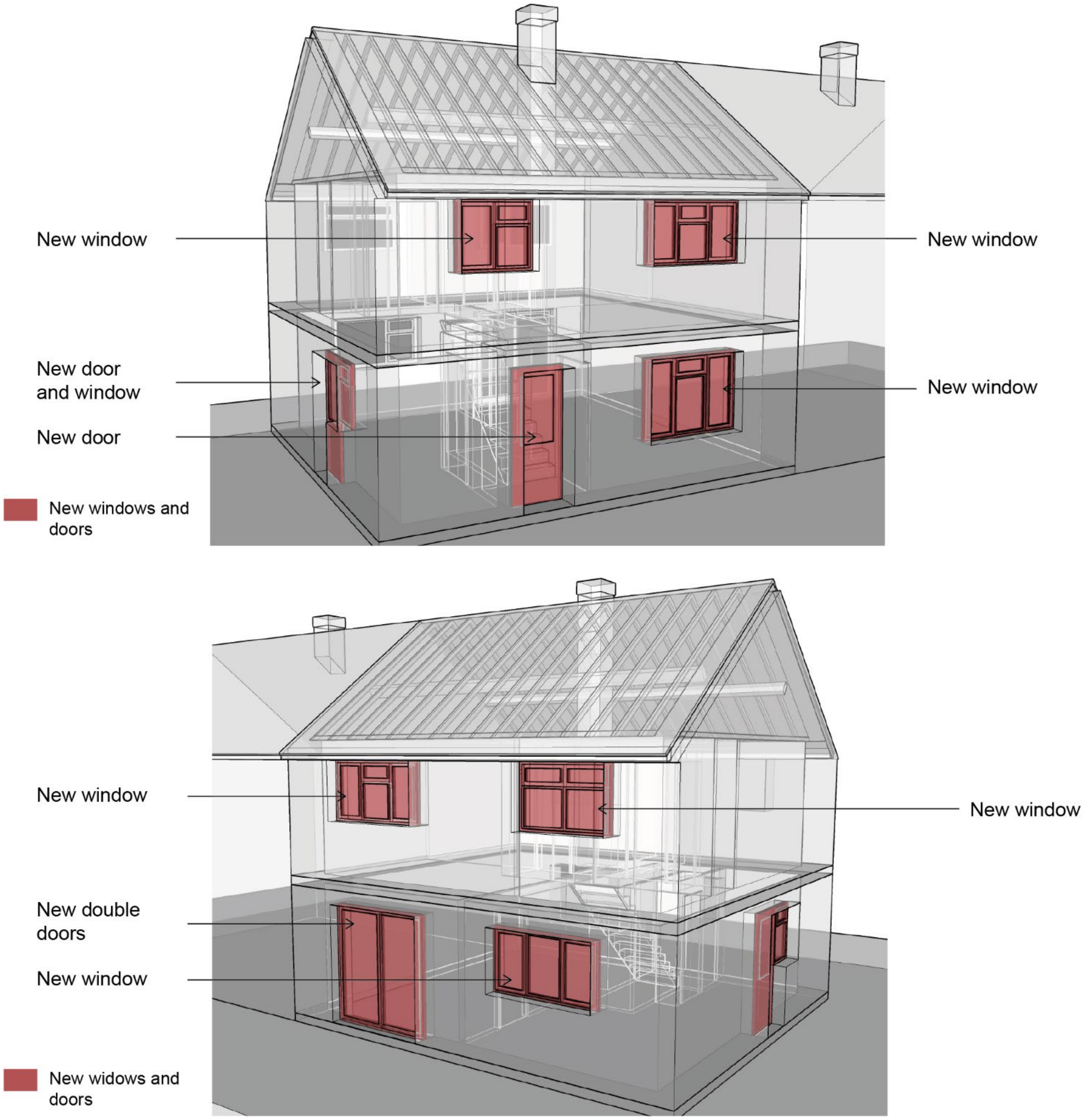


Figure 1-8 Stage 1: Installation of new windows and doors (04KG.G)[3]

[3] The external wall insulation has been removed from the graphic for clarity

2.02 DEEP 04KG

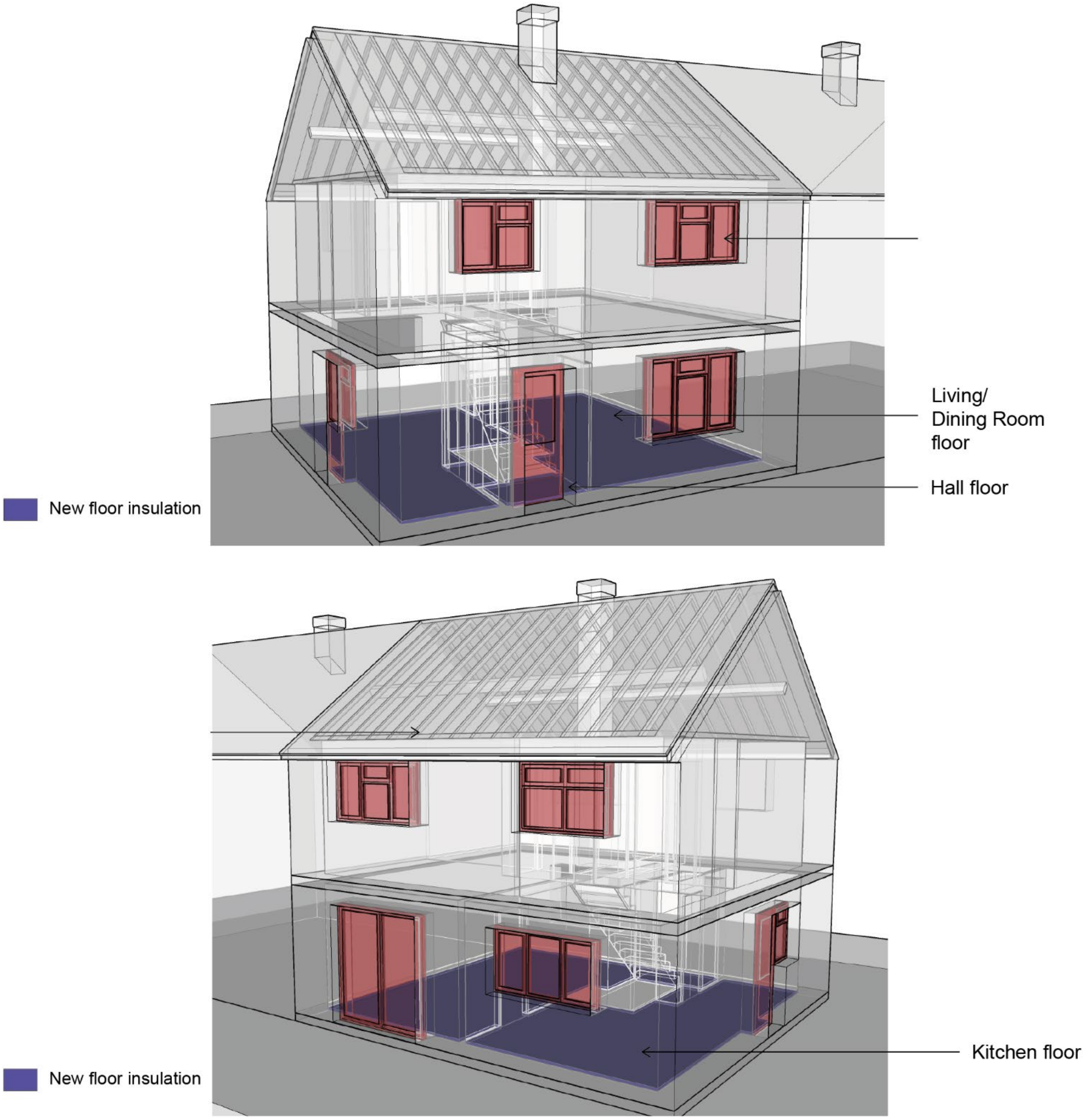


Figure 1-9 Stage 2: Installation of 20 mm aerogel blanket to solid ground floor (04KG.G.F)[4]

[4] The external wall insulation has been removed from the graphic for clarity

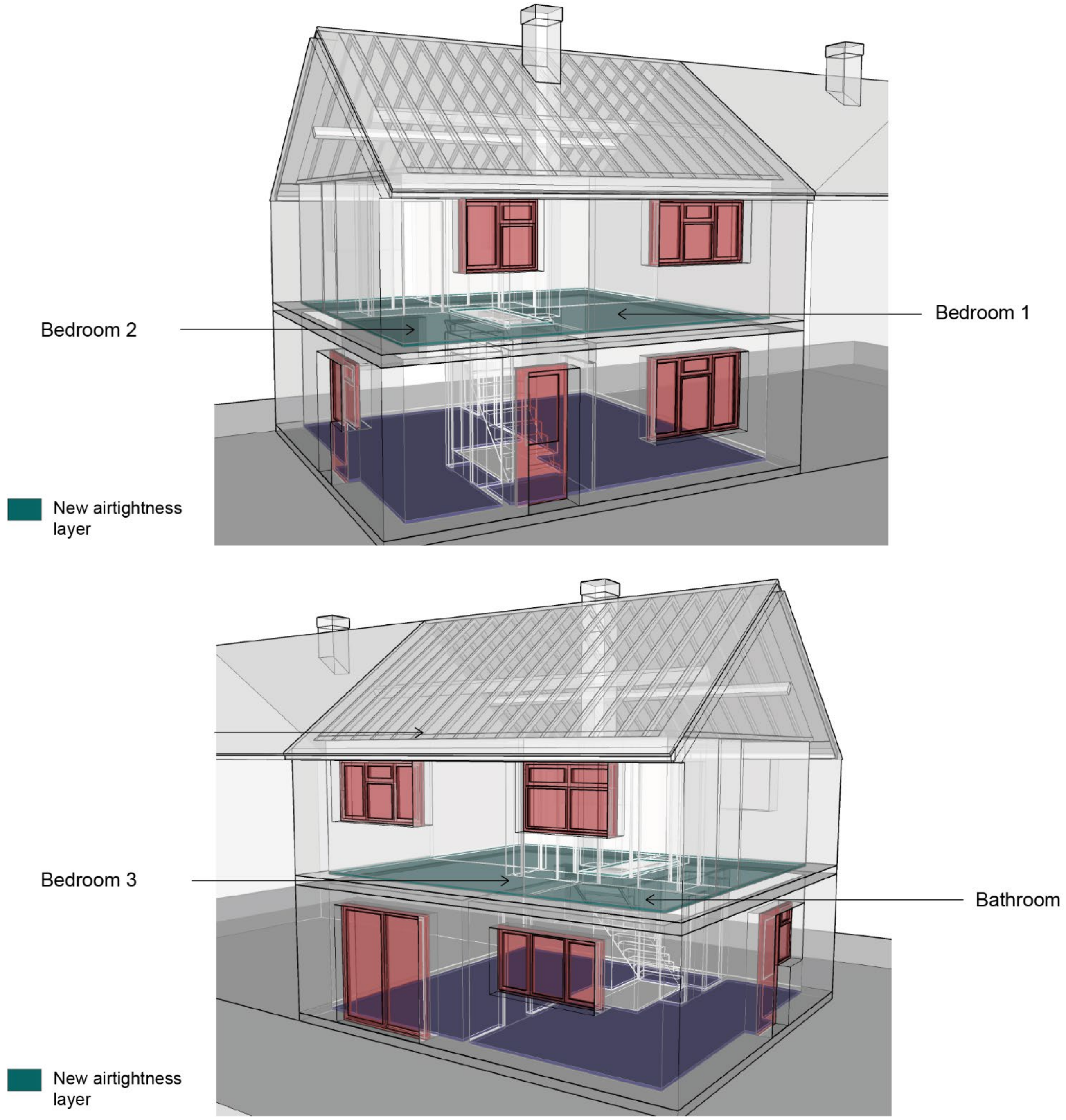


Figure 1-10 Stage 3: Airtightness improvements, intermediate floor, and penetrations sealing[5]

[5] The external wall insulation has been removed from the graphic for clarity

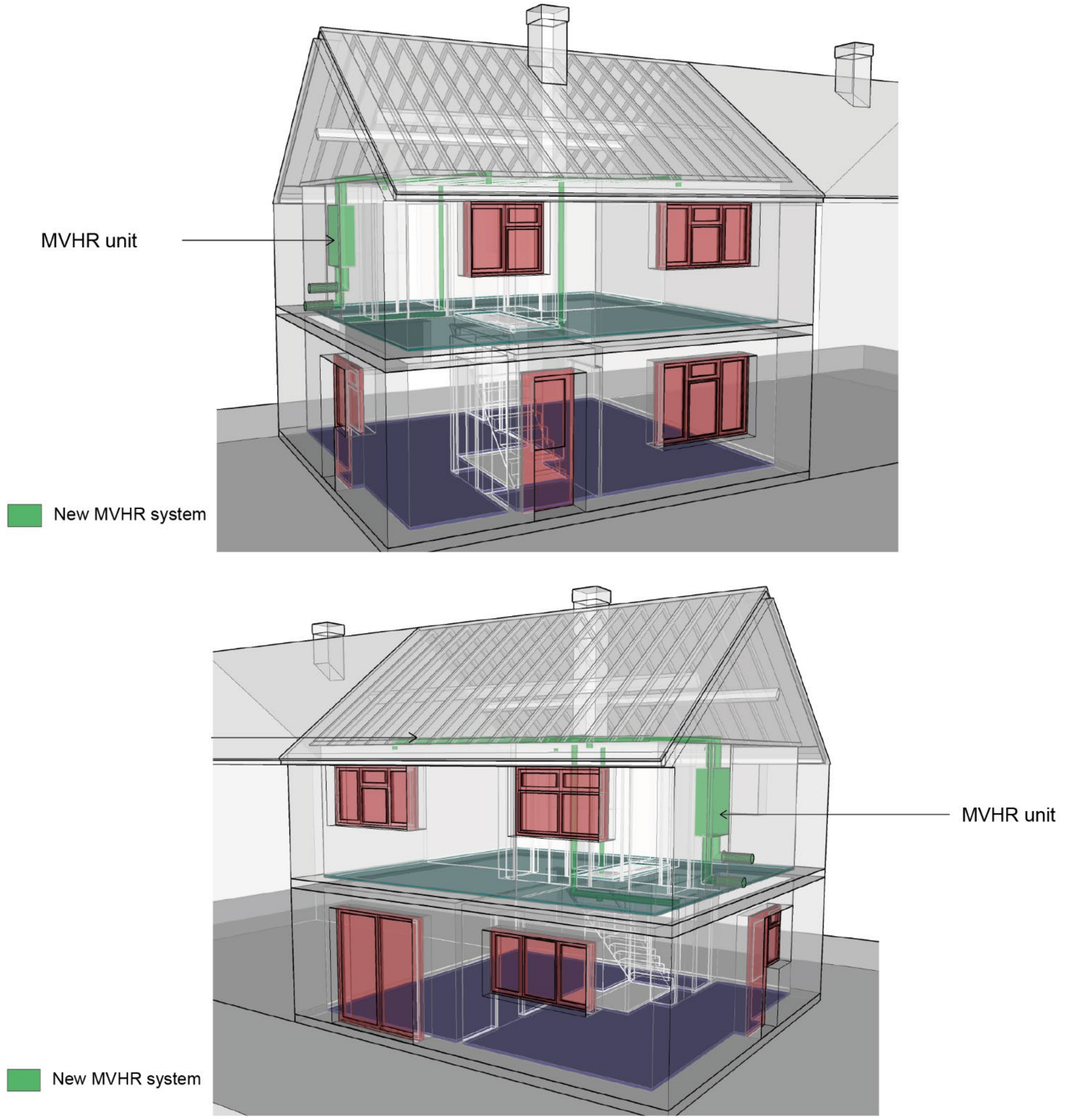


Figure 1-11 Stage 4: MVHR installation[6]

Case study and retrofit summary

04KG provided an opportunity to investigate the impact of several fabric improvements, which included new double glazing and composite doors, a novel approach to low disruption ground floor insulation, and improvements to airtightness.

Following the fabric retrofits, the opportunity later arose to investigate the implications of installing MVHR, more commonly installed in new builds, to explore its potential as a retrofit measure.

[6] The external wall insulation has been removed from the graphic for clarity

2 Fieldwork and modelling methods

BPE tests and modelling activities were undertaken on 04KG at each retrofit stage, in accordance with the methodologies listed in the DEEP Methods 2.01 Report. This section outlines the specific implementation of these methods at 04KG including any variations and additions.

2.1 Environmental data collection

Internal environmental data logging equipment is described in detail in the DEEP Methods 2.01 Report. Internal environmental data collected at 04KG included air temperature, Relative Humidity (RH) and CO_2 levels. External environmental data was collected via a weather station, installed on the south façade of the dwelling, to collect data on vertical solar irradiance and air temperature. This was supplemented by an external air temperature sensor positioned outside 04KG, placed at the rear of the home, attached to a downpipe to ensure that air temperatures were recorded on both sides of the house.

2.2 Measured survey

A detailed survey of the building was undertaken. From this, a digital version of the house was developed using SketchUp, which was used to calculate dimensions for each element and to draw up the plans shown in Figure 1-3. Plans, sections, and elevations were directly exported to generate the geometry for use in Dynamic Simulation Modelling (DSM). The construction makeup of the existing building was also assessed, where access could be gained, to observe the material construction.

2.3 Airtightness and thermography

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

2.4 Heat flux density measurement and U-values

26 Hukseflux HFP01 Heat Flux Plates (HFPs) were installed on different elements in 04KG. These were used to measure the baseline U-values, measure improvements achieved by the fabric upgrades, quantify party wall heat exchange, calibrate models, and estimate the fabric heat loss (HTC_f). These were compared with coheating tests and HTC disaggregation. The HFP locations are listed in Table 21 and visualised in Figure 21 and Figure 22. Thermography was undertaken to identify the most representative location for each fabric element, and multiple locations for each element were measured where possible.

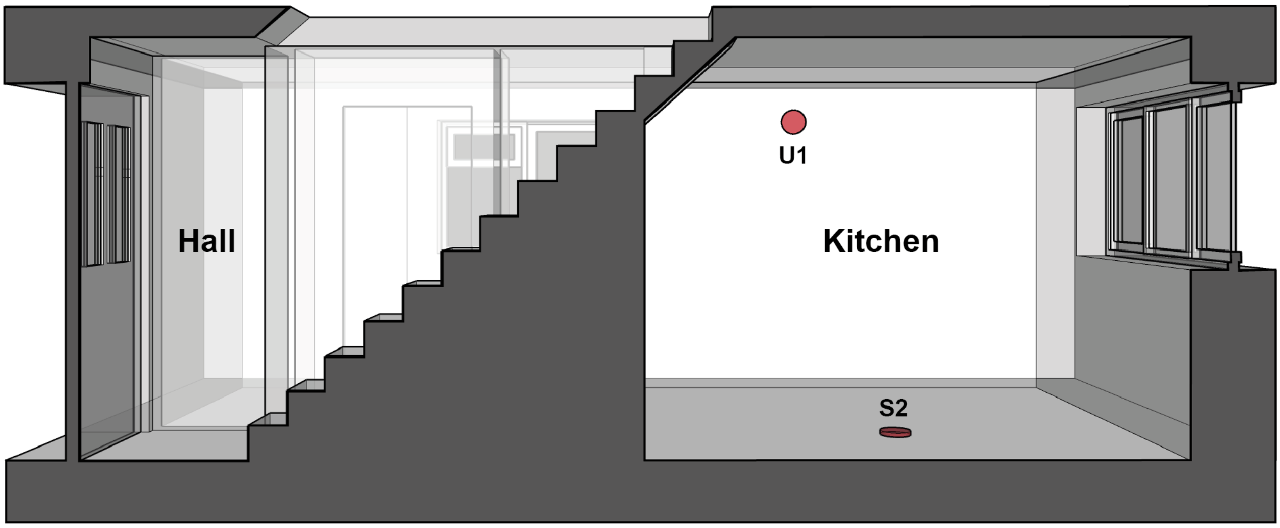
Table 2-1 HFP locations

HFP	Element	Room
U1	Gable wall	Kitchen
U2	Ground floor	Living/Dining room
U3	Ground floor	Living/Dining room
U4	Party wall	Living/Dining room
U5	Party wall	Living/Dining room
AD1	Gable wall	Bedroom 2
AD2	Gable wall	Bedroom 2
AD3	Gable wall	Bedroom 2
AD4	Gable wall	Bedroom 2
AD5	External wall	Bedroom 3
AD6	External wall	Bedroom 3
AD7	External wall	Bedroom 3
AD8	External wall	Bedroom 3
AD9	External wall	Bedroom 3
AD10	Ceiling	Bedroom 1
AD11	Ceiling	Bedroom 1
AD12	External wall	Bedroom 1
AD13	Party wall	Bedroom 3
AD14	Party wall	Bedroom 3
AD15	Party wall	Bedroom 1
AD16	Party wall	Bedroom 1
S1	External wall	Living/Dining room
S2	Ground floor	Kitchen
S3	Ground floor	Living/Dining room
S4	Ground floor	Living/Dining room
S5	External wall	Living/Dining room

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

Due to the building geometry, several the HFPs had to be installed in non-ideal locations. This is common in the domestic setting, as there is a limited surface area in which to place such sensors. In some areas where strong thermal bridging may be expected, such as near corners or interfaces between different components or constructions, heat flux density measurements were taken to provide context to the whole fabric heat loss and inform weighted average calculations.

It should be noted that, while every effort was made to measure representative U-values, the in-situ U-values are based on a limited set of measurements. This limited set of measurements cannot capture the full and varied behaviour of an element, though attempts were made to capture any variation in the U-value uncertainty.



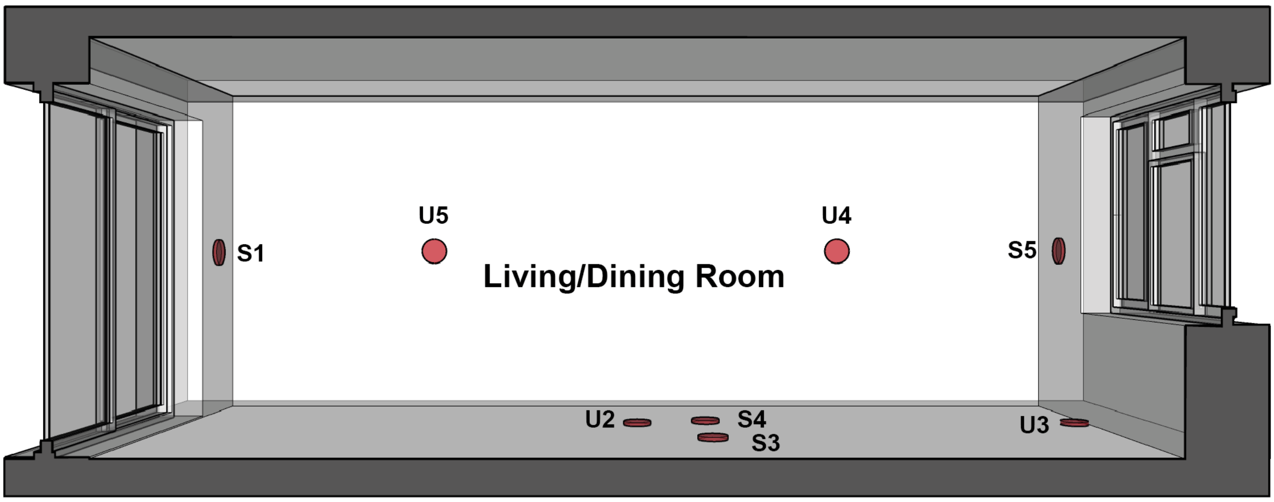


Figure 2-1 Ground floor HFP locations

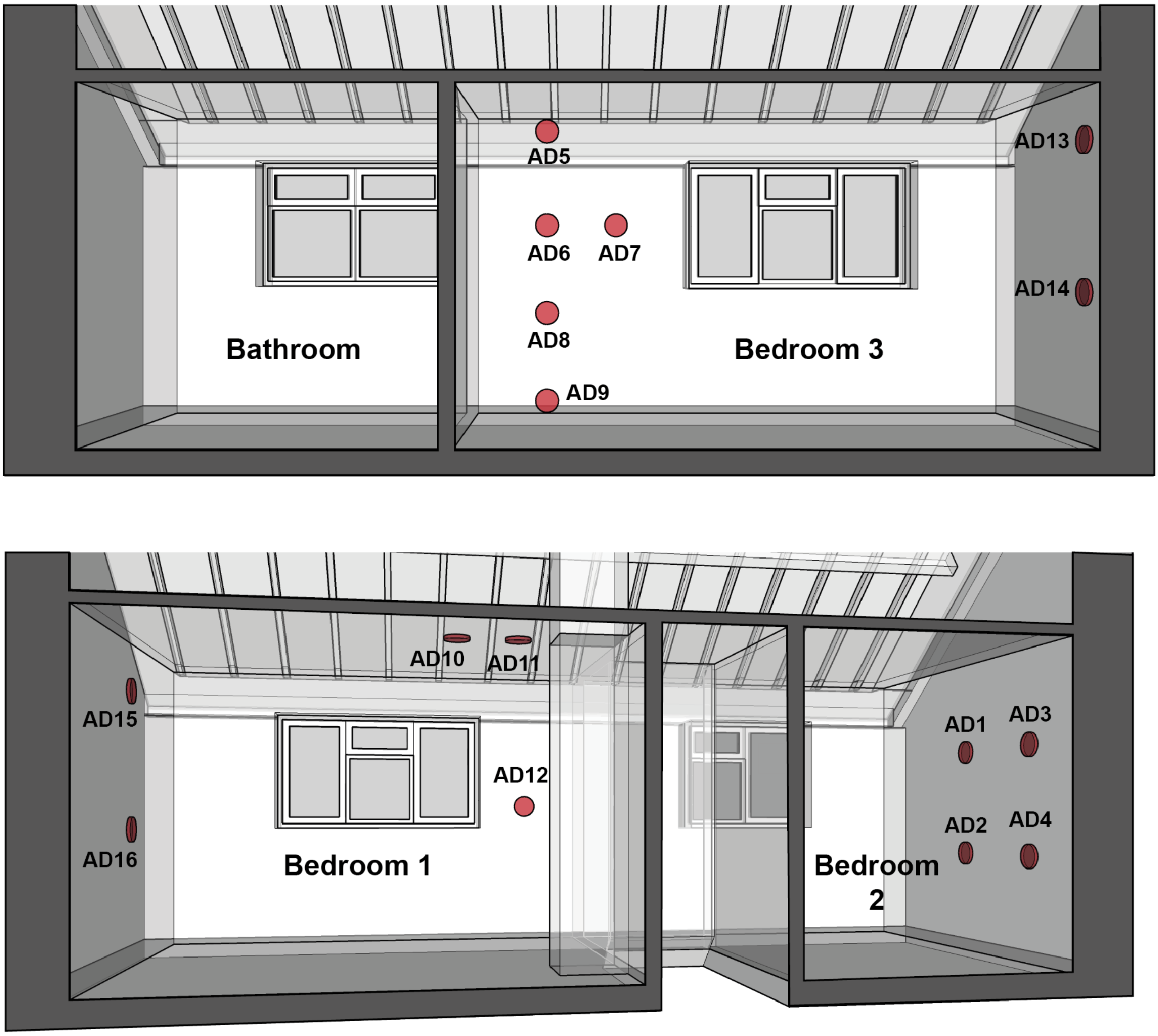


Figure 2-2 First floor HFP locations

While the BRE Calculator has the capacity to calculate the U-value of windows, in the case of 04KG, the necessary manufacturer details of the windows were not available. This included the glazing U-value, the frame U-value, and internal construction, to estimate the linear Ψ-value. The U-values for the windows had to be estimated from survey observations and are, therefore, uncertain as an energy model input.

2.5 Whole house heat transfer coefficient (HTC)

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

2.6 Whole building energy modelling

The modelling methodologies undertaken are explained in detail in the DEEP Methods 2.01 Report. DEEP first used 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 compared how these restrictions affected the HTC that BREDEM predicts. These were also compared with the HTC predicted by DSM (using DesignBuilder software version 7.0.0.088 [5]) at each retrofit stage. Table 2-2 describes the approach taken to understand how their predictions change as default inputs are overridden.

Table 2-2 Modelling Calibrations Stages

Calibration step	Infiltration	U-values	Bridging
1	Default[7]	Default[7]	Default[8]
2	Measured[9]	Default[7]	Default[8]
3	Measured[9]	Calculated[10]	Default[8]
4	Measured[9]	Measured[11]	Default[8]

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

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

Case study method summary

A deep dive into the 04KG retrofit case study was undertaken involving coheating tests, blower door tests, and 26 heat flux density measurements on fabric elements, taken before and after each of four retrofits performed.

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

These methods collectively investigated the energy performance associated with different approaches to retrofit, as well as the usefulness of models in the prediction of these factors.

[7] Provided by Appendix S RdSAP 2012 version 9.94
[8] Provided by Appendix K RdSAP 2012 version 9.94
[9] Derived from Blower door test
[10] Derived from BRE Calculator
[11] Derived from Heat flux plate measurements

3 Results

This chapter first presents results of the in-situ field trials: airtightness tests, U-values, and the whole house heat loss as measured by the coheating test. The fabric retrofits are first discussed, then a separate section is provided to discuss the MVHR retrofit. The chapter then describes how modelled predictions compared with the measured data and how successful the four calibration steps were at improving predicted heat loss, including assessing thermal bridging. The model outputs are discussed in terms of their implications for EPCs, space heating, CO_2 emissions, fuel bills, and paybacks.

3.1 Airtightness improvements

Several of the retrofits have impacted the infiltration rates in the house, and most (though not all) have served to reduce air leakage. Figure 3-1 presents the home's infiltration rate at each retrofit stage, measured by the blower door test.

Figure 3-1 shows the assumed infiltration rates in the EPC model which are much higher than measured, especially after the airtightness improvements are made. This has implications for the accuracy of EPCs, and especially how they predict energy savings from fabric and MVHR retrofits. Specifically, EPCs do not capture the benefits of airtightness improvements.

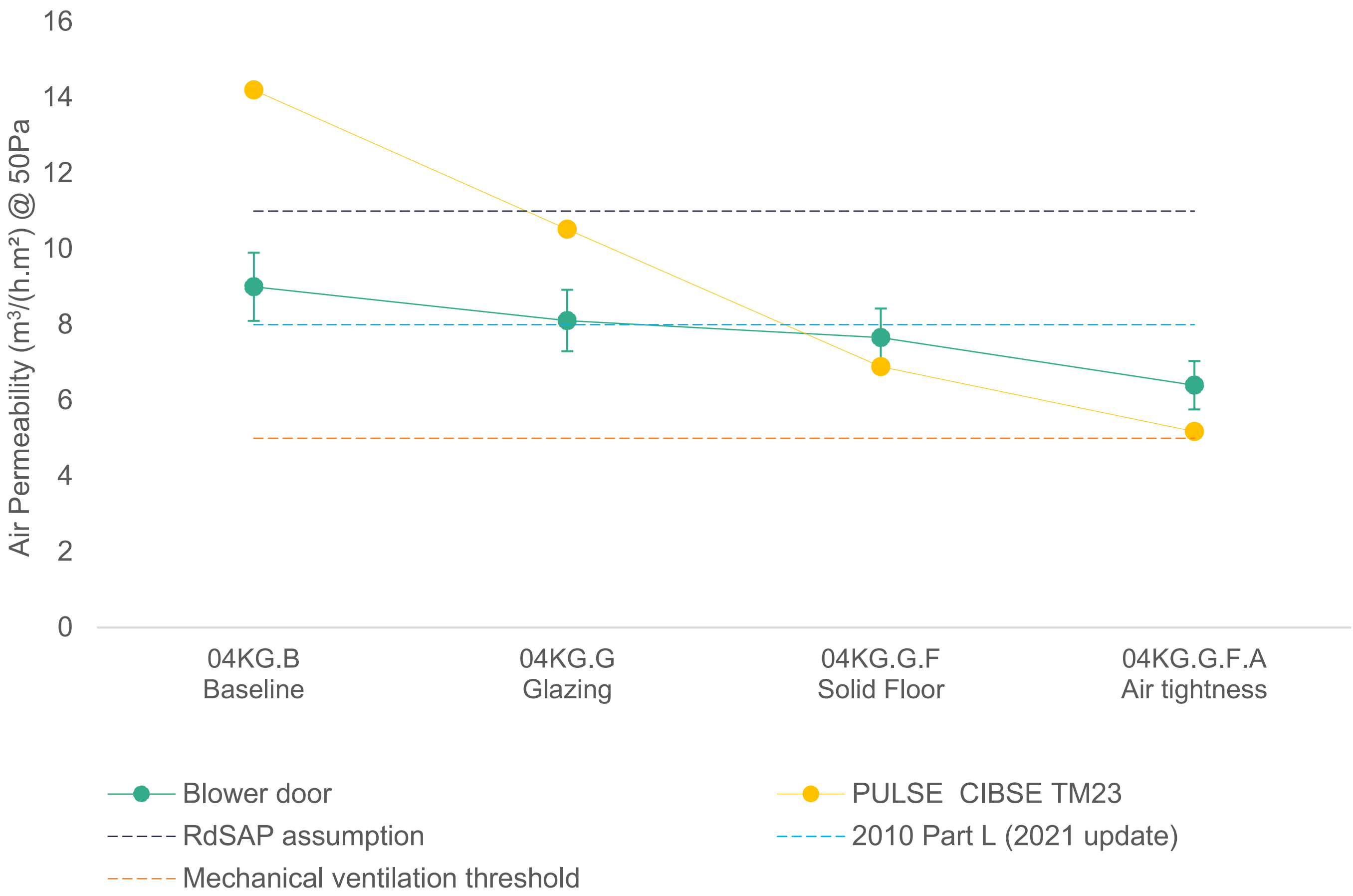


Figure 3-1 Airtightness improvements made at each retrofit stage

Also shown in Figure 3-1 are the results for the low-pressure Pulse test, which are observed to report more infiltration than the blower door test in the base case and post glazing retrofit. However, as the airtightness improved to about the 8 $m^3/(h·m^2)$ @ 50Pa, the Pulse test results appeared to correlate better with the blower door test values.

With the airtightness of this test house within the range expected for new build UK dwellings, the Pulse tests completed were mainly successful and showed a pattern with blower door tests undertaken at the same stage.

Where both low-pressure Pulse and blower door tests were undertaken at the same site visit, it was possible to provide a direct comparison of valid Pulse tests and blower door air permeability results to see how the conversion factor recommended in TM23:2022 ($5.254*(AP_4)^{0.9241}$) [6]. Such a comparative analysis is provided in the DEEP Report 2.0 Case Studies Summary.

The Building Regulations limiting value has also been provided for context (8 $m^3/(h·m^2)$). This house performs roughly in line with this value, even before the retrofits have taken place.

The airtightness sealing initially achieved a mean air permeability of 5.4 $m^3/(h·m^2)$ @ 50Pa, but accelerated shrinkage of mastic seals caused by the coheating test conditions saw many of these fail, and the final mean air permeability increased to 6.4 $m^3/(h·m^2)$ @ 50 Pa.

Some air leakage paths that were detected in the original condition of the property remained throughout the entire retrofit project. Figure 3-2 shows air leakage behind the boiler, whilst Figure 3-3 shows air leakage at the ground floor perimeter in the kitchen. Both details were obscured by fixtures and fittings and not immediately accessible, so were not addressed as part of the retrofit. Given their obstructed natures, it’s likely that many airtightness retrofits would neglect air leakage pathways such as these.

Figure 3-4 shows air being drawn down from the loft around the loft hatch and electrical service penetrations. Figure 3-5 illustrates the severity of infiltration at the front door threshold, with the very cold emerging air signifying a direct air leakage path from out to inside.

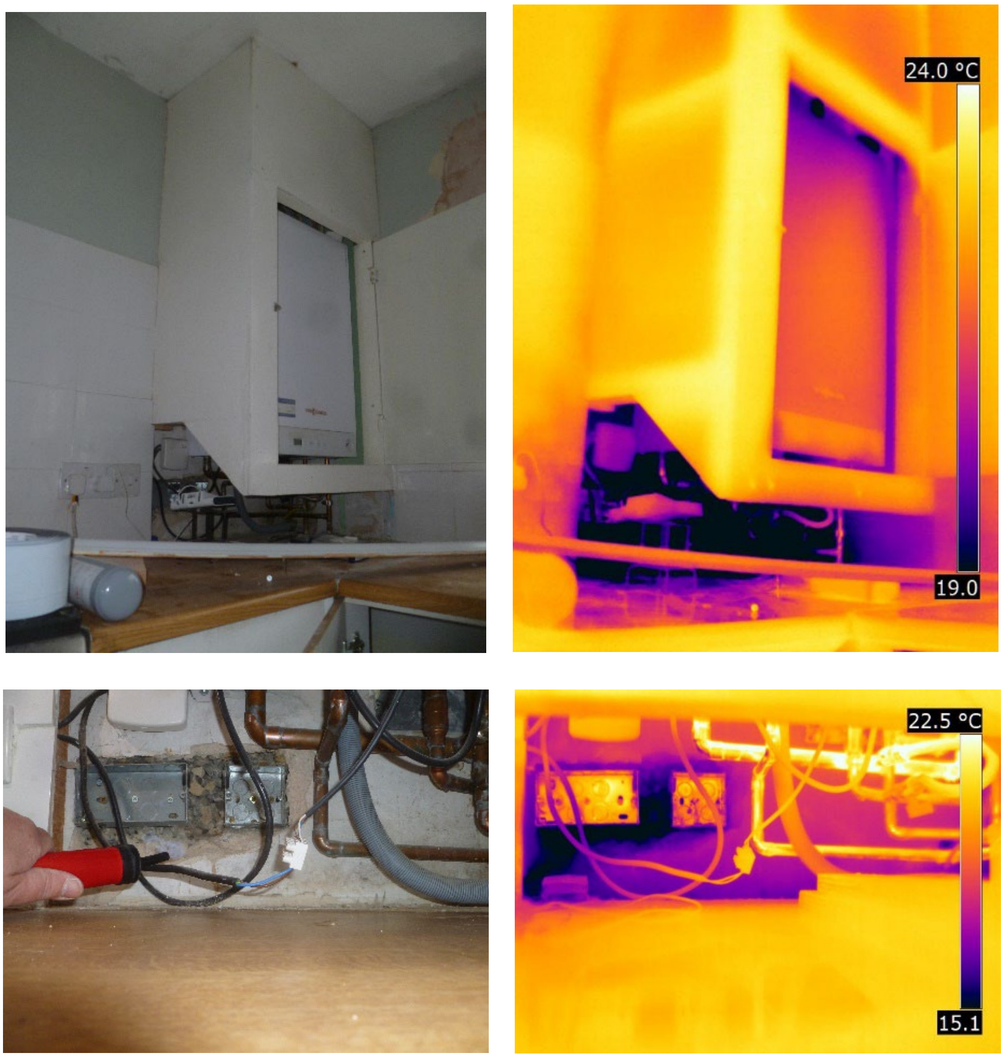


Figure 3-2 Air leakage at the unfinished no-fines wall around the boiler

Figure 3-3 Air leakage behind the kitchen units at the floor perimeter under depressurisation

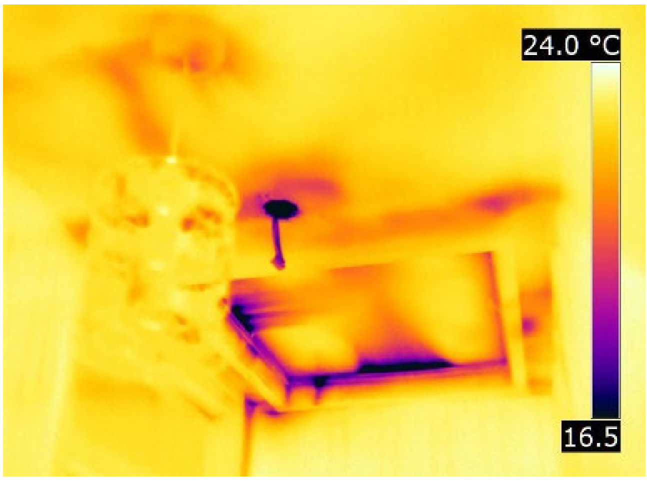


Figure 3-4 Air leakage at the loft hatch and other ceiling penetrations

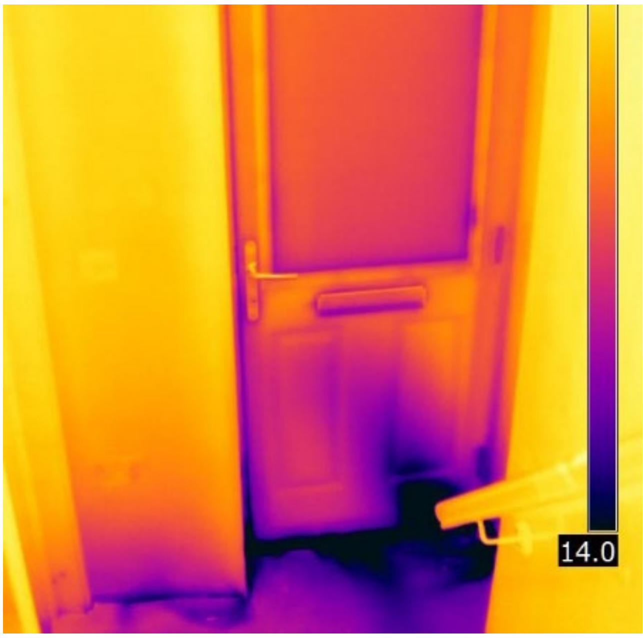


Figure 3-5 Air leakage at the external front door threshold

3.1.1 New glazing impact on airtightness

Despite being already reasonably airtight by existing UK standards (9.0 $m^3/(h \cdot m^2)$ @ 50Pa opposed to a UK mean of 11.5 $m^3/(h \cdot m^2)$ @ 50Pa for the existing stock, improvements were still achieved by the retrofits.

In this instance, the installation of the new glazing achieved a reduction from 9.0 to 8.1 $m^3/(h \cdot m^2)$ @ 50Pa, which is just within the error margin of the test, but indicative of a possible slight improvement. This may indicate that either the ageing seals in the original window casements were not as effective as those in the new windows, or that the air barrier between the wall and the windows themselves was not previously as effective as in the new installation.

Post-retrofit, air leakage was still observed at some locations around the windows and the patio doors. Figure 36 shows air leakage remaining at the threshold of the new patio door, whilst Figure 37 shows air leakage at the bedroom window trickle vents, corners, and at the jamb.

Thus, the benefit of installing new glazing was not as large as it could have been. The trickle vents were also observed to not be well-fitting or particularly airtight. The implications are that glazing replacements do not necessarily achieve their potential airtightness improvements if airtightness is not routinely checked as part of the installation.

Figure 3-6 The new patio doors under depressurisation

Figure 3-7 Air leakage at window trickle vents and jamb in the bedroom[12]

[12] The cold strip at the wall - ceiling junction is caused by the EWI only continuing up to window head level.

3.1.2 Solid ground floor retrofit impact on airtightness

The next retrofit was the solid ground floor retrofit stage. This was not expected to reduce the infiltration rates substantially, since the solid ground floor slab does not pose the same risk of air movement as suspended timber ground floors with built-in joists. This was confirmed, since the apparent small improvement observed, from 8.1 to 7.7 $m^3/(h \cdot m^2)$ @ 50Pa, was within the uncertainty of the test method.

3.1.3 Air leakage sealing impact on airtightness

Following this, airtightness specific measures were undertaken by specialist airtightness contractors. The approach adopted involved installing plywood to the intermediate floor surface to create a secondary air barrier, plus some remedial sealing around service penetrations in the external walls and ceilings. This was effective in significantly reducing the mean air permeability to 5.4 $m^3/(h \cdot m^2)$ @ 50Pa, making it just slightly above the maximum recommended level for MVHR to be energetically efficient (5.0 $m^3/(h \cdot m^2)$ @ 50Pa). However, subsequent coheating tests caused accelerated shrinkage that resulted in adhesion failure of some of the mastic and tape seals, resulting in the final air permeability achieved being 6.4 $m^3/(h \cdot m^2)$ @ 50Pa, a 16 % reduction.

Homes that have airtightness levels below 5 $m^3/(h \cdot m^2)$ @ 50Pa are expected to have some form of continuous mechanical ventilation system, which can include MVHR. The ideal target for MVHR to work most effectively is below 3 $m^3/(h \cdot m^2)$ @ 50Pa. In this instance, it was not possible to achieve this performance level since the remaining air leakage pathways, such as those behind the boiler and built-in kitchen units as shown in Figure 3-2 and Figure 3-3, could not be readily accessed. Removing these fixed items to perform sealing here would have been disruptive, time consuming, and would have incurred significant extra cost; an entire new kitchen might have been necessary had the existing units been damaged. A homeowner would be unlikely to undertake this, though these issues could be addressed when the items are replaced in the future.

Despite the airtightness contractors having sealed the intermediate floor, Figure 3-8 shows air being drawn into the intermediate floor void from the no-fines external gable wall above the side entrance under dwelling depressurisation. Figure 3-9 shows further indirect infiltration on the rear external wall. These suggest that covering the intermediate floor surface restricted the flow of air through these interconnected voids but could not eliminate it.

Figure 3-8 Following airtightness work, cooler air could still be observed being drawn into the intermediate floor under dwelling depressurisation in the kitchen

Figure 3-9 Following airtightness work, cooler air could still be observed being drawn into the intermediate floor under dwelling depressurisation, in the bedroom floor

As mentioned, the accelerated shrinkage and settlement resulting from the subsequent coheating test saw the mean air permeability rebound from 5.4 to 6.4 $m^3/(h \cdot m^2)$ @ 50 Pa, with some of the tapes and mastic sealants used as part of the airtightness retrofit already starting to develop adhesion issues in a number of areas.

Areas of failed mastic at the intermediate floor room perimeters appeared to result from a lack of elasticity in the mastic, rather than poor surface preparation, as shown in Figure 3-10. This suggests that approaches to reducing air leakage in homes that rely on sealants and tapes may not be robust, even when applied by specialists.

This may be significant for both retrofit and new builds, where often, tapes and mastic seals are applied before testing to achieve compliance with standards. These findings indicate that where this takes place, the homes may temporarily achieve compliance, but subsequently have a lower level of performance during occupation.

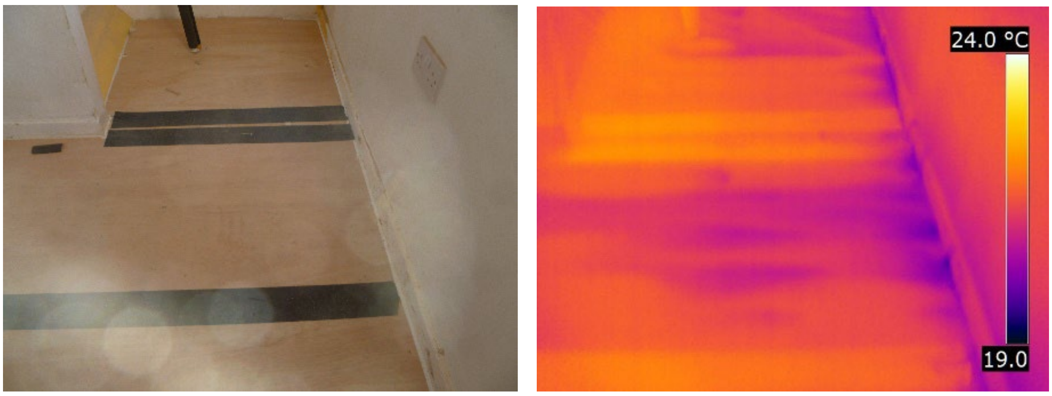


Figure 3-10 Air leakage into bedroom 2 intermediate floor void under depressurisation and through the failing mastic perimeter seal following coheating

The implication is that it is likely to be difficult to achieve the recommended airtightness levels in homes like 04KG, to a level where MVHR may be beneficial in reducing energy consumption. There remain several non-energy benefits associated with the installation of an MVHR system that should also be considered. However, to measure these would require longitudinal monitoring of the internal environment, which is out of scope of the DEEP project.

In this house type, the implication of not being able to access penetrations through walls to retrofit seals may be more pronounced than in other constructions. As can be seen in Figure 3-11, it can be difficult to create neat penetrations in the external wall without damaging the surround wall, making airtight seals difficult to achieve and increasing the chance of air leakage.

Figure 3-11 No-fines construction around boiler flue wall penetration

3.1.4 Inter-dwelling air exchange and party wall bypass

Significant differences in surface temperature between the party wall and gable wall were observed in the loft. The warmer area observed at the ridge of the party wall suggests air was being warmed up inside gaps in the no-fines party wall and rising through interconnected voids and emerging at the top, as shown in Figure 3-12. This finding is consistent with other studies showing that no-fines construction has a party wall bypass.

To further investigate this, a co-pressurisation airtightness test was undertaken on the property directly following the window and door retrofit. Both the test house and the connected property were maintained at the same pressure to remove drivers for air movement across the party wall. This test was performed under pressurisation only and saw the air permeability fall from 8.3 to 6.9 $m^3/(h\cdot m^2)$ @ 50 Pa under co-pressurisation, verifying that air movement into or across the party wall is taking place.

Co-pressurisation is likely not representative of air movement across the party wall under natural conditions. However, it illustrates that a significant proportion of the measured air leakage from the standard blower door test is *not* exchanged with the external environment, but inter-dwelling exchange of pre-conditioned air. This finding is replicated across other DEEP case studies and a discussion of this is included in the DEEP Report 2, Case studies summary. The findings have implications for measurements of infiltration using blower door tests, their inferred heat loses, and fresh air provision in adjoined dwellings; i.e. EPCs awarded to homes with attached dwellings could be underestimated, with homes receiving less fresh air than anticipated.

Figure 3-12 The party wall (left) and gable wall (right) in the loft

3.1.5 CO_2 decay tests

Timed CO_2 releases were undertaken in the house in its original condition in November and December 2020. Analysis of the CO_2 decay indicated ventilation rates of between 0.66 & 1.22 h^{-1} in the living room by the point of release, with an average of 0.95 h^{-1} and 0.47 & 0.55 h^{-1} in the first floor master bedroom.

The results suggest that the ventilation rate of the ground floor was noticeably higher (almost twice) than that of the first floor. However, some of this higher rate may be explained by dispersal and distribution of CO_2 through the property rather than just air leakage. Following releases, the CO_2 concentration upstairs peaked over an hour after downstairs peaked, suggesting the bulk movement of air from downstairs to upstairs happened at quite a slow rate due to the reasonable level of airtightness of the property.

Timed CO_2 releases were repeated following the window/airtightness retrofit in December 2020. Analysis of the CO_2 decay indicated ventilation rates between 0.79 and 1.12 h^{-1} on the ground floor by the point of release, with an average of 0.93 h^{-1} and 0.40, 0.44 & 0.45 h^{-1} in the firstfloor bedroom. The results suggest that the ventilation rates had only marginally reduced, but the time between the CO_2 concentration peaks upstairs triggering peaks downstairs had increased more significantly, by up to two hours. The airtightness retrofit had involved covering and edge-sealing the intermediate floor, leaving the only clear route for air from downstairs to upstairs as the stairwell, extending the longer period between peaks of CO_2 concentration.

Further timed CO_2 releases in November 2021, following additional airtightness measures, displayed ventilation rates commensurate with the increased airtightness of the house. Analysis of the CO_2 decay indicated ventilation rates between 0.60 & 0.78 h^{-1} (with an average of 0.675 h^{-1}) on the ground floor. However, the lower ventilation rates prevented accurate analysis of the first floor decay rates, due to elevated concentrations from the ground floor continuing to affect the first floor for an extended period.

In summary, these results show the complexity in deriving reliable whole house airtightness and ventilation data based on discontinuous CO_2 releases and decay analysis. For the multi-zonal analysis required for most homes, techniques where CO_2 is equally dispersed throughout the home may be more appropriate.

3.2 U-value improvements

Three methods were adopted in deriving U-values:

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

All three methods are used in DEEP, for comparison, and this section reports on the difference between them. The report considers implications of the method selected on accuracy of energy and heat loss predictions, the contribution of fabric elements to the HTC, and the predicted benefit achieved by retrofits. A summary of the U-value measurements for each of the fabric elements is presented in Figure 3-13 and Figure 3-14.

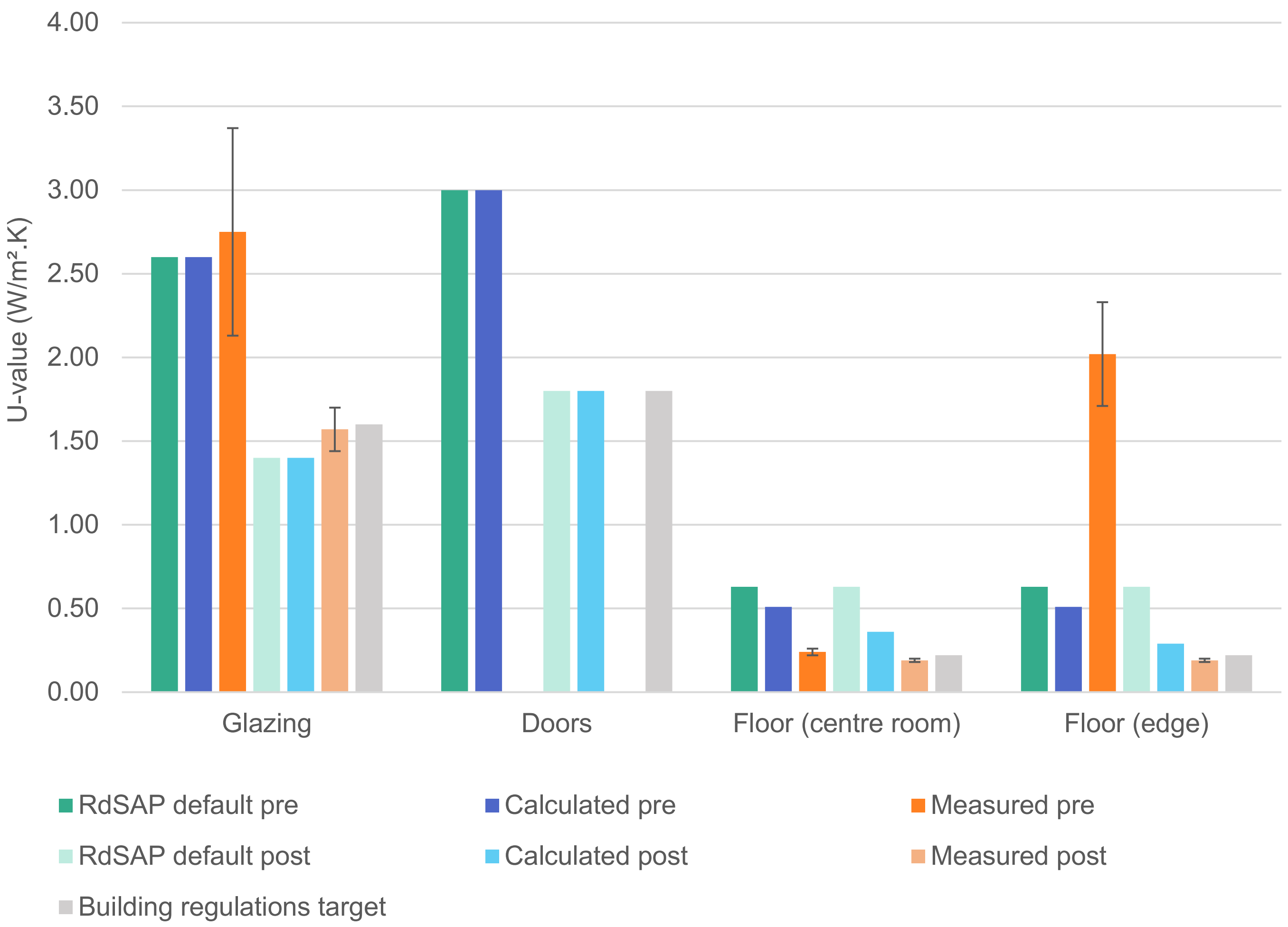


Figure 3-13 Pre- and post-retrofit fabric U-values that were improved (W/(m^2·K))

Two ground floor U-values are reported in Figure 3-13: the ‘centre room’, calculated from plates far from the edges of the concrete slab (plates U2 at the baseline, and later S2, S3, S4); and the ‘edge’, calculated from plate U3 to identify relative heat loss occurring at the wall-to-floor junction. However, given the variability apparent between the floor edge and centre, particularly at the baseline stage, these HFPs alone are likely representative of the entire ground floor. To effectively measure ground floor U-values, it has been shown that multiple HFPs arranged representatively across the floor are required to capture the heterogeneity in heat flow [4-6]. The ground floor retrofit in 04KG was not planned until after the initial testing of the base line home had taken place, so for the pre-retrofit stage there were only two HFPs installed, which is insufficient to gain a holistic understanding of the ground floor heat losses. Therefore, the calculated pre-retrofit ground floor U-value has been used to estimate pre-retrofit ground floor heat loss. The post-retrofit U-value is based on five HFPs, which are more representative of the entire ground floor heat losses, and so this U-value is used in post-retrofit heat loss estimates.

The measured glazing U-values shown are centre pane values, so again does not include the frame. This is a limitation, but it is not expected to make a significant difference in the whole house HTC. Glazing is more prone to temperature variation than opaque elements, so is harder to measure in real conditions. It was not possible to measure the U-values for the door, owing to a lack of HFPs, with priority being given to the larger fabric elements responsible for the greatest proportion of heat losses. As the door U-values were not measured, the RdSAP defaults based on Appendix S were used in the pre-retrofit case, and the declared values by the manufacturer used for the post-retrofit stages. The U-values of the fenestrations are therefore a source of uncertainty.

Figure 3-14 shows the U-values measured for the walls and the ceiling that were not altered as part of the retrofit.

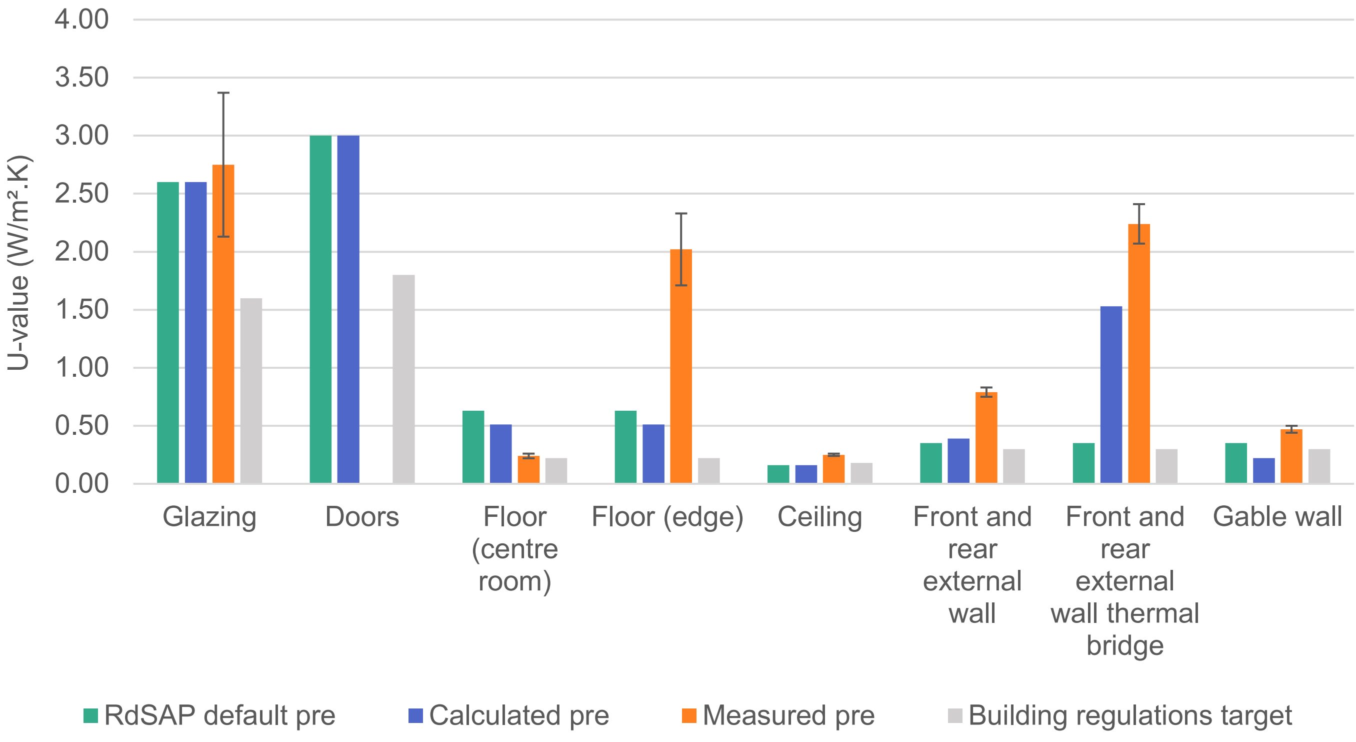


Figure 3-14 U-values of fabric elements that were not retrofitted (W/(m².K))

The external wall U-values are separated into 'Front and rear', and 'Gable'. This is because the front and rear walls displayed a thermal bridge that ran around the first floor, below the loft ceiling. This was caused by the EWI not continuing behind the soffit and facia boards. This resulted in an uninsulated strip in all the front and rear external walls in the upstairs rooms, which is shown in Figure 3-15. This increase in heat loss through the wall was captured and integrated into the area weighted U-value for the front and rear walls. The U-value of this strip alone is also quoted in Figure 3-15 for context. The analysis suggests the thermal bridge resulted in a U-value for the front and rear walls that was a third higher than that of the gable wall, causing a large performance gap. Additionally, this strip may pose a condensation risk in the bedrooms and bathroom.

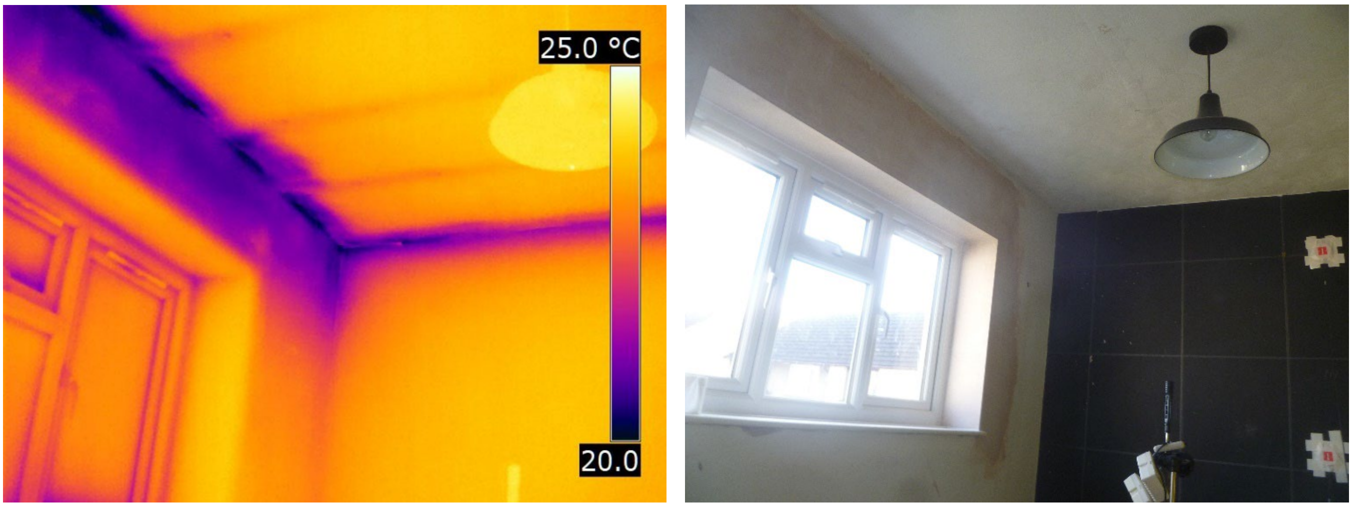


Figure 3-15 Thermal bridge at first floor ceiling caused by EWI stopping at the box soffit

A summary of all the pre- and post-retrofit U-values for 04KG derived from each method is in Table 3-1.

RdSAP does not allow the inclusion of the uninsulated strip of external wall, meaning it assumes the front and rear external walls have a similar U-value to the gable wall. The calculated and measured U-values shown are, however, area weighted to include this, so the gable U-values can be considered different to the front and rear U-values.

Additionally, RdSAP does not allow consideration of the floor insulation, since it is thinner than 50 mm. The BRE calculator suggests this reduced the floor U-values by 37 %. Measured U-values were not taken pre-retrofit, as mentioned, since the floor retrofit was not part of the initial retrofit plan, however, post-retrofit U-values are shown. While these values are based on five HFPs distributed throughout the home, there were not sufficient HFPs to account for heat loss from edge effects. For this reason, the floor post-retrofit U-values calculated by the BRE calculator are higher than those measured.

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

	Pre-retrofit			Post-retrofit U-value (% improvement)		
	RdSAP Default	Calculated	Measured	RdSAP Default	Calculated	Measured
Glazing	2.60	2.60	2.75 ± 0.62	1.40 (46 %)	1.40 (46 %)	1.57 ± 0.13 (43 ± 63) %
Doors[13]	3.00	3.00	-	1.80 (40 %)	1.80 (40 %)	-
Ground floor	0.63	0.51	-	0.63 (0 %)	0.29 (43 %)	0.19 ± 0.01 (-)
Front & rear Walls	0.35	0.39	0.73 ± 0.04	-	-	-
Gable wall	0.35	0.22	0.47 ± 0.03	-	-	-
Ceiling	0.16	0.16	0.25 ± 0.01	-	-	-

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

Element	RdSAP default predicted reduction (W/(m²·K))	Calculated predicted reduction (W/(m²·K))	Measured reduction (W/(m²·K))	RdSAP defaults prediction gap (W/(m²·K))	'as-built' performance gap (W/(m²·K))
Glazing	1.20	1.20	1.18 ± 0.63	0.02 ± 0.63	0.02 ± 0.63
Doors[13]	1.20	1.20	-	-	-
Ground floor	0	0.22	-	-	-

[13] No HFP recordings were obtained for the Doors

3.2.1 Contribution of fabric heat loss (HTC_f) to HTC

Table 3-3 shows an estimate of the fabric heat losses (including repeated bridging), based on the area of the fabric and area weighted U-values, as measured by the HFPs before and after the cumulative retrofits. For the pre-retrofit ground floor U-value and both the pre- and post-door retrofit U-values, the BRE calculator was used in the absence of reliable HFP measurements.

Since 04KG already had EWI, and there was a relatively large area (10 % of heat loss area) of glazing (the patio doors were considered as glazing), the heat loss attributable to these pre-retrofits was equal. When new glazing was installed, the heat loss was predicted to reduce by 20 W/K, meaning external walls became the most significant heat loss element.

Table 3-3 Impact of retrofit on fabric plane element heat loss (including repeated bridging)

Element	Pre-retrofit (W/K)	*Proportion of heat loss Pre-retrofit*	Post-retrofit (W/K)	*Proportion of heat loss Post-retrofit*
External walls	45	*35 %*	45	*49 %*
Ground floor[14]	20	*16 %*	8	*8 %*
Roof	10	*8 %*	10	*11 %*
Glazing (windows and patio door)	45	*35 %*	25	*28 %*
Doors[14]	7	*5 %*	4	*4 %*

The ground floor and door retrofits resulted in relatively small reductions in HTC, of 12 and 3 W/K respectively[15]. These changes are illustrated in Figure 3-16, which also shows the difference between the RdSAP assumed heat losses, those calculated using the BRE calculator, and those derived from the area-weighted HFP measurements (which attempted to account for repeated thermal bridging).

The main observations from this are that the measured external wall U-values were much higher than expected, and that the floor retrofit was assumed to make no improvement in the fabric heat loss of the floor according to the RdSAP default values. This is because the software does not allow for insulation values thinner than 50 mm to be considered.

[14] Measured U-values are assumed to be equal to the calculated values
[15] No uncertainties can be calculated for these values since the pre retrofit U-value is based on calculations

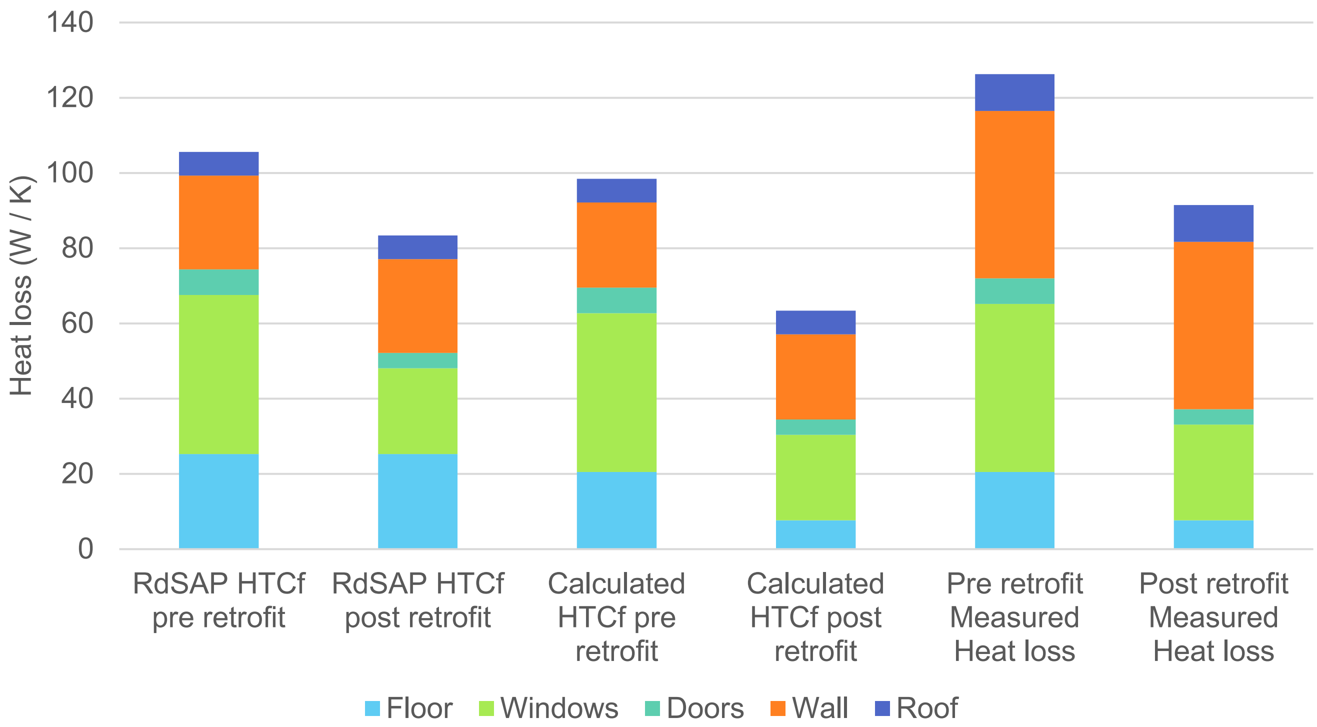


Figure 3-16 Heat loss of fabric elements pre and post-retrofit

U-value improvement summary

The savings assumed by RdSAP for the glazing were similar to the calculated reductions, as were those that were measured by the centre pane HFP, despite the latter not accounting for the window frames. However, several features of this home lead to different U-values compared to those predicted by RdSAP when producing EPCs.

Firstly, RdSAP did not account for the ground floor retrofit in its U-value predictions, since the insulation was thinner than 50mm.

Secondly, the U-value measurements picked up underperformance in the existing EWI, and specifically quantified the additional heat loss caused by the EWI not extending behind the soffit and facia boards.

This underperformance meant that the RdSAP predicted value was much lower than achieved by the EWI in the home. Despite this, the EWI appears to have reduced the heat loss from the home substantially. For instance, in the base case, the same amount of heat was lost through the windows as the external walls.

There was considerable variation in the U-values derived from the HFPs positioned on the edge of the ground floor pre-retrofit (2.02 ± 0.20 W/(m^2·K)) and in the centre of the room (0.24 ± 0.02 W/(m^2·K)). The markedly different values confirm that edge effects substantially influence solid ground floor heat losses, and that to reliably measure the U-values for ground floors, multiple HFP measurements must be used in representative locations.

Since it was not possible to derive U-values in the baseline home, the BRE U-value calculator was used as the baseline reference U-value, so savings from the ground floor retrofit can only be predicted.

3.3 Whole house heat loss (HTC) improvement

In this case study the approach to improving HTC involved standard measures applied to the thermal envelope (improvements in insulation and in fabric air infiltration) and a reduction in ventilation heat loss via the installation of MVHR. These two approaches are qualitatively different and for the sake of presentational clarity, this section deals with standard fabric measures and section 3.5 with MVHR performance.

3.3.1 Impact of fabric retrofits on HTC

The cumulative reduction in HTC achieved by the fabric retrofits, as measured by coheating tests, was (30 ± 10) W/K (19 ± 6) %. The measured heat loss for 04KG at each stage is shown in Table 3-4.

Table 3-4 Test house measured HTC after each retrofit stage

Retrofit stage	HTC (W/K)	HTC Uncertainty	HTC Reduction (W/K)	Percentage reduction
04KG.B Base case	154	9 (6 %)	-	-
04KG.G Glazing & doors	148	8 (5 %)	6 ± 12	(4 ± 8) %
04KG.G.F Solid floor insulation	119	13 (11 %)	29 ± 15	(20 ± 10) %
04KG.G.F.A Airtightness improvements	124	4 (3 %)	-5 ± 14	(-4 ± 11) %
Cumulative reduction			***30 ± 10***	***(19 ± 6) %***

The HTC for each test phase is shown in Figure 3-17 and the following sections discuss the results for the specific retrofit.

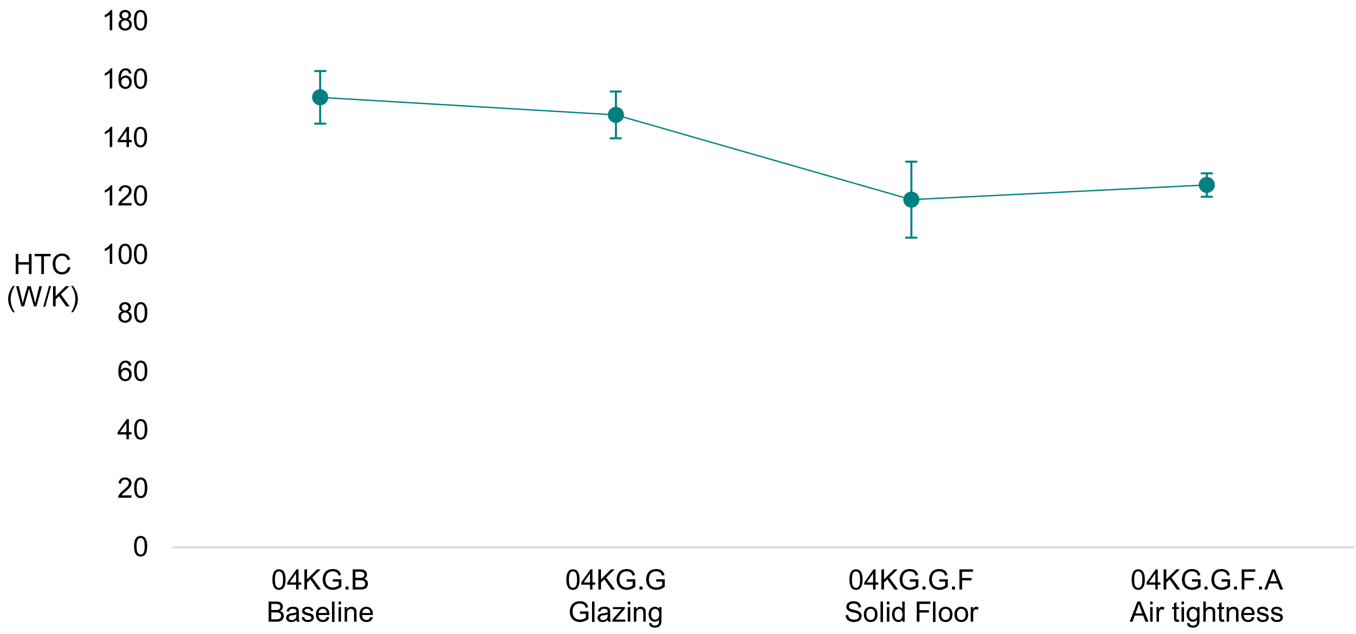


Figure 3-17 Coheating HTC at each retrofit stage

With the exception of the solid ground floor insulation stage which had an uncertainty around 11 %, the coheating tests had lower levels of uncertainty (3 % and 6 %) than the 8 % to 10 % previously estimated [10, 11]. This uncertainty in the solid floor insulation stage was due to an increase in solar and party wall heat loss, which cannot be perfectly accounted for.

Glazing and doors: 04KG.G

As already discussed, the new glazing units (windows and the patio door) were expected to be responsible for around 50 % of the plane element fabric heat losses in the building, according to the U-value measurements. As reported in section 2.4, the reduction achieved by the new double glazing was expected to be in the region of 20 W/K based on the U-value improvements. There was, however, uncertainty in the pre- and post- U-values of the glazing, as discussed in Section 2.4.

The coheating test measured an HTC change of only 6 W/K (from 154 ± 9 W/K to 148 ± 8 W/K), a value that was within the uncertainty of the test. This disagrees with the expected change. It is possible, therefore, that the original glazing was actually performing better than assumed, or that the installation quality of the new glazing was not as high as expected. The glazing involved replacing window frames and insulating gaps between the wall and the frame that were pre-existing. In addition, the no-fines construction presented problems during the installation due to the tendency of no-fines to be rather friable when the edges of window openings are exposed (as can be seen in Figure 3-7). Gaps around the frames were insulated during the installation of the new windows but the results suggest some air leakage persisted. Additionally, the trickle vents were not well sealed to the frame, causing additional heat loss.

The benefit of replacing existing double glazing can only be determined if prior knowledge of the performance of the existing glazing is known. It would be beneficial for windows to have performance standards stated on frames to support future retrofits. The improvement made will depend on the performance of the existing double glazing and the installation quality of the new windows. More investigations are needed on different house and window types to understand the impact of replacing old double glazing in the UK housing stock.

Solid ground floor insulation: 04KG.G.F

The 20 mm of aerogel blanket insulation laid on top of the solid ground floor resulted in a significant reduction in HTC of (29 ± 15) W/K, or (20 ± 10) %. This is a much greater reduction than was anticipated by the measured U-values, which predicted a reduction of 12 W/K. One potential reason for this difference is that the baseline U-value for the ground floor was based on the calculated floor U-value, since only centre room HFPs were installed pre-retrofit, and so this may not be representative of the improvement in floor heat loss.

Post ground floor retrofit, additional HFPs were installed to gain a deeper understanding of the ground floor behaviour. The U-values in the centre did not decrease considerably, but the HFP placed near the floor and wall junction measured a U-value of (0.36 ± 0.02) W/(m^2·K). Thus, the insulation appeared to be having more impact at the edges of the floor. This finding highlights the complexity of ground floors and indicates that more research is needed into how heat loss via ground floors can be measured and calculated.

Conventionally, a solid ground floor insulation retrofit requires the ground floor concrete slab to be dug up to lay down insulation and then a screed to be poured on top. The aerogel blanket solution provided a much lower disruption alternative and was akin to the installation of an underlay. It is not known if this HTC saving was comparable with conventional solid ground floor insulation, but the results indicate this solution could provide substantial reductions to householder space heating requirements, along with improvements to thermal comfort. More testing on a greater range of house types would be needed to fully understand the benefits and risks if this product were installed more widely in the UK housing stock.

Figure 3-18 Image of the 20 mm Aerogel floor insulation

Figure 3-18 shows the make-up of the floor insulation used, including the 3 mm plywood top to provide a rigid floor surface on which the final floor finish can be laid. The aerogel insulation is encapsulated in a foil to reduce risk that the fibres are disturbed, as the fibres can cause irritation. The boards were taped after being installed, as shown in Figure 3-19.

Figure 3-19 Installed floor insulation

Infiltration heat loss reductions

Despite a 16 % reduction in airtightness achieved by the airtightness measures, the impact was not significant enough to achieve a measurable change in HTC (-5 ± 14 W/K). The uncertainty of the coheating test HTC during the solid ground floor stage was 11 %, while the other coheating tests were between 3 % and 6 %. This additional uncertainty may be masking any small reduction in HTC related to the airtightness improvements. The HTC due to ventilation can alternatively be estimated via Equation 1. Note that the shelter factor, which describes how exposed a property is to wind, is set at 0.85 for consistency with RdSAP.

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

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

According to Equation 1, the HTC saving achieved from the airtightness improvements from 7.7 to 6.4 $m^3/(h \cdot m^2)$ @ 50 Pa would be 3 W/K or slightly less than 3 % of whole house HTC. A small change such as this is challenging to detect, even for the coheating test which is widely regarded as the most precise HTC measurement method available.

The main airtightness measure undertaken was to install plywood over the top of the intermediate floor. Although the intermediate floor is not deemed to form part of the main air barrier of the dwelling, the leakage identification highlighted that air was moving from the occupied spaces into the intermediate floor void and from here into the walls.

Post-retrofit there were still several areas where infiltration was observed, for instance around the edges of trickle vent seals and between the window frame and the walls, as well as penetrations through the wall that were inaccessible behind built-in kitchen and bathroom cupboards and the gas boiler.

More research is required to investigate the HTC reductions that can be achieved via airtightness improvements, as well as the appropriateness of the n/20 rule of thumb. Attempts to disaggregate whole house HTC into fabric and ventilation heat loss using n/20 should be treated with caution. This has been demonstrated in a recent publication, where this rule of thumb is shown to be inappropriate for a sample set of 21 buildings [12]. Investigation using a larger sample set would be required to identify an alternative rule of thumb for UK archetypes.

The HTC cumulative reduction from each stage is shown in Figure 3-20 which highlights that there is a large uncertainty with the individual stages but that combined, a significant reduction has been achieved.

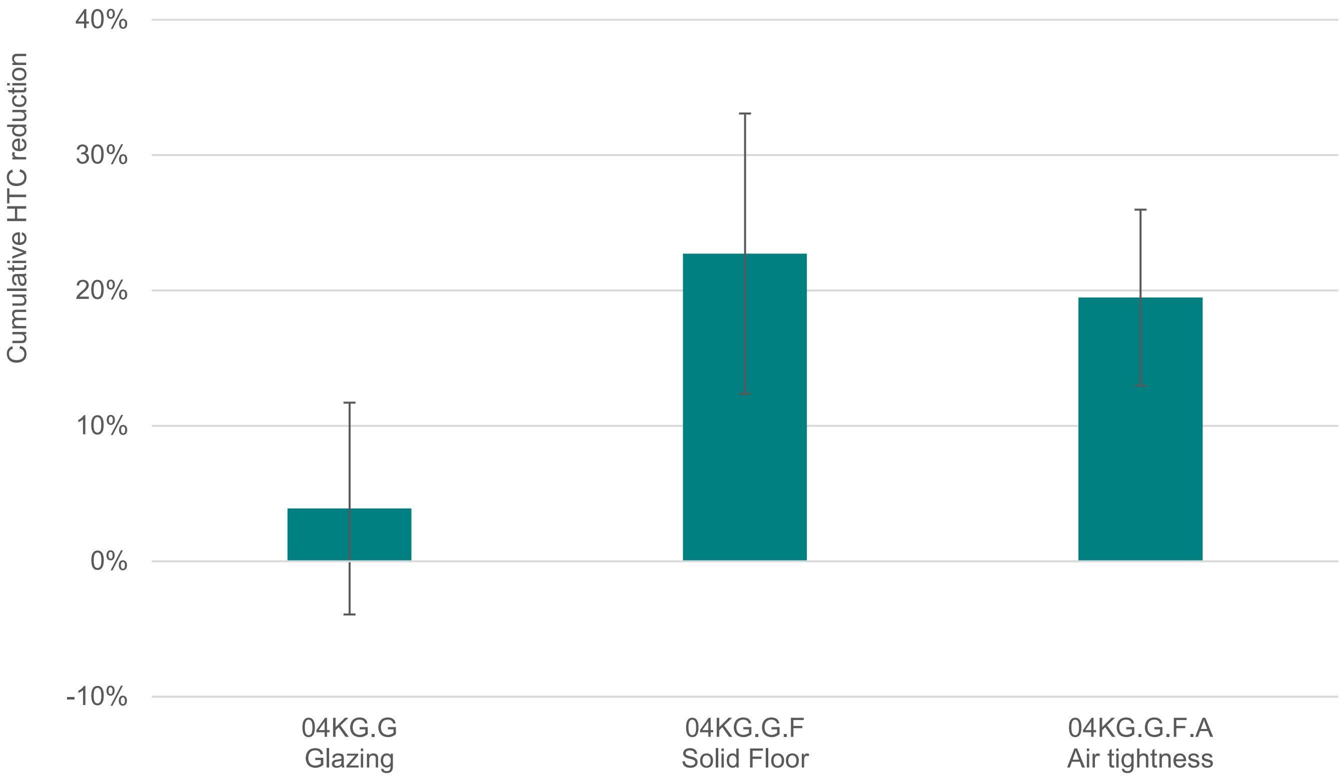


Figure 3-20 Cumulative HTC savings achieved by retrofits

3.3.2 QUB and the coheating test results

An alternative method of measuring the HTC – the QUB - was undertaken in 04KG to compare against the coheating test. The QUB method is described in full in the DEEP Methods 2.01 Report. In total 12 QUB tests were performed on 04KG. These were done to investigate the reliability and accuracy of the QUB test, and were undertaken immediately after the coheating test for each applicable retrofit stage.

The 12 successful QUB tests were completed on 04KG across the ground floor insulation (3) and airtightness (9) stages. The tests were completed in November 2021 (ground floor insulation) and December 2021 (airtightness). For both stages the tests had a 10-hour duration. These tests all had a compliant α value (heat loss / heat gain ratio), and the reference HTC used to determine this was a provisional result of the coheating test. This was ensured by use of a secondary set of timer and thermostatically-controlled heaters that maintained optimal starting temperature, in line with the forecast external temperature. The α value was recalculated based on the final coheating HTC measurement and remained compliant for all tests.

Figure 3-21 shows the individual QUB HTC measurements against the upper and lower uncertainty boundaries of the corresponding coheating measurements. 04KG is a semi-detached house, however, for this comparison the raw coheating result was used (without correction for party wall losses).

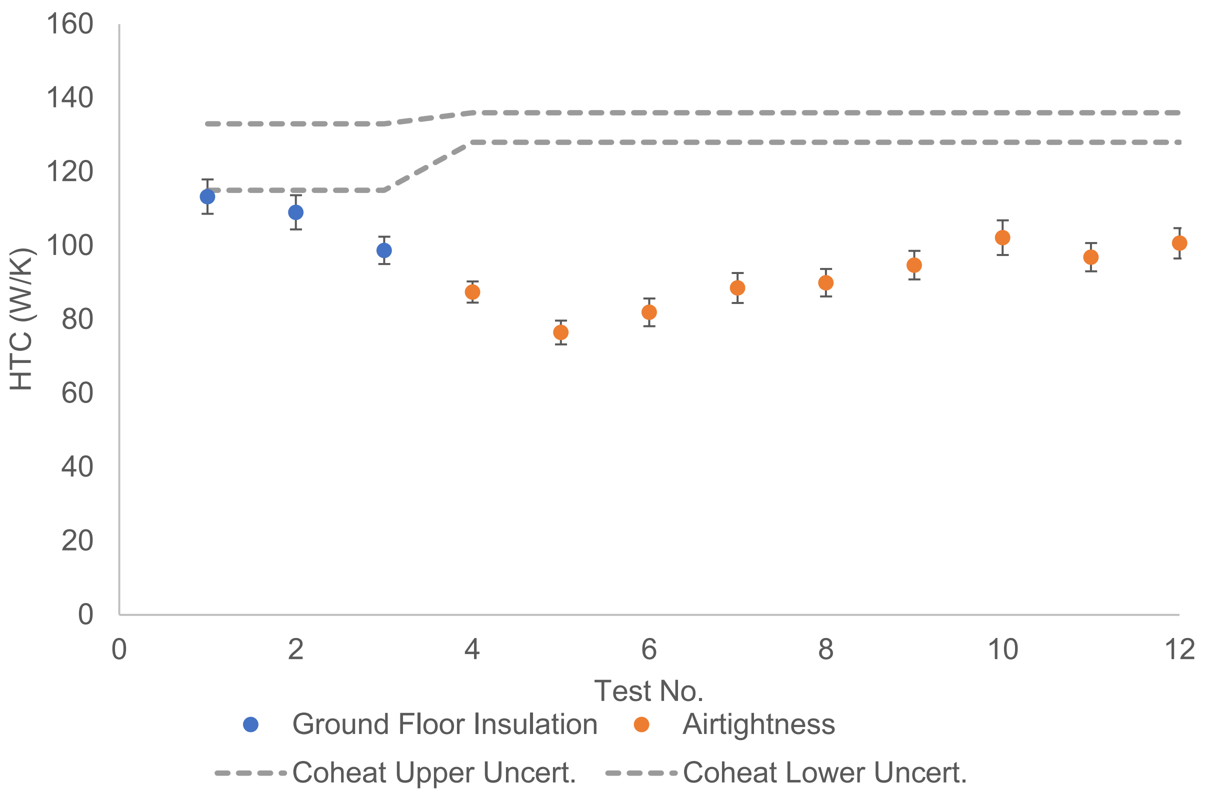


Figure 3-21 Comparing individual QUB HTC and coheating measurements

Only one QUB measurement has overlapping confidence intervals with the respective coheating test; with all remaining results lower than the coheating measurements. The uncertainty weighted average of the QUB measurements is presented in Figure 3-22.

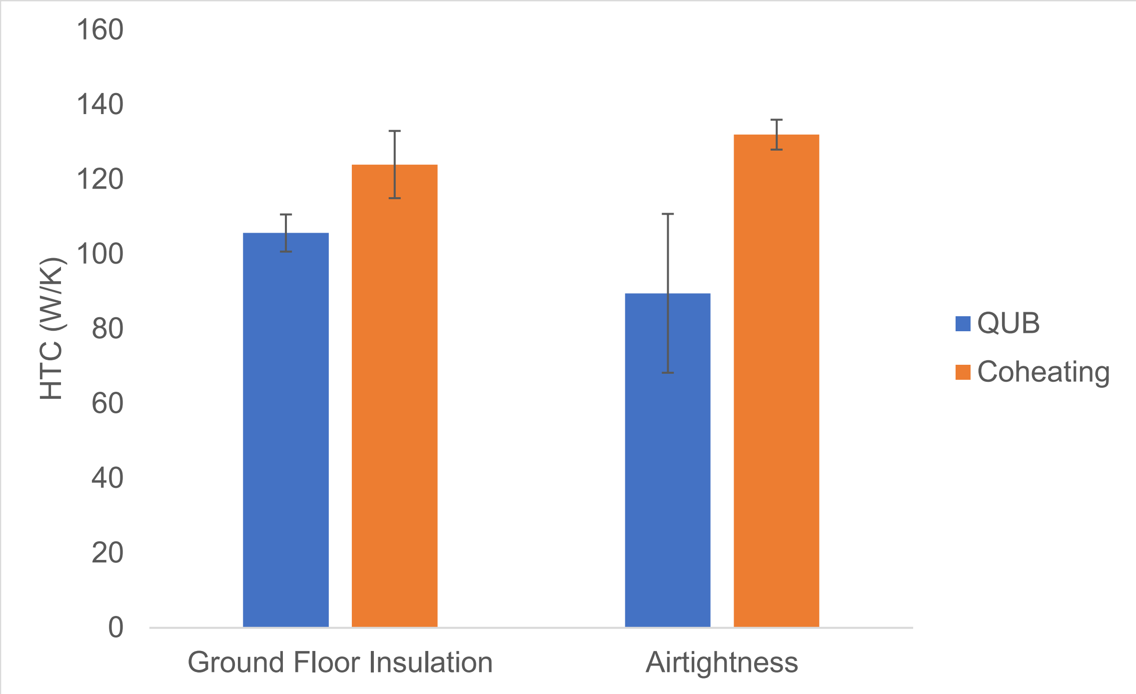


Figure 3-22 Average QUB HTC measurement vs coheating measurement

The relative difference between the average QUB and coheating HTC measurement is 15 % for the ground floor insulation stage and 32 % for the airtightness stage. Studies have reported a difference of between 1 % and 15 % when comparing the two methods [13,14]. There were building characteristics and test conditions that were present in the tests that could be contributing to this larger difference.

Previous work has suggested that a larger HTC measured through coheating could be attributed to a larger internal/external temperature difference, and the use of fans that result in larger infiltration heat loss [15]. As the difference between the measurements is larger for the airtightness stage where, proportionally, infiltration heat loss will be less than the ground floor insulation stage, these results do not align with this suggestion. Further investigation with use of comparative infiltration measurements, e.g. tracer gas, would be needed to verify this.

The solid slab on ground floor construction could also be contributing to the difference between QUB and coheating HTC measurements. Heat losses through the ground floor to the outside will not follow the internal / external temperature difference, rather it is impacted by the ground temperature. While ground temperature does vary seasonally, it is much more stable than external temperature.

The QUB tests were conducted at a lower internal temperature (average 21 °C) to the coheating measurements (~25°C). Assuming a constant ground temperature for both test methods, proportionally more heat loss through the ground will occur during the coheating test. As both methods consider all losses proportional to ΔT, and ground losses were not decoupled, a larger HTC measurement from coheating could be achieved.

Further work should be undertaken to isolate the impact of the ground heat loss, e.g. through thermal calibration tests, and see if this makes the HTC measurements more comparable. This would also identify the impact of varying levels of thermal charge in the concrete slab which could occur as a result of completing the test directly after coheating.

Whole house heat loss improvement summary

The HTC of the building has been cumulatively reduced by the retrofits by (30 ± 10) W/K, or (19 ± 6) %.

According to the coheating test, the savings were achieved primarily via the 20 mm of Aaerogel installed on the solid ground floor, which achieved a reduction of 29 ± 15 W/K (20 ± 10) % - albeit clearly with a large uncertainty. The new windows and the airtightness result reduced and then increased the HTC by roughly the same margin, each potentially cancelling out the impact of the other. In both instances, though, this change in HTC was within the uncertainty of the test.

In the case of the glazing and doors, the reduction in HTC was just within the uncertainty of the test, suggesting that the new double glazing has only marginally better thermal resistance than the original double glazing found in 04KG.

If leakage around new trickle vents and between the frame and the new windows had been addressed in this stage, a measurable reduction in HTC may have been achieved. Ensuring that airtightness testing accompanies glazing retrofits would improve the performance of these retrofits.

The airtightness measures were successful in reducing airtightness by 16 %, though this resulted in no change to the measured HTC.

3.4 Measured vs. modelled retrofit performance

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

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

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

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

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

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

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

3.4.1 Measured HTC; aggregate vs. disaggregated approaches

The measured aggregate HTC from the coheating test and the disaggregated HTC calculated from summing the HTC_v, HTC_f and HTC_b are presented in Figure 3-23.

Comparing these two approaches to derive the whole house HTC, is often termed 'closing-the-loop' analysis. It is useful in both exploring where heat losses are occurring and as a reference point for the whole house HTC measured by the coheating test. The HTC_f is derived by multiplying the area (m²) of each fabric element by its U-value (W/(m²·K)). The HTC_v is previously described in Equation 1. The thermal bridges are assumed to be equal to the defaults used in the RdSAP EPC model and so represent an area of uncertainty in this assessment.

As can be seen, the disaggregated HTC is within the uncertainty bounds of the coheating during the glazing test and relatively close in the other stages. The discrepancies are likely to be due to: uncertainty in the n/20 rule of thumb for estimating ventilation heat loss, the thermal bridging heat loss (assumed to be the same as the default value used in RdSAP, while in reality it is expected to change when elements are retrofit), unaccounted for point thermal bridges, and the plane element heat losses being based only on a small range of heat flux measurements that are not capable of capturing heterogeneity.

The glazing retrofit is assumed to reduce HTC much more than the ground floor retrofit, by the disaggregated method, while the reverse was measured in the coheating test. Also, a marginal reduction in HTC is predicted for the airtightness retrofit in the disaggregated method, though uncertainty in the preceding coheating test means this cannot be identified.

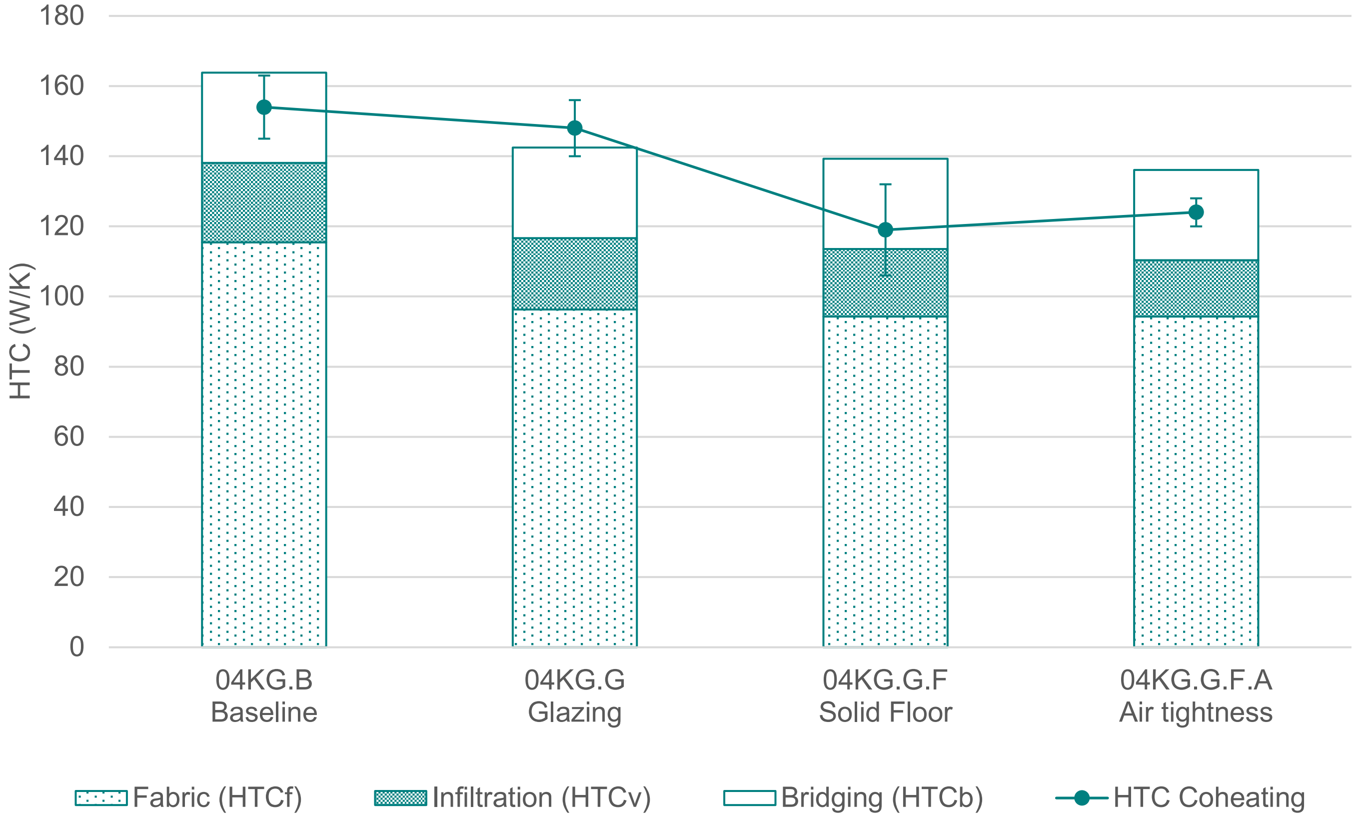


Figure 3-23 Aggregated vs. disaggregated measured HTC

Table 3-5 identifies the absolute and relative heat losses predicted by the disaggregated method. As can be seen, the relative changes in heat losses achieved remain roughly equal throughout the retrofit, despite the drop in overall HTC. Again, as discussed, the disaggregated method does not register heat loss reductions from the MVHR stage.

Table 3-5 Whole house heat loss via disaggregated methods

Retrofit stage	HTC_f W/K	HTC_v W/K	HTC_b[16] W/K
04KG.B Base case	115 (70 %)	23 (14 %)	26 (16 %)
04KG.G Glazing & doors	96 (68 %)	20 (14 %)	26 (18 %)
04KG.G.F Solid floor insulation	94 (68 %)	19 (14 %)	26 (19 %)
04KG.G.F.A Airtightness improvements	94 (69 %)	16 (12 %)	26 (19 %)

[16] Assumption based on RdSAP default bridging values

3.4.2 Measured vs. modelled HTC, calibration step 1

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

- Steady-state models predict higher HTC values than the coheating test and DSM models.
- When RdSAP default inputs are used, no benefit is predicted by the ground floor retrofit since the insulation was thinner than 50 mm.
- No benefit is attributed from the airtightness retrofits, since the default inputs do not allow the infiltration rate to be altered.

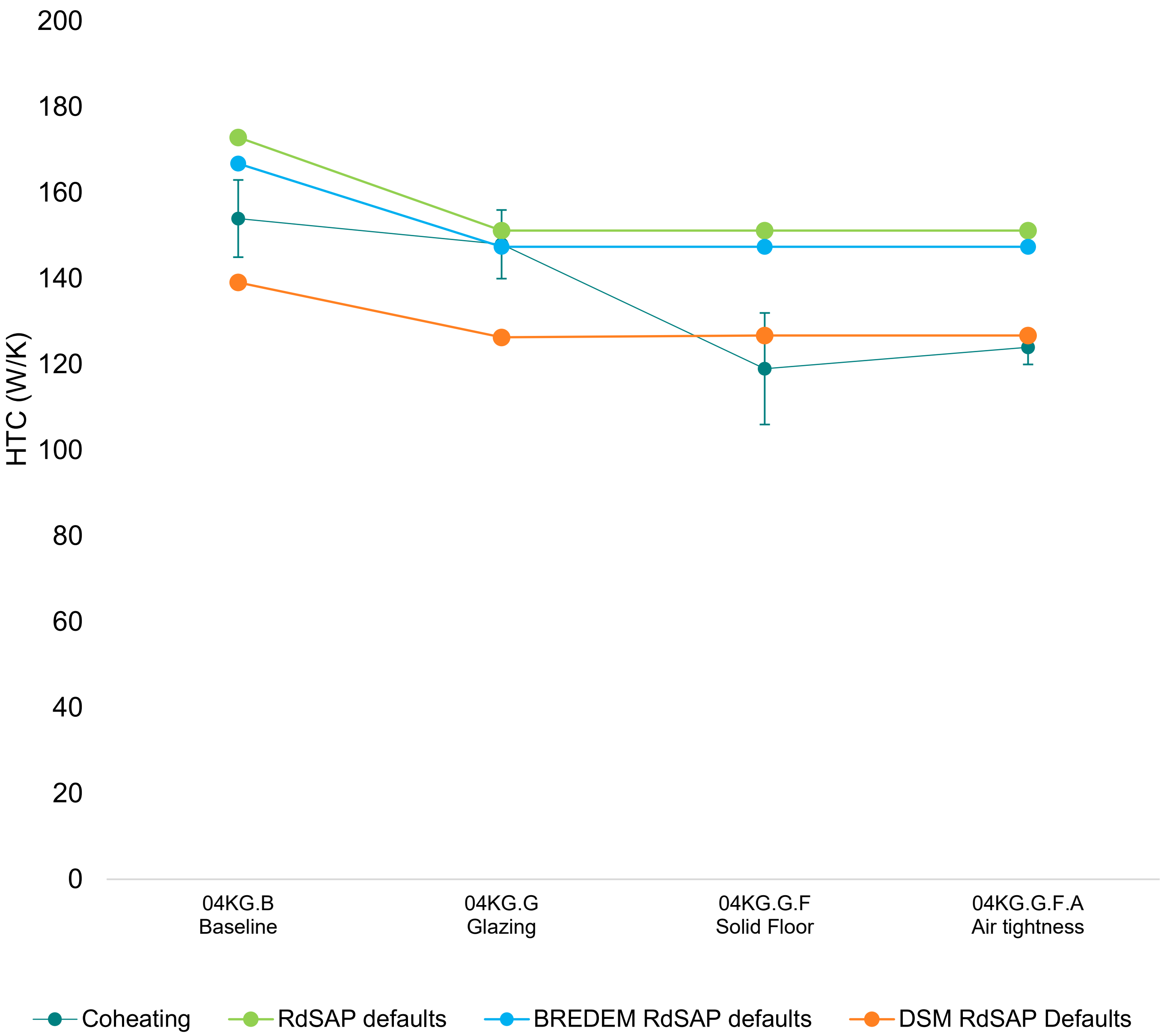


Figure 3-24 Measured vs modelled HTC calibration step 1: default inputs

3.4.3 Measured vs modelled HTC calibration step 2: measured infiltration

In this first calibration step, the models used infiltration rates derived from the blower door test as this data is the most likely to be acquired in practice. The impact of this compared to the previous calibration stage can be seen in Figure 3-25:

- RdSAP is not shown since it is not possible to alter the infiltration rate in the software.
- Including the measured air leakage heat losses brings the steady-state model into seemingly good agreement with the coheating value, being within the uncertainty of the coheating test in every phase.
- The DSM modelled predictions, however, get further away for the measured result for all but the solid floor retrofit. This suggests that DSM may be underpredicting HTC in this stage.
- A reduction of 4 W/K in the HTC is predicted by all the models due to the airtightness retrofit, which reduced the air leakage by approximately 1.4 $m^3/m^2.hr$ @ 50 Pa (16 %).

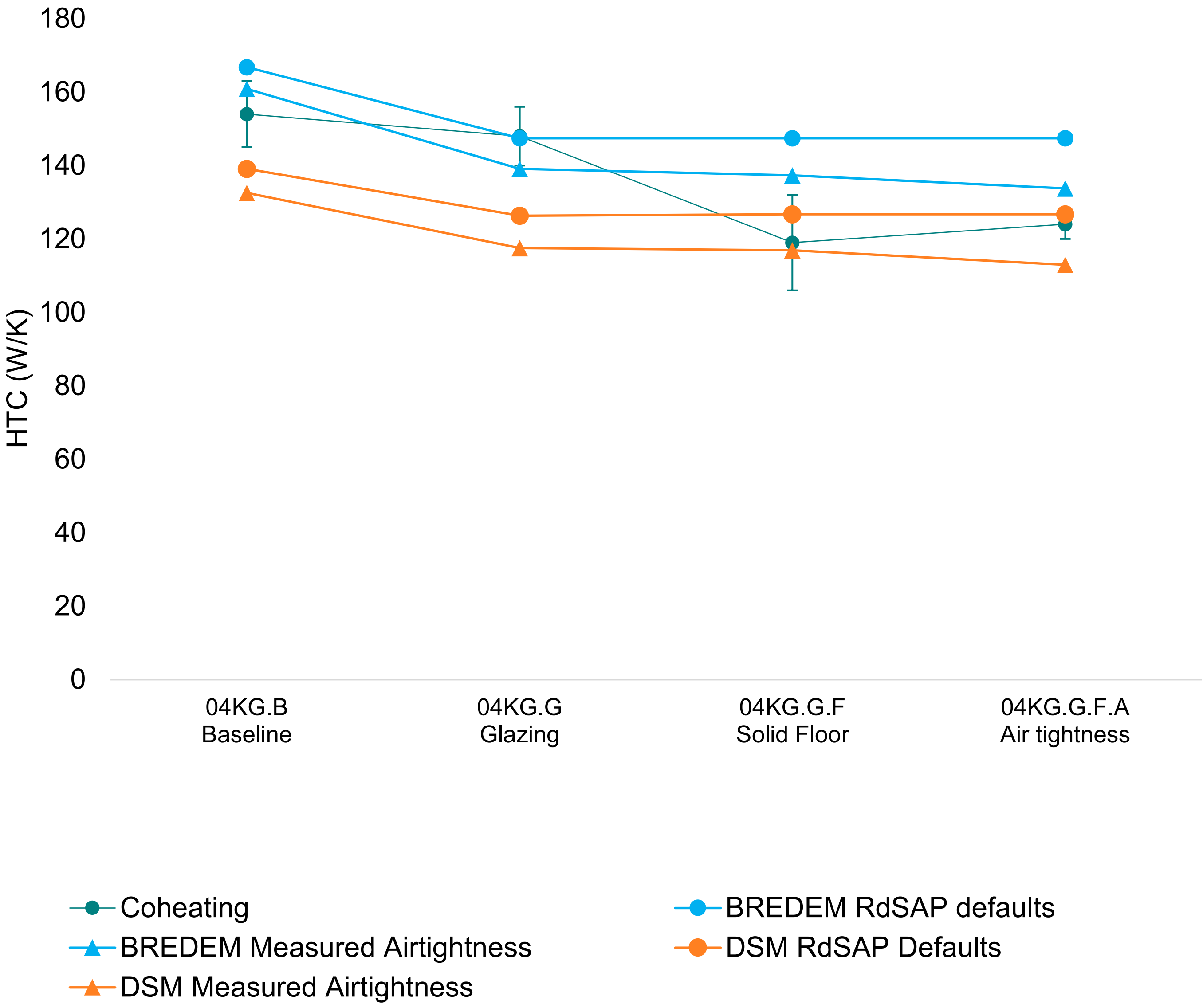


Figure 3-25 Measured vs modelled HTC calibration step 2: measured infiltration

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

In this step, the models included U-values defined using the BRE calculator, which needs more detailed surveys. It often requires assumptions or destructive investigations to establish the nature and thickness of construction layers. The impact of this compared to the previous calibration stage can be seen in Figure 3-26:

- RdSAP is not shown since it is not possible to include calculated U-values in the software.
- Using calculated U-values means that a benefit from the ground floor insulation can be predicted, resulting in an 8 W/K and 14 W/K reduction in the HTC in the DSM and steady-state models, respectively.
- The RdSAP default U-values assumed higher U-values for the gable wall than were measured, since IWI was found to have been installed here. This meant that when using the calculated U-values, the predicted HTCs in both DSM and BREDEM reduces. This resulted in the steady-state model often underpredicting HTC and the DSM underpredicts the HTC substantially compared to the coheating value.

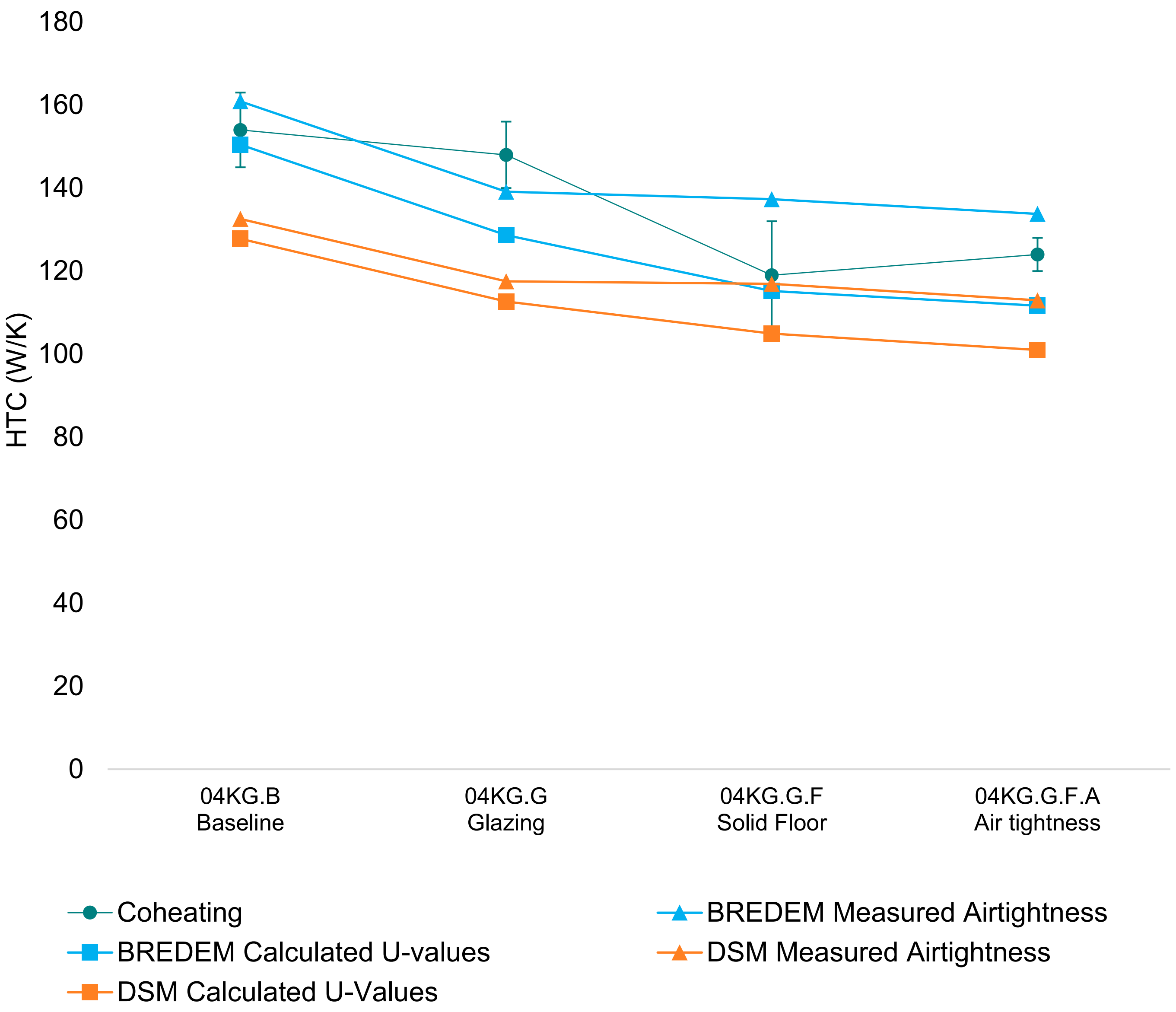


Figure 3-26 Measured vs modelled HTC calibration step 3: Calculated U-values

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

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

- Including the measured U-values increases the HTC predicted by all the models since the external wall U-values were measured to be higher than the calculated and default predictions used in the models.
- This calibration stage brought the BREDEM and DSM predictions back into better agreement with the coheating value. This indicates that since calculated U-values cannot capture unknown fabric heat loss characteristics, especially where destructive surveys cannot confirm construction build-ups for all elements, they may not always lead to more accurate models.
- The RdSAP software substantially overestimates heat loss because it assumes a much leakier building, in addition to the measured U-values being worse than the defaults.
- It is worth reiterating that the RdSAP predicted HTC still does not predict any benefits for the ground floor retrofit stage, since RdSAP is not capable of accounting for any insulation thinner than 50 mm.
- The results suggest that increasing the flexibility of RdSAP to use measured blower door test results and to include insulation thicknesses less than 50 mm, would increase the accuracy of EPCs.

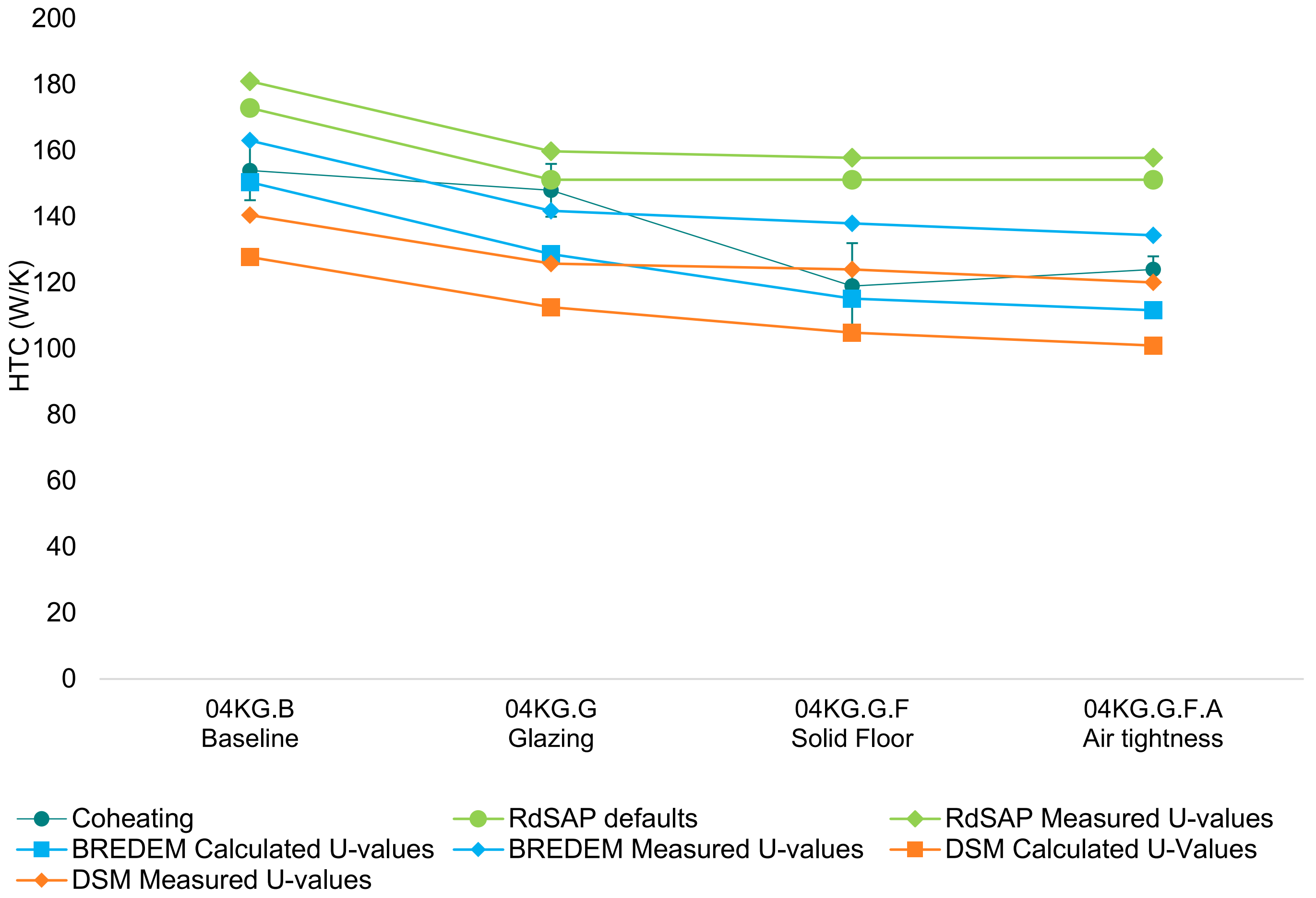


Figure 3-27 Measured vs modelled HTC calibration step 4: measured U-values

Measured versus modelled HTC summary

The HTC resulting from the disaggregated method is in fairly good alignment with the coheating HTC. However, the amount of non-repeating thermal bridging heat loss is based on the RdSAP default values for a house of this age. Since the case study home has had a ground floor retrofit and previously had EWI, which did not extend to the roof nor the ground floor, the thermal bridging heat losses may be expected to have changed, and so this is an area of potential error.

The default inputs for generating EPCs assume a much higher air leakage than was measured, and inputting the measured airtightness of the home brings the steady-state estimates of HTC in line with the coheating value.

The ground floor and gable wall U-values were measured to be worse than they were calculated to be. This means that when using measured U-values, the HTC is much closer to the HTC predicted using the defaults. This highlights the risks involved in using calculated U-values only. This can result, in some instances, in less accurate models if there are unknown heat transfers or construction characteristics that are not factored into the calculations.

EPCs do not account for airtightness or any insulation < 50 mm, which may impact on willingness to install these measures. When they are included for the ground floor and airtightness retrofits (by replacing defaults with measured data), the HTC was predicted to reduce by between 5 and 18 W/K depending on which model was used. The implications of EPCs being unable to capture these benefits are therefore significant in terms of EPC accuracy and retrofit savings predictions.

3.5 Retrofitting MVHR in the case study home

Following the fabric retrofits, the opportunity arose to investigate the implications of installing an MVHR unit. Case study 04KG had several features that make it suitable for MVHR, having already had other fabric upgrades and adequate space to house the unit and ductwork. However, it was not ideal since the windows had already been installed with trickle vents, which should not be present with MVHR as they short circuit the system when open. Additionally, 04KG did not achieve an airtightness of <3 $m^3/(h·m^2)$ @ 50 Pa, thought to be needed to maximise MVHR savings. Furthermore, it did not even achieve the <5 $m^3/(h·m^2)$ @ 50Pa airtightness threshold, used to indicate homes the level at which mechanical ventilation should be installed [13, 14]. It is possible to reduce the airtightness at the home later, including removing or sealing the trickle vents, though there was not sufficient time in the research programme to allow for this.

The MVHR retrofit presented here therefore comments on the practical issues associated with retrofitting MVHR, as well as the implications of an MVHR being installed outside of recommended airtightness boundaries. It was also possible to model the likely annual benefit of the MVHR in this case study home, though monitoring of energy and air quality while the home was occupied was outside the scope of the project. The MVHR was installed following a specific design created for the property from an MVHR specialist, providing extracts from kitchen and bathrooms and supply vents to bedrooms and living rooms. The following sections discuss the impacts of the MVHR retrofit on measured airtightness and space heating demand, with the modelled energy savings presented in Section 3.6.

3.5.1 Method for evaluating the impact of MVHR on space heating demand

The coheating tests have been used in this case study to assess the impact on HTC of different retrofits. Since MVHR is a technology to improve the efficiency of the purpose-provided ventilation, which the coheating test deliberately excludes, an alternative method to determine any impact of the MVHR on energy efficiency was therefore required.

A new test termed a ‘ventilated energy balance’ test was therefore performed to establish the baseline energy use when purpose-provided natural ventilation was in operation, i.e. the coheating protocol was followed with window trickle-vents ‘open’. Then a second test was performed after MVHR installation, with the MVHR system turned on, and trickle vents closed. The electrical energy consumed by the MVHR was also monitored and in this way a relative energy demand with and without the MVHR operational could be compared.

As stated, the coheating protocol requires purpose-provided ventilation to be sealed-up, in the same way that a pressurisation test does. This is because the HTC of a home only considers background ventilation and does not account for purpose-provided ventilation. Thus, the output of the ventilated energy balance test is more similar to the heat loss of a home in-use, though without occupants. It is therefore, referred to in this report as the in-use HTC (iHTC).

While the protocol adopted was different to the coheating test, the iHTC units are also in W/K. However, since the coheating HTC is a steady-state value, and the energy balance test incorporates a dynamic component, the two test methods and their outputs should not be directly compared, i.e. two iHTC values may be compared with each other, but not with an HTC. This is particularly important since the amount of purpose provided ventilation via trickle vents is highly susceptible to change based on external conditions, specifically wind direction and speed (i.e. the iHTC recorded during more windy periods would be higher than the iHTC in calm conditions).

Thus, while a relative comparison may be useful in this case study to compare natural ventilation and MVHR states, more research would be needed to understand how useful and robust the energy balance test is, what the implications need considering when comparing different iHTC values, and if iHTC has any other meaningful uses.

3.5.2 Impact of MVHR on airtightness

The airtightness improvements prior to the MVHR installation achieved an airtightness of 5.4 $m^3/(h·m^2)$ @ 50Pa making it just slightly above the maximum, and far from the recommended, level for MVHR [16, 17]. However, as described in the previous section, the coheating test caused accelerated shrinkage that caused some mastic and tape seals to fail meaning the airtightness of 04KG prior to the MVHR installation had increased to 6.4 $m^3/(h·m^2)$ @ 50Pa.

After the MVHR system was installed and the ventilated energy balance test had been completed, the home's airtightness was again tested and found to be even higher. This means that the installation of the MVHR unit itself caused more air leakage, with the mean air permeability rising to 8.5 $m^3/(h·m^2)$ @ 50Pa - i.e. similar to the house in its original condition. This has substantial implications for how the MVHR may be expected to perform, which is discussed in the next section.

Air leakage detection revealed that the main cause for this increase was due to the installation of the new fitted grilles and ductwork, creating new penetrations through the building envelope, including the external wall, loft, and intermediate floor. Figure 3-28 shows ductwork above the MVHR unit passing directly into the loft with large gaps around the penetrations. This will have undoubtedly had a detrimental impact on the airtightness of the dwelling, and performance of the MVHR, though issues could be appropriately fixed post-test.

Figure 3-28 Air leakage at the insulated ductwork above the MVHR

This is an important finding, with implications generally for the potential of MVHR to be retrofitted into homes. Commissioning of MVHR systems does not currently require the airtightness of the home to be tested in parallel, which leaves room for unintentional air leakage related to the MVHR installation to go unnoticed. This may be a specific issue for retrofitting MVHR since new build homes are required to have an airtightness test. Furthermore, using before and after airtightness tests (as recommended in PAS2035 for complex retrofits) may go some way to addressing this issue for retrofits. More generally it highlights the importance of compliance tests taking place in parallel to MVHR commissioning.

3.5.3 Impact of MVHR on iHTC

It is important to consider the limitations of the experimental approach, specifically that the amount of actual ventilation experienced through trickle vents can vary considerably. The W/K of the iHTC will therefore reflect this variability. In the MVHR stage, one can expect all energy use for fans to end up in the form of heat input in the home, which is why the energy balance test includes this in the calculations. This will therefore increase energy input into the house and increase the iHTC, all other things being equal. However, savings may be expected since the recovered heat is being distributed back into the house, which will offset some energy being provided by the heaters which could in turn reduce the iHTC.

Table 3-6 shows the iHTC for 04KG with and without the MVHR installed. The baseline in this instance is the case study home with trickle vents 'open', termed 04KG.O, while the result for the home with the MVHR running is termed 04KG.M. It also identifies the amount of purpose-provided ventilation measured during the tests, though the ventilation provided by the trickle vents will vary throughout the test according to wind and pressure differences.

An additional 1.4 $m^3/(h\cdot m^2)$ @ 50Pa of ventilation was measured to enter the dwelling via the trickle vents during the blower door test, equivalent to 0.06 ACH. This is substantially less than the 0.5 additional ACH being provided by the MVHR. However, it is important to note that the trickle ventilation is dynamic and greatly affected by wind, so the ventilation taking place during the tests will be at times much higher than the value shown in Table 3-6, which was measured during calm conditions.

As mentioned, trickle vents were closed for the MVHR stage. This suggests that more fresh air is delivered to the home via MVHR on average, though this may also mean that there is more air to heat, which can increase space heating demand compared to natural ventilation.

Table 3-6 iHTC measured before and after MVHR retrofit

Retrofit stage	Airtightness $m^3/(h\cdot m^2)$ @ 50Pa	Purpose provided ventilation (ACH)	iHTC (W/K)	iHTC Uncertainty	iHTC Reduction (W/K)	Percentage reduction
04KG.O Vents open	7.8 (0.33 ACH)	0.06[17]	140	5	-	-
04KG.M MVHR	8.5 (0.36 ACH)	0.5	133	8	-7 ± 9	(-5 ± 7) %

[17] It is not possible to know how ACH varied during the test period, as this measurement was undertaken under calm conditions. Windy conditions could see ACH being many times more than this.

The findings suggest that the MVHR system has not significantly changed the iHTC, as the difference was measured to be (-7 ± 9) W/K, or (-5 ± 7) %. The heat recovery that was taking place was not of sufficient magnitude to detectably offset the additional energy demands caused by:

- Additional electricity used to power the fans
- Additional purpose provided ventilation from MVHR in 04KG.M beyond the trickle vent provision in 04KG.O
- Additional infiltration caused by the MVHR installation

Further investigation suggests that it is probable that the ventilation via the trickle vents experienced during the test was more than the 0.06 ACH measured by the blower door test at the start of the experiment. This was expected, and Figure 3-29 shows windspeeds at Leeds Bradford Airfield (LBA), located just over 20 km from 04KG, during the coheating test. Here there were substantially higher wind speeds than occurred at 04KG during the blower door test. While the case study home will have had different local wind conditions to LBA, it is indicative of how variable wind speeds are, and suggests higher wind speeds than when the blower door took place.

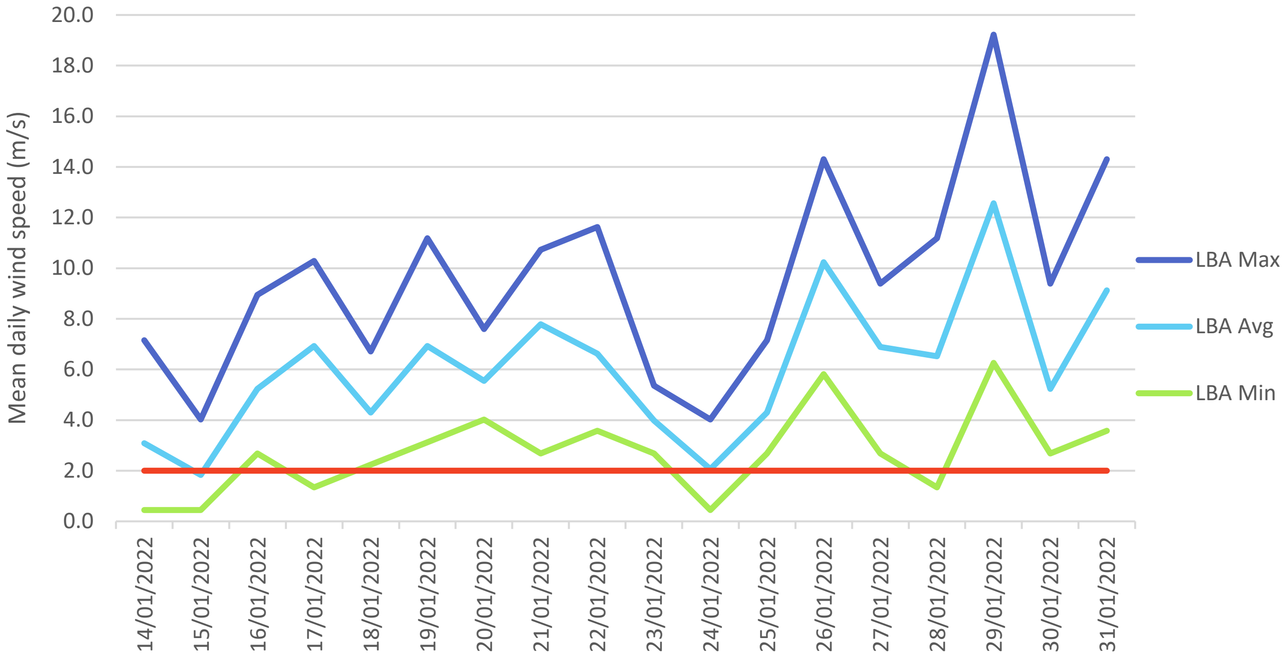


Figure 3-29 Wind speeds at Leeds Bradford Airfield during the coheating test and at 04KG during the blower door test

As mentioned, longitudinal monitoring to measure the lived-in energy savings was not possible in this project. Thus, the benefit of redistributing excess internal gains to other parts of the home, where the heat would be useful, could not be assessed. This is a limitation of the energy balance test, which means one of the benefits of MVHR cannot be accounted for.

Additionally, it was not possible to evaluate the performance of the MVHR in different house types, nor could a longitudinal evaluation of air quality, thermal comfort, or overheating with and without the MVHR take place. Evidence on these issues would be necessary to gain an understanding of the potential for MVHR as a retrofit measure for the UK housing stock. It was possible, however, to undertake energy modelling of the MVHR unit to predict how it may affect annual space heating demand, carbon emissions, and EPCs.

MVHR retrofit performance summary

Installing the MVHR system itself was observed to increase air leakage in the home, which has implications for retrofitting MVHR. It may be beneficial, therefore, to ensure airtightness checks are installed in parallel to MVHR commissioning to minimise this risk in MVHR retrofits. In this case study, this resulted in the house being well above the recommended airtightness threshold.

The MVHR saw a (-7 ± 9) W/K change in iHTC, i.e. no measurable difference. It is possible a reduction may have been detected if the home's airtightness had achieved the recommended <5, or especially <3 $m^3/(h \cdot m^2)$ @ 50Pa.

The ventilated energy balance may not be the ideal way to evaluate the benefit of MVHR, since it does not allow for internal gains to be redistributed throughout the house, which is one of the key benefits of MVHR systems.

More longitudinal monitoring of air quality and comfort metrics in addition to energy consumption in a range of house types is needed to understand how successful MVHR can be as a retrofit measure.

3.6 Predicting EPC band, annual space heating and carbon emissions

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

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

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

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

As mentioned, in this case study the MVHR installation worsened the air leakage in the home. Therefore, to investigate what the predicted benefit of the MVHR may have been had this not occurred, an additional model scenario was undertaken called ‘MVHR predicted’, to describe the performance if the infiltration rate was equivalent to that of the naturally ventilated home.

3.6.1 ‘MVHR Predicted’ performance

As discussed, the field trials had suboptimal infiltration rates for the MVHR to perform efficiently. In addition, purpose provided ventilation assumed in the models by the MVHR was 0.5 ACH, yet the manufacturers details specify 0.6 ACH for this house. Also, the specific fan power being assumed in the models is higher (2 W/l/s) than the manufacturer’s specification (0.72 W/l/s).

To evaluate by how much these factors were affecting the modelled performance of the MVHR a sensitivity analysis was produced in the steady-state (BREDEM) model, to understand how MVHR could more appropriately be represented in EPCs. The ‘MVHR Predicted’ scenario describes what impact optimal MVHR inputs would have on EPC band, space heating, and carbon emissions using the following inputs:

- Infiltration rate of 3 $m^3/(h \cdot m^2)$ @ 50Pa (0.15 ACH)
- MVHR provided ventilation rate of 0.6 ACH
- Specific fan power of 0.72 W/l/s

3.6.2 Impact of retrofits on EPC bands

Several policy mechanisms set EPC targets, and the Government has set an ambition that all homes where practically possible will achieve an EPC band C by 2035 [18]. The impact of the retrofits on EPC in this case study, as predicted by each model at each calibration stage, is shown in Figure 3-30 and the salient points are described below:

- Since the home previously had EWI, it was already judged to be an EPC Band C and none of the fabric retrofits were substantial enough to improve the EPC Band.
- DSM predicts a higher SAP score since it predicts lower space heating requirements than steady state, though when MVHR is added it predicts a lower SAP band.
- MVHR reduces the SAP score since additional purpose provided ventilation is added. Furthermore, the electrical power to run fans is greater than the heat that is recovered. This is exacerbated by the fact that, according to costs within SAP, electricity to run fans cost more than gas to provide the heating.
- The RdSAP default input model version uses the heat recovery assumed in the EPC of 66 % with a utilisation factor of 0.7, i.e. 46 %, while all the other scenarios use the manufacturer's heat recovery efficiency of 83 %; thus the EPC predicts lower EPC scores.
- The 'MVHR predicted' sensitivity analysis (only undertaken using the BREDEM model), explores what EPC score could have been achieved if an infiltration rate of 3 $m^3/(h \cdot m^2)$ @50 Pa (0.15 ACH) was achieved (RdSAP does not allow changes to infiltration rates). It also updates the specific fan power (SFP) to reflect the manufacturer's specification (SFP cannot be altered in RdSAP). Under these assumptions, the EPC score would be roughly the equivalent of the naturally ventilated home. This suggests that even when inputs are favourable, MVHR may not necessarily improve a home's EPC.

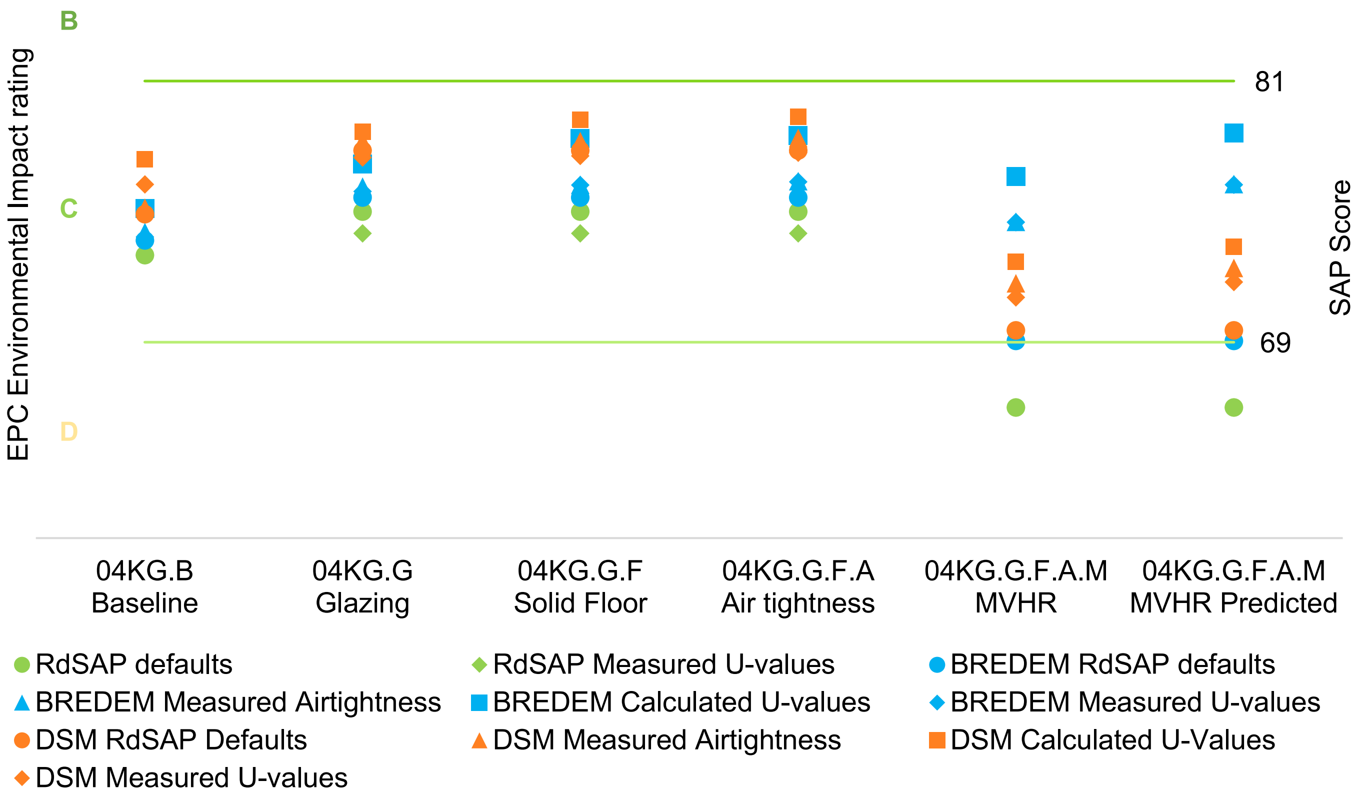


Figure 3-30 Predicted impact of retrofits on EPC band

3.6.3 Impact of retrofits on annual space heating

The Social Housing Decarbonisation Fund (SHDF) Wave 1 evaluates retrofit success by setting an annual space heating target of 90 kWh per m² for retrofits [19]. The predicted annual space heating demand for the case study retrofits is shown in Figure 3-31.

- The home is already below the SHDF target energy consumption rate for all the models since it has had EWI insulation.
- The use of measured air leakage and calculated U-values reduces the space heating demand. The inclusion of the measured U-values, conversely, increases the space heating demand as measured U-values are greater than those calculated, cancelling out the better airtightness to some extent.
- The glazing and ground floor retrofits further reduce the space heating demand by between 10 % and 30% depending on which model is used.
- The RdSAP model assumes slightly more space heating demand may be needed than BREDEM, since it assumes a much higher infiltration rate than was achieved in reality.
- The RdSAP model predicts more space heating demand when the MVHR is installed, because it assumes a higher rate of ventilation is provided to the home compared to natural ventilation, and only minimal heat recovery (equivalent to an efficiency of 46 % -66 % with a utilisation factor of 0.7).
- In DSM and BREDEM the MVHR provides a reduction in space heating demand, as they can account for its actual heat recovery efficiency.
- The additional sensitivity analysis assuming an airtightness of 3 m^3/(h·m²) @ 50Pa, and the manufacturer's specification for the SFP, suggest MVHR reduces space heating by around 30 %, though it is not known how much is due to the airtightness or heat recovery.

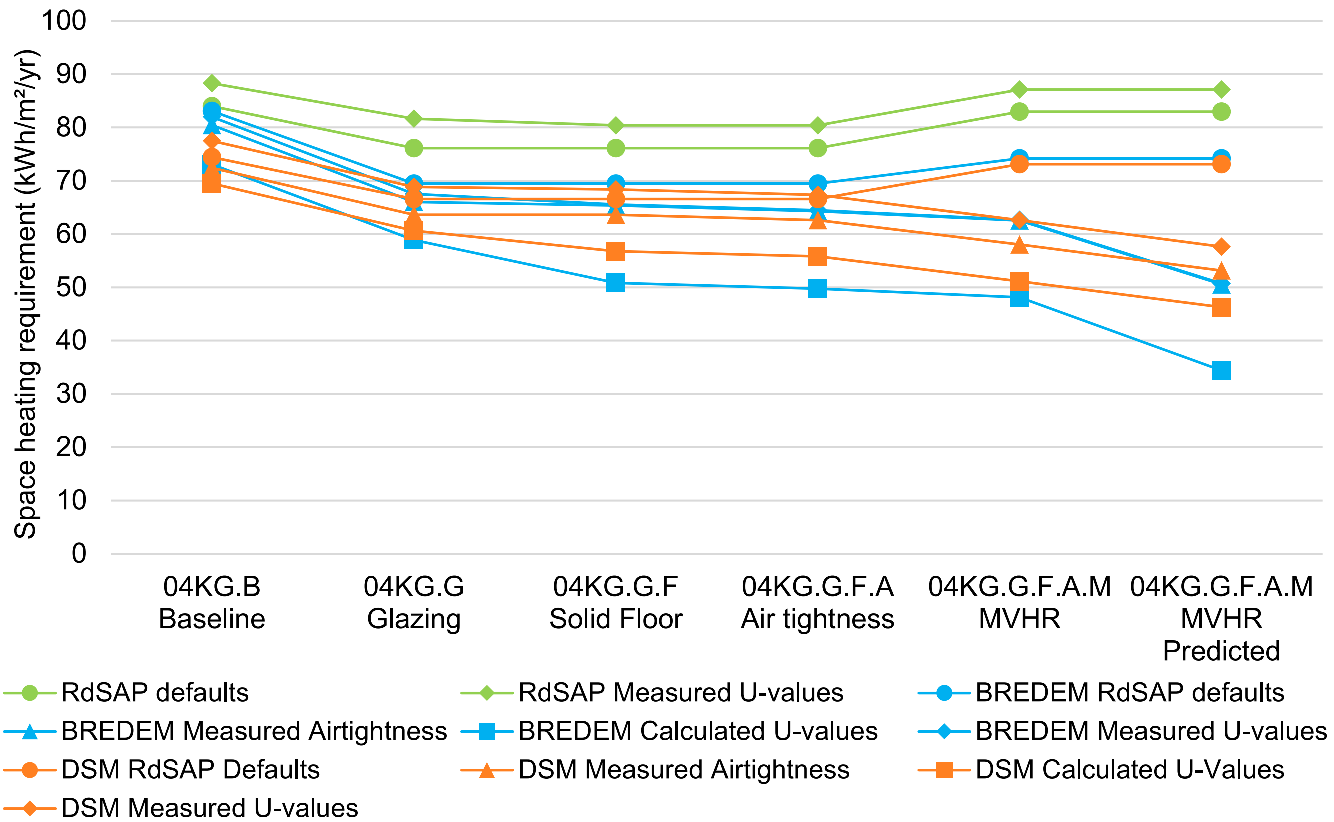


Figure 3-31 Predicted cumulative reduction in annual space heating demand

3.6.4 Impact of retrofits on CO_2 emissions

Space heating in homes is responsible for around 15 % of the UK's CO_2 emissions [20]. 04KG's CO_2 emissions were predicted to reduce by between 8 % and 36 %, depending on which model and inputs were assumed. The savings achieved are shown in Figure 3-32.

- The fabric retrofits have achieved some CO_2 emission savings, with a reduction of around 6 % to 18 % of the total house annual emissions, depending on which model is used. These are modest since the home was already relatively well insulated.
- Most of the savings are expected from the glazing retrofits, while the airtightness improvements have a marginal saving.
- The MVHR increases the home's CO_2 emissions (negative reduction) due to additional energy consumption via fans. Fans use electricity, which has a higher carbon intensity assumed in RdSAP than the heat it is recovering, which is derived from gas. As electricity becomes a less carbon intense fuel this will alter the impact of MVHR on CO_2 emissions.
- In the sensitivity analysis scenario 'MVHR Predicted', which includes the manufacturer's SFP and assumes the home meets the airtightness threshold of 3 $m^3/(h \cdot m^2)$ @50 Pa (0.15 ACH), there were savings in CO_2 emissions. However, it is not known how much is from airtightness improvements compared to heat recovery. This suggests models can predict MVHR's potential to reduce CO_2 emissions when using specific data and performance criteria, i.e. using default values results in no predicted carbon benefit from MVHR.

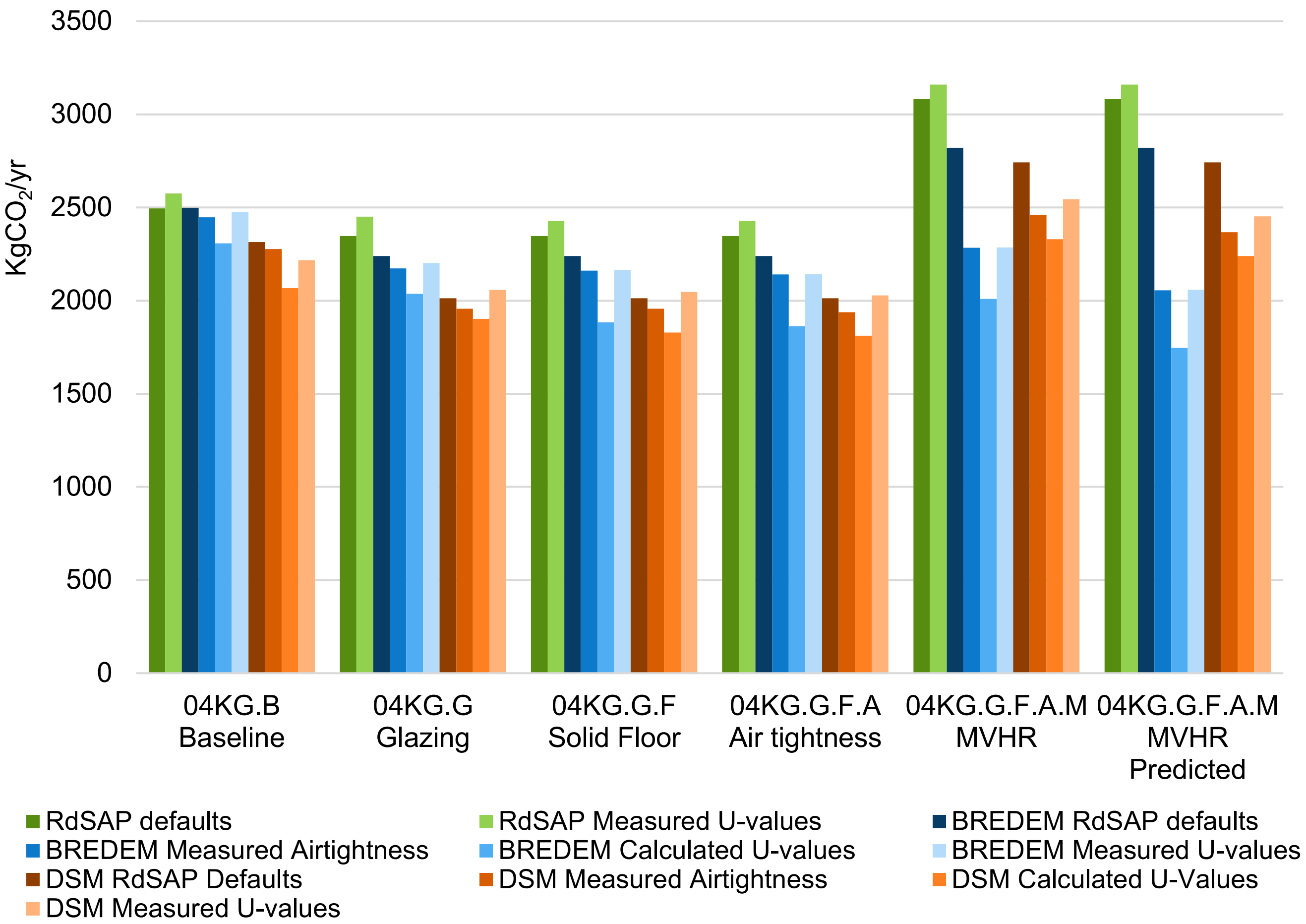


Figure 3-32 Annual CO_2 emission after each retrofit

3.6.5 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 are summarised here:

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

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

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

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

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

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

Weather
Due to the temporal resolution and variability of weather, it is not possible to match to the BREDEM inputs in the same way as the internal gains. The weather file used in the DSM was selected due to the close similarities between monthly average external temperature values (CIBSE Test Reference Year file for Leeds [21]) as discussed in the DEEP Methods 2.01 Report.

Differences specific to 04KG
In contrast to the findings from other case studies, the heat demand predicted by BREDEM and DSM models, using the same inputs, is in close agreement. This could be related to the adjoining semi-detached dwelling to the south of 04KG, which helps to reduce the impact of the hourly solar irradiation on the external surface temperatures in most of the heat balance calculations. However, the real orientation of the dwelling leads to the solar heat gains through glazing being approximately 750 kWh higher in the DSM model.

For the 01BA baseline scenario, using measured infiltration rate and U-values, BREDEM predicts a space heating demand that is only 431 kWh/year higher than DSM. 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 upon the thermal transmittance and area of constructions, and background infiltration rates. The DSM models mimic the coheating test conditions and therefore use a top-down method the calculate the HTC. Using an unrestricted version on the BREDEM software, it is possible to overwrite the HTC with that calculated in the DSM model.

Following this adjustment, the normalised annual space heating demand in BREDEM is 4,664 kWh, compared with the DSM estimate of 6,074 kWh, meaning that BREDEM predicts a demand that is lower by 1,411 kWh. The BREDEM calculations can be further normalised by using the DSM volume of conditioned space (10.28 m^3 less in the DSM model). Following this final adjustment, the BREDEM estimate is 1,660 kWh lower than the DSM output, even though the DSM model includes a greater amount of solar gain. This is perhaps indicative of the effect the neighbouring dwelling has in shading the south facing elements, with exposed façades more often out of direct sun.

Predicting EPC band, space heating and carbon reductions summary

The EWI had already increased the EPC to a C rating and the ground floor, glazing, and airtightness retrofits did not achieve enough points to increase this. These results suggest that achieving an EPC beyond a C will be difficult for solid walled homes and may need elevated levels of fabric improvement than installed here, or installation of renewables.

Additionally, space heating was already below the SHDF target though the glazing, ground floor, and airtightness retrofits were successful in reducing this by a further 9 % to 30 %, which also reduced CO_2 emissions by 6 % to 18 %.

MVHR was shown to have the potential to reduce space heating demand between 5 % and 19 % in this case study home. However, the additional electricity consumption needed to power the fans was shown to increase annual fuel bills and CO_2 emissions for the home, since SAP assumes that electricity is more expensive and more carbon intensive than gas.

RdSAP models always assume a default infiltration rate in homes which is far higher than would be recommended for an MVHR system (more than double in this case study). Thus, MVHR retrofits will always result in a worse EPC score when RdSAP is used. If MVHR is to be a retrofit measure in the future, this may needs considering in future RdSAP updates.

3.7 Overheating risk of retrofitting

As part of the overall DEEP project, Loughborough University has carried out parametric analysis of overheating scenarios using a 10-year weather data file. The overheating analysis in this section is complementary to this work and uses the overheating assessment method from CIBSE TM59, which is cited in the PAS2035 guidance [22].

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* [23]. The two assessment criteria are defined as follows:

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

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

Overheating assessment has been carried out at each stage of the retrofit. Following the TM59 guidance, the initial assessment was completed using the CIBSE Design Summer Year 1 (DSY1) file for a 2020s high emission scenario at the 50th percentile, for Leeds in this instance.

There are three different DSY files available for the 14 UK regional locations. They use actual year weather data that simulate different heatwave intensities: DSY1 represents a moderately warm summer, DSY2 represents a short, intense warm spell, and DSY3 a longer, less intense warm spell [21]. Assessment was also carried out for future weather scenarios, using the DSY1 files for the 2050s and 2080s high emission scenarios at the 50th percentile.

As with all naturally ventilated homes, it is the percentage of openable area in the windows that has the strongest influence on overheating risk. These are illustrated in Figure 3-33.

(a) pre-retrofit

(b) post-retrofit

Figure 3-33 Percentage of opening area for openable windows

In the case of 04KG, there were two retrofit measures that intuitively would be expected to help mitigate against excessive overheating: replacing the glazing with windows that allow for a greater proportion of openable area and adding an MVHR system that includes a summer bypass mechanism that increases the air changes under normal operation. Of these, the glazing retrofit has the most significant impact, as can be seen in Figure 3-34 and Figure 3-35.

Unlike many of the other case study dwellings included in DEEP, 04KG had already undergone EWI retrofit. In many other cases, the introduction of SWI notably helps to reduce overheating by limiting heat transfer through the solid wall construction. This is evident in the pre-retrofit overheating analysis for Criteria A as all rooms are not considered at risk of overheating in the current (2020s) climate scenario. However, due to the requirement for internal doors to be closed overnight in the TM59 methodology, the bedrooms are at risk of overheating in the baseline scenario under Criteria B. This is, however, mitigated at the first stage of retrofit.

Overall, 04KG includes a relatively low risk of overheating when compared to the other DEEP case study dwellings. This is emphasised by most rooms not being considered at risk of overheating in the 2050s climate scenario. All of the retrofit measures, except the airtightness measures, help to reduce overheating under Criteria A, although these reductions are marginal for all measures that are introduced after the glazing retrofit.

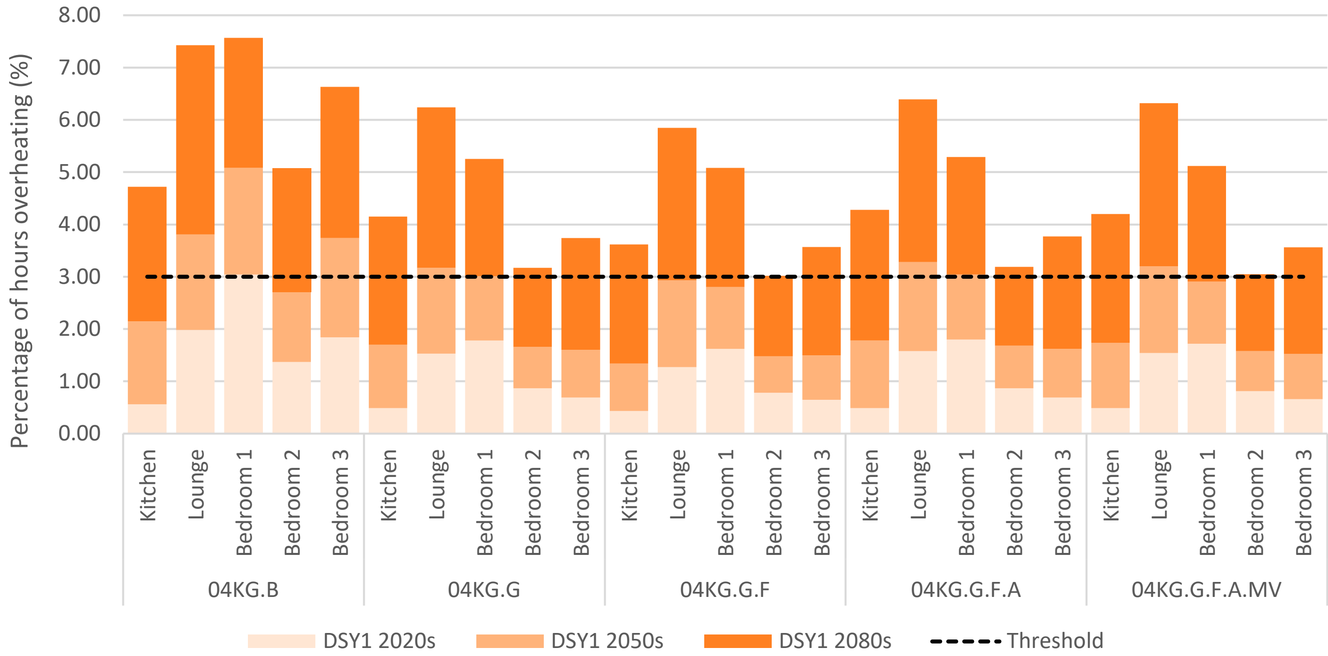


Figure 3-34 Modelled overheating under TM59 Criteria A

Results for Criteria B, however, show that apart from the glazing, the remaining measures have very little impact on the extent of overheating. The MVHR summer bypass does help, though, to reduce the extent of overheating a little more than the other (non-glazing) retrofits.

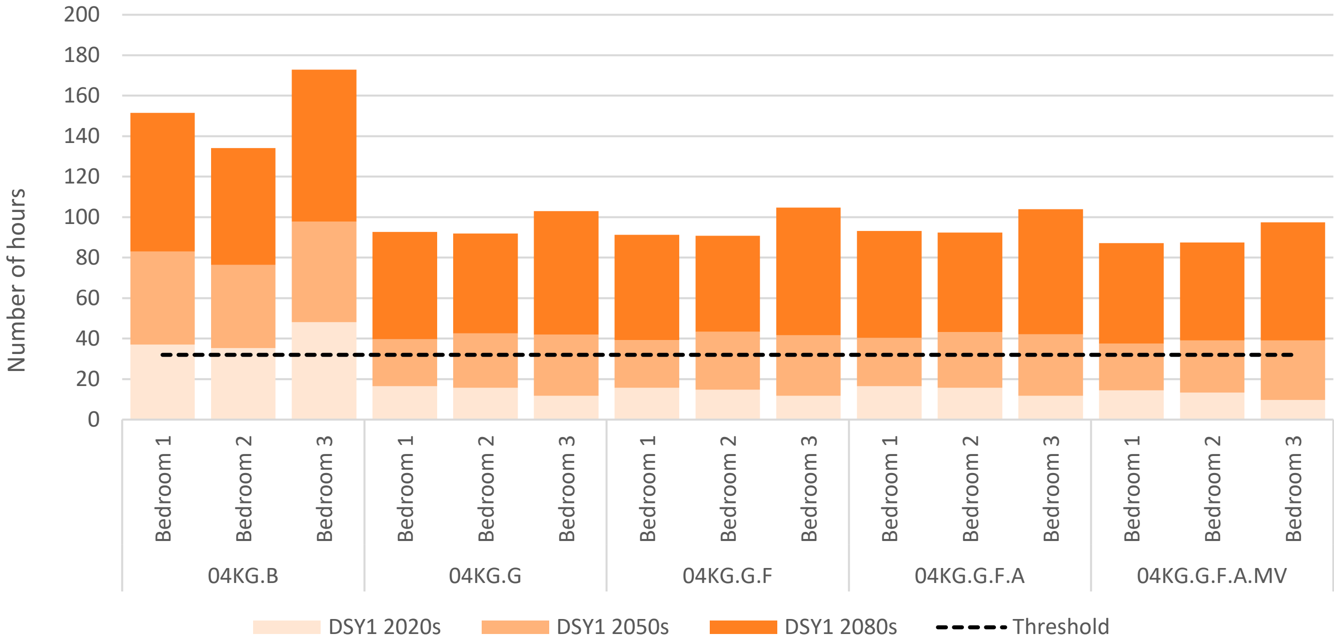


Figure 3-35 Modelled overheating under TM59 Criteria B

Further investigations into the mitigation potential for external shading may be a useful exercise, though it is beyond the scope of the DEEP project. The results suggest that without direct interventions to reduce solar gains (such as external shading), overheating in homes will become an increasing problem for homes like 04KG.

Overheating risk of retrofit summary

The baseline dwelling performs relatively well in terms of overheating, with only the bedrooms being at excessive risk under the current climate scenario (2020s). Existing EWI is the major reason for this when compared with other case studies.

Upgraded windows with larger opening areas mean that even bedrooms are not considered at risk of overheating for the 2020s. All rooms under Criteria A are comfortable in the 2050 climate scenario as well, with the exception of the living room which marginally exceeds thresholds.

As the focus of DEEP is primarily fabric performance, it is important to note that more sophisticated operation of the MVHR system may help to mitigate night-time overheating more effectively than these models suggest. Although the summer bypass has been considered in these models, detailed HVAC modelling could include more sophisticated schedules and set points that increase the air change rate in response to warmer conditions.

3.8 Retrofit costs and fuel bill savings

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

In this project, the costs of undertaking each retrofit were evaluated to be either enabling works that were linked specifically to getting the house ready for the retrofit (making repairs etc.), or the actual cost of the retrofit. Decoration costs were excluded from the costs reported here since the landlords were undertaking their own Decent Homes repairs following the retrofits and would take on some of the decoration work. However, costs associated with decorating were outside the scope of this project; these have been found to represent around 14 % of the cost of IWI [24] though may be different for EWI, loft and floor insulation, and new windows and doors.

The costs of the 04KG retrofits are outlined in Table 3-7. This includes the activities that took place that were not directly associated with the retrofit itself. As can be seen, there were significant enabling works that were experienced for the glazing retrofit and MVHR retrofit that were not anticipated and have considerably increased the total retrofit costs.

Table 3-7 Cost of retrofits

Retrofit	i) Retrofit work	Retrofit costs	ii) Enabling work	Enabling work costs
04KG.G New glazing and composite doors	Replace old fenestrations with A+ rated windows, glazed patio doors, and composite external doors.	£ 5,600	Repair and make good plaster work to and around all windows and doors, new window sills where needed.	£ 3,600
04KG.G.F Solid floor insulation	Fit 20 mm Aerogel boards on top of existing concrete slab, tape joints, and fit plywood finish.	£ 9,423	-	-
04KG.G.F.A Airtightness measures	Install plywood floor to intermediate floor, tape joints and seal the floor perimeter, seal accessible air leakage paths around cracks and gaps with sealant.	£ 3,920	-	-
04KG.MVHRH	Design, install & commissioning of MVHR equipment and penetrations through fabric made good.	£ 10,568	New ceiling to accommodate ductwork and reinstatement of ceiling lights.	£ 2,000

The no-fines construction was particularly crumbly and, thus, when the windows and doors were removed there was substantial damage to the openings, which required repairs. The MVHR required a new ceiling to be installed in the kitchen since the floor joists were not deep enough to encase the ductwork. This also meant the ceiling integrated spotlights needed to be reinstated by an electrician. Engaging an additional trade and making these repairs greatly added to the cost. These findings may have implications for the wider MVHR retrofit market, suggesting innovations around ductwork sizing may be needed to ensure costly ceiling alterations are not required.

The total cost of the retrofits was £35,105. Table 3-8 shows the breakdown of the costs. There are no reliable benchmark costs for the solid floor, airtightness measures, and MVHR retrofits. The costs for the benchmark glazing retrofits are shown, as well as the costs for suspended floor insulation for comparison, since the aerogel insulation could be installed on any floor type. Conventionally, retrofitting solid floor may be more expensive than suspended floors, as they require the ground floor slab to be dug out before being insulated and re-screeded.

The project is likely to have higher than normal costs since the retrofits were staged, meaning efficiencies could not be made in undertaking the work all at once. Additionally, the project was a one-off, meaning no economies of scale could be made. Also, with the exception of the new glazing, these retrofit measures are rarely installed in retrofit scenarios, meaning they may attract a premium.

Table 3-8 Breakdown of cost of retrofits

Retrofit	Total cost	Labour	Materials	Proportion of total cost	Treated area (m^2)	Cost per area (£/m^2)	Benchmark (£/m^2) [25]
04KG.G New glazing and composite doors	£ 9,200	42 %	58 %	26 %	16	£ 920 per window	£ 400 - 800 per window
04KG.G.F Solid floor insulation	£ 9,423	30 %	70 %	27 %	40	£ 235	£ 95[18]
04KG.G.F.A Airtightness measures	£ 3,920	77 %	23 %	11 %	169	£ 23	-
Fabric retrofit total	*£ 22,543*						
04KG.MVHRH	£ 12,562	54 %	46 %	36 %	169	£ 74	-
Grand Total	**£ 35,105**						

It is interesting to note that the solid floor retrofit cost was predominantly for the material, indicating that if aerogel could be produced more cheaply, then the cost of this retrofit has the potential to fall considerably. The opposite is true of the airtightness measures, where the main cost involved is that of employing the specialist to deploy the retrofit measures. The MVHR and the glazing retrofit costs were split roughly equally between materials and labour.

3.8.1 Predicted fuel bill savings

The modelling has predicted the annual fuel bill costs according to the assumptions on fuel costs in RdSAP 2012 version 9.94 of 3p per kWh gas and 13p per kWh electricity. Given the

[18] Cost shown is for suspended under floor insulation

substantial rise in energy costs resulting from recent public health and geopolitical events, these values are substantially out of date at the time of writing. The indicative annual fuel bills are, however, shown in Figure 3-36 for context.

Marginal fuel bill savings are achieved by the air tightness (between 0 and 1 %) and floor (between 1 and 5 %), retrofits (except when using default U-values). The window replacements were more successful, reducing bills by 4 % and 1 2%. The addition of the MVHR is predicted to increase annual fuel bills between 7 % and 33 %, shown as negative savings, since more energy is used to power fans and heat the additional ventilation provided by the MVHR than is saved by the heat recovery.

The sensitivity analysis, in BREDEM, which assumes the home achieves an infiltration rate of <3 $m^3/(h \cdot m^2)$ @ 50Pa and uses actual SFP, suggests that MVHR could be effectively cost neutral, however; though the DSM did predict it would still have higher running costs than the naturally ventilated home. The benefit of MVHR therefore would be that of more fresh air with no major change in running costs (though air quality was not assessed in these field tests).

The DSM predicts a lower space heating demand generally than the steady-state models, and thus shows lower fuel bills, though similar percentage savings. Adding in the measured air tightness tended to improve the predicted savings since the home was more airtight than the default models, though adding in the measured U-values worsened the amount of savings that were predicted, as these tended to be higher than predicted (i.e. a prediction gap).

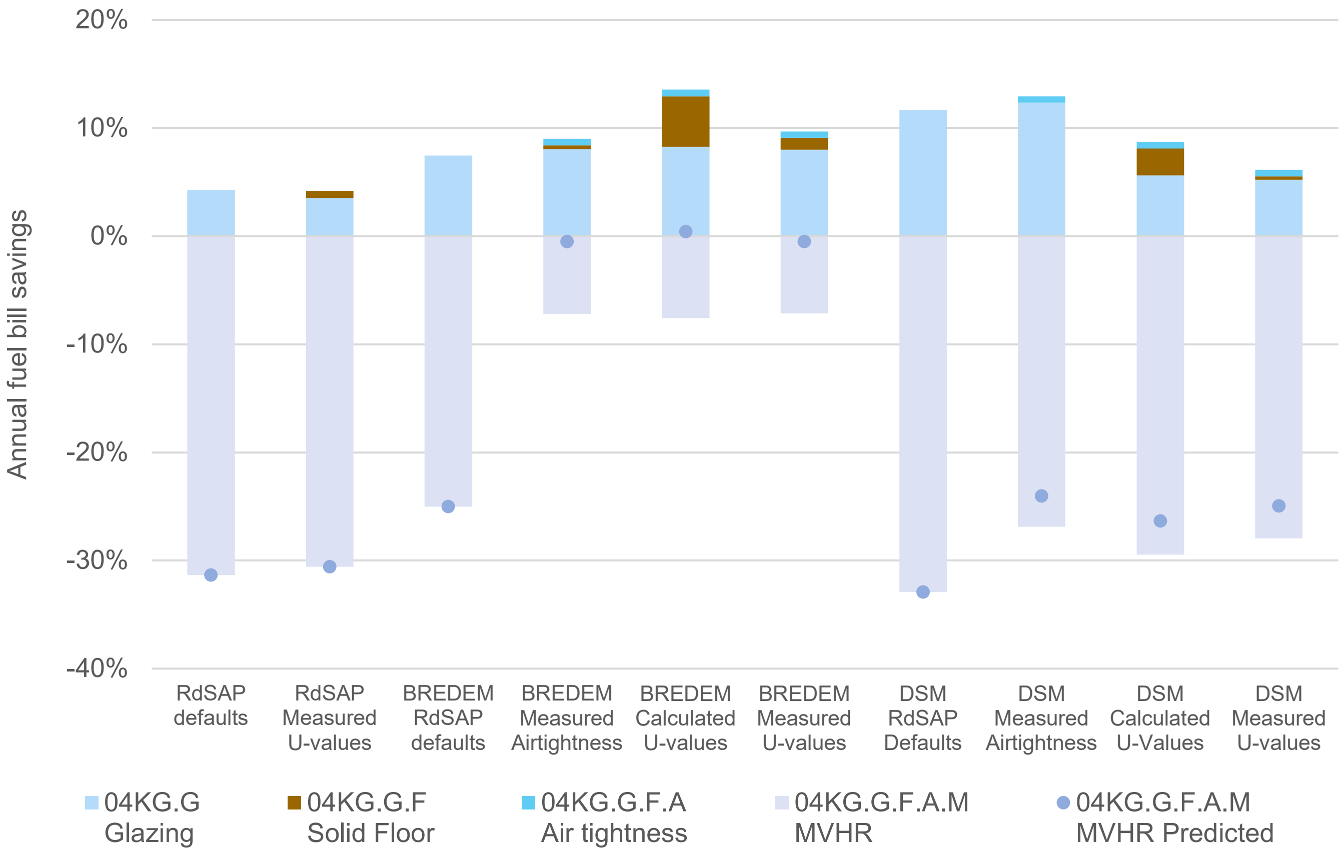


Figure 3-36 Predicted annual fuel bills

Retrofit costs summary

The costs presented may not be representative since they are based on one case study. The project has, however, found that some retrofits can encounter significant enabling costs. This suggests that forecast budgets for retrofits for policy makers, as well as individual homeowners and landlords, may require revisions. More information on the additional enabling costs for retrofits is needed, in addition to more up to date benchmark costs for delivering the specific retrofits.

The floor retrofit had high material costs since aerogel is an innovative product. Conversely, the costs of the airtightness improvements were predominantly for labour. The glazing and MVHR installation had a roughly equal split between labour and materials. This is important to consider when identifying how the costs of retrofits can be reduced.

The changes to fuel bill savings that were modelled in this case study are not representative of current day fuel bills but are shown as indicative examples of existing assumptions in government modelling software.

The fabric retrofits only made marginal fuel bill savings, and because the unit price of gas was assumed to be only 3p per kWh, the fabric retrofits were predicted to make little impact on household bills.

The MVHR increased electricity consumption to run its fans. Additionally, because electricity is assumed to be four times the cost of gas, and because more ventilation is provided via MVHR systems, this meant that overall fuel bills increased, even though some heat was being recovered.

The DEEP Case Studies Summary 2.00 discusses the cost effectiveness and paybacks of the case study retrofits in more detail and in the context of recent price rises.

4 Conclusions

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

New double glazing and external doors
Double glazing has been installed in millions of homes over the last few decades. The thermal performance of double glazing has improved over recent years, but seals around windows may deteriorate over time. Therefore, replacing the existing glazing in 04KG was expected to reduce heat losses.

The HTC measured by the coheating test shows that the new double glazing retrofit did not achieve a significant reduction, falling by (6 ± 12) W/K, or (4 ± 8) %. The models predict that a saving of between 13 and 22 W/K may be achieved, though the exact performance of the existing fenestrations could not be determined so there is some uncertainty associated with this.

The findings cannot confirm that new double glazing will always reduce heat losses, and this will depend on the thermal performance of the incumbent windows. It is difficult, however, to determine the performance of existing glazing. Without better identification and documentation of glazing performance, it is challenging to identify which homes may benefit from new double glazing.

The case study suggests installing new windows could reduce the air leakage in the home, since there was a measured reduction from 9 to 8.1 $m^3/(h \cdot m^2)$ @ 50Pa. However, this is within the uncertainty of the test. The result may have been more conclusive, but infiltration around the windows and door thresholds post-retrofit remained visible when using thermography under depressurisation. Additionally, the trickle vents were not well sealed to the frames. These findings suggest that unless air leakage is performed alongside glazing retrofits, and if trickle vents have ineffective seals, airtightness improvements may not be achieved when new windows are installed.

Solid ground floor insulation
Conventional solid ground floor insulation requires the ground floor slab to be dug out, insulated, and re-screeded, which is time-consuming, costly, and disruptive. This case study trialled a low disruption alternative retrofit, a 20 mm of aerogel board installed on top of the ground floor slab. This was a relatively expensive retrofit, though it was simpler to install. The coheating tests suggest the retrofit reduced the HTC of the home by (29 ± 15) W/K, or (20 ± 10) %.

The uncertainty in this result is high, due to large solar gains and party wall heat losses experienced during the test. However, the reduction is still more than was predicted: the energy models suggested a saving of between 2 and 14 W/K, while the U-value changes indicated a 12 W/K saving may be achieved. This implies that more needs to be understood around the way models account for ground floor heat losses and how these can be measured.

The results suggest that this approach to ground floor insulation could be a viable alternative, though more research is needed to understand how it performs in homes with suspended timber ground floors, and how it affects condensation and moisture accumulation in timber joists.

Airtightness improvements
There is little data on the effectiveness of different airtightness improvement measures, making them difficult to justify in energy improvement advice, and incentivise via policy instruments. Currently, only draught-stripping of windows and doors is part of supported measures. Furthermore, the benefit provided by more general airtightness improvements is excluded from RdSAP assessments, meaning they register no benefit in EPCs. The approach adopted by the specialist airtightness contractors in this case study was focused around sealing the intermediate floor surface; something that is not conventionally considered part of the primary airtightness envelope.

Sealing of the intermediate floor perimeter, taping of plywood flooring joints, and sealing accessible wall penetrations and gaps, complimented the plywood intermediate floor. These approaches combined were successful in achieving a mean air permeability of 5.4 $m^3/(h \cdot m^2)$ @50 Pa. However, the subsequent coheating test caused accelerated shrinkage, resulting in the failure of some mastic and tape seals, meaning the final airtightness value was measured to be 6.4 $m^3/(h \cdot m^2)$ @ 50Pa, or a 16 % reduction. This case study therefore raises serious questions on the longevity of seals and tapes for the airtightness retrofit market. The extent to which these strategies are adopted to enhance performance levels to only temporarily achieve compliance when blower door testing is undertaken is not known.

Inter-dwelling air exchange
The co-pressurisation tests undertaken at the case study and the adjacent home displayed the phenomenon of inter-dwelling air exchange, which has implications for homes and the blower door test. The results suggest around 17 % of the air leakage reported by the blower door test may in fact be inter-dwelling air exchange, being induced by elevating the pressure in the home beyond that which would normally be experienced, except in extreme wind. More research is needed to understand the extent of inter-dwelling air exchanges in blower door tests in different house types and how this may relate to in-use air exchange. The potential implications of this phenomenon could be significant:

- Any air infiltration to or from an adjacent home, rather than from the outside, may not represent a heat loss since it may be at indoor temperatures already. Using infiltration rates derived by blower door tests in energy models may therefore overestimate ventilation heat losses. The infiltration rate from blower door tests is used in full SAP, and this may mean that EPCs awarded to homes with attached dwellings could be underestimated.
- Homes with infiltration above 5 $m^3/(h \cdot m^2)$ @ 50Pa are exempt from requiring permanent mechanical ventilation. However, if the blower door overestimates the amount of external air entering homes, then homes marginally above the threshold may actually be marginally below the threshold, meaning the occupants have insufficient fresh air. This has implications for occupant health, noise pollution, and fire safety. This raises the possibility that some naturally ventilated homes actually fall below 5 $m^3/(h \cdot m^2)$ @ 50Pa threshold and should have permanent mechanical ventilation fitted.

Mechanical Ventilation with Heat Recovery (MVHR)
Conventionally, MVHR is installed in new build homes. This case study has highlighted several concerns specific to retrofitting MVHR that make this a particularly challenging measure. Specifically, the installation of the MVHR system corresponded with a 16 % increase in infiltration. This was caused by the holes created for the new ducting and grills that penetrated through the building fabric not being adequately sealed. The requirement that airtightness tests are undertaken alongside MVHR commissioning may minimise the impact of this, which would ensure that both the system, and the conditions in the home are appropriate.

MVHR retrofits currently result in a worse EPC score when RdSAP defaults are used. If MVHR is to be a retrofit measure in the future, this issue needs to be resolved by allowing more flexible inputs (e.g. allowing specific heat recovery %, SFP, MVHR ventilation rate and whole house infiltration rates to be input into RdSAP).

When using the RdSAP default inputs, the assumed increase in electricity consumption related to MVHR operation appears to be much higher than the manufacturer's data suggests, and the heat recovery efficiency to be much lower, at almost 50 % of the manufacturer's efficiency. However, at the time of writing there is no in-use data available, either within the DEEP project or outside it, to challenge these assumptions.

For this case study, there was insufficient heat recovery by the MVHR to offset additional energy demand caused by the excessive infiltration (caused by the installation itself), additional purpose provided ventilation, and the fan use, when the MVHR was fitted. Additionally, since electricity is assumed to be four times more expensive than gas in the version of SAP used, the MVHR resulted in a worse EPC Band for the home. It was also predicted to increase annual fuel bills between £125 or £175 per annum.

An additional sensitivity analysis investigated the impact of updating the assumed SFP electricity consumption of the MVHR with the manufacturer's data, and assuming the infiltration rate in the home achieved the 3 $m^3/(h \cdot m^2)$ @ 50Pa (0.15 ACH) recommended threshold. This analysis suggests that the MVHR could lead to an overall reduction in space heating and carbon emissions for homes, and the home would receive more fresh air. However, based on the current ratio between the price of electricity compared to gas, it suggested the MVHR would not improve the EPC score or running costs for the home.

It is not known how much of the predicted heat demand reduction is due to better airtightness in the home generally, or from the heat recovery specifically, though these are seen to be interdependent, i.e. the airtightness would only be possible if mechanical ventilation was installed to provide sufficient fresh air for occupants.

The assessment performed here is not ideal for considering the holistic benefits of MVHR for homes. For instance, it was beyond the scope of the DEEP project to undertake longitudinal monitoring of the home with the retrofitted MVHR. This could have collected data on energy savings made in-situ, under realistic fuel price scenarios, as well as record the impact of further reducing the home's infiltration rate to within acceptable thresholds. It would also have allowed monitoring of the internal air quality and comfort delivered by the MVHR, which are some of its main benefits.

The investigations show that the amount of ventilation required to be delivered by MVHR is substantially higher than that assumed to be delivered into naturally ventilated homes in energy models. More information is needed to understand how much ventilation is delivered in naturally ventilated homes, and how effective trickle vents are in providing fresh air, to inform models and comparisons between naturally and mechanically ventilated homes.

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