Department for Energy Security & Net Zero

LEEDS BECKETT UNIVERSITY
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DEEP Report 2.06

Case Study 00CS

October 2024

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Executive summary

00CS is one of fifteen case study homes retrofitted in the DEEP project. The case studies were used to identify the performance of, and risks associated with, retrofitting solid walled homes. The data from the case studies was used to evaluate the accuracy of modelled predictions around retrofit performance and risk.

The findings from this case study should be interpreted in the context of the house typology, which was a large, rural, stone detached cottage in an area of outstanding natural beauty (AONB); and the specific retrofits of floor insulation and secondary glazing, all of which are described in the report. The case study provides useful insights, though more data, including that generated by the other DEEP case study dwellings, is needed to make broader generalisations for the housing stock.

In this case study, the application of a 10 mm aerogel carpet underlay to the ground floor and the impact of secondary glazing was assessed. These retrofits were selected as they represent low disturbance retrofit options for homes in AONB or where there are other restrictions and where solid wall insulation, and replacement of the existing glazing may not be possible. Loft insulation was not considered, as the dwelling appeared to already have a well-insulated loft, though the investigations revealed discontinuities that may be increasing condensation risk.

Neither the ground floor retrofit, nor the addition of secondary glazing, resulted in a measurable change in the home's heat transfer coefficient (HTC), according to the coheating tests. However, this is because the whole house heat loss of the home prior to retrofit was very large (376 W/K), with around 90 % of the heat loss attributable fabric elements or air leakage that were not improved by the retrofit.

The home's Energy Performance Certificate (EPC) did not record any reduction in HTC resulting from the ground floor insulation, since the aerogel blanket was only 10 mm thick, and RdSAP does not consider any insulation thicknesses under 50 mm. However, when these input assumptions were overridden in RdSAP with the actual measured U-values, the EPC predicted a 2 % reduction in HTC achieved by the ground floor insulation, compared to a 6 % change attributable to the secondary external glazing.

Additionally, the home had half the air leakage than was assumed in the EPC. Its measured infiltration rate showed a performance level acceptable for new build homes, being between 7.0 and 8.5 $m^3/(h \cdot m^2)$ @ 50Pa. This suggests that EPC estimates of airtightness in homes do not always reflect reality and can result in an underprediction of energy efficiency. Thus, there may be benefit in revisiting the RdSAP methodology around air leakage.

The case study also highlights that DSM, unlike steady-state models, accounts for internal walls when calculating the volume of the home that needs space heating. This case study home was of a heavyweight construction with a number of very thick internal walls (up to 500 mm thick in places) and so resulted in 15 % less calculated dwelling volume in the DSM. This is one of the main reasons why RdSAP predicted a 40 % higher HTC than the DSM. Thus, EPCs generated using RdSAP data may be predicting higher space heating demand and fuel bills, and worse SAP scores, while also predicting larger retrofit saving predictions than are achieved in practice. Accounting for internal walls in RdSAP may therefore improve the accuracy of EPCs.

1 Introduction to 00CS

Case study 00CS is a two-storey, four-bedroom detached stone house with large amounts of exposed thermal mass, allowing the DEEP project to investigate the implications of undertaking Building Performance Evaluations (BPE) and energy modelling in such a building. The home possesses a predominantly solid ground floor (with only a single ground floor room being suspended timber flooring), and so it was selected in DEEP to investigate the potential for a low disturbance approach to ground floor insulation; a 10 mm aerogel carpet underlay. The home also had secondary glazing installed behind the original single glazing, meaning the benefit of secondary glazing could also be investigated. Thus, this case study is useful in describing the performance and implications of two relatively low disturbance retrofit measures. These may be an option for homeowners to install where traditional or historically significant details or fabric reduce the practicability of more intrusive retrofit interventions.

1.1 DEEP field trial objectives

00CS is one of fourteen DEEP case studies, which, collectively, will attempt to investigate research objectives listed in Table 1-1. Not all the objectives are addressed by each case study.

Table 1-1 DEEP Research objectives

Objective	Rationale
Model input accuracy	Policy relies on models with known limitations; exploring inputs and model robustness 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 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 Case study research questions

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

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

Data collected from case study 00CS will contribute to the formation of a body of evidence from the DEEP project, that may begin to address these questions.

1.3 Case study house information

00CS, shown in Figure 1-1, is a four-bedroom detached stone cottage. It is located in the North York Moors National Park and was built in the late 18th century. The external stone walls vary in depth but are on average 510 mm thick. However, the exact make-up of the wall is not known. The dwelling also has two chimney stacks, each with a log burning stove fitted.

The ground floor is mostly a solid concrete slab, which may have been poured more recently, except for a small portion of suspended timber floor in the dining room and flagstones placed onto compacted earth in the under stairs store. There is single glazing throughout, though removable secondary glazing panels have been installed internally throughout.

There are over 2.3 million detached four-bedroom houses in England and Wales, representing around 9 % of the housing stock [1]. There are roughly 4.1 million homes built pre 1900 [2], but it is difficult to estimate how many share similar building characteristics with 00CS.

Figure 11 and Figure 12 show an image of the case study home and its site plan respectively.

Figure 1-1 Case study house, south elevation

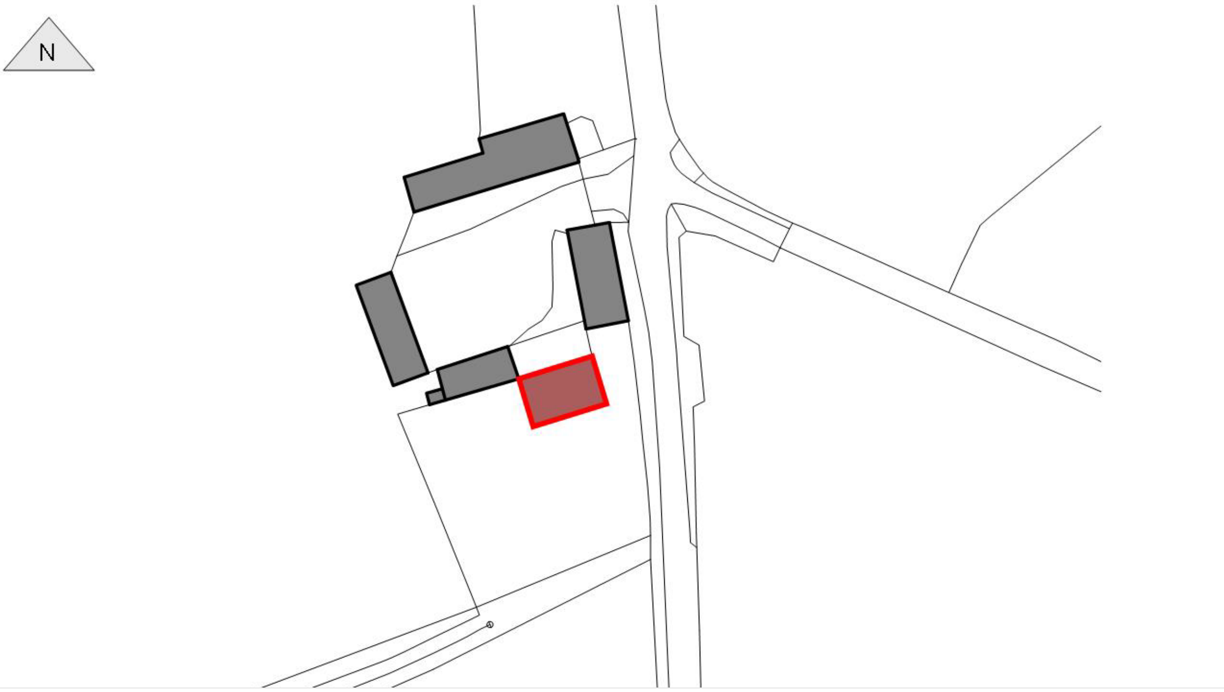


Figure 1-2 Case study house site location plan

Floor plans, elevations and sections can be seen in Figure 1-3, Figure 1-4 and Figure 1-5 respectively.

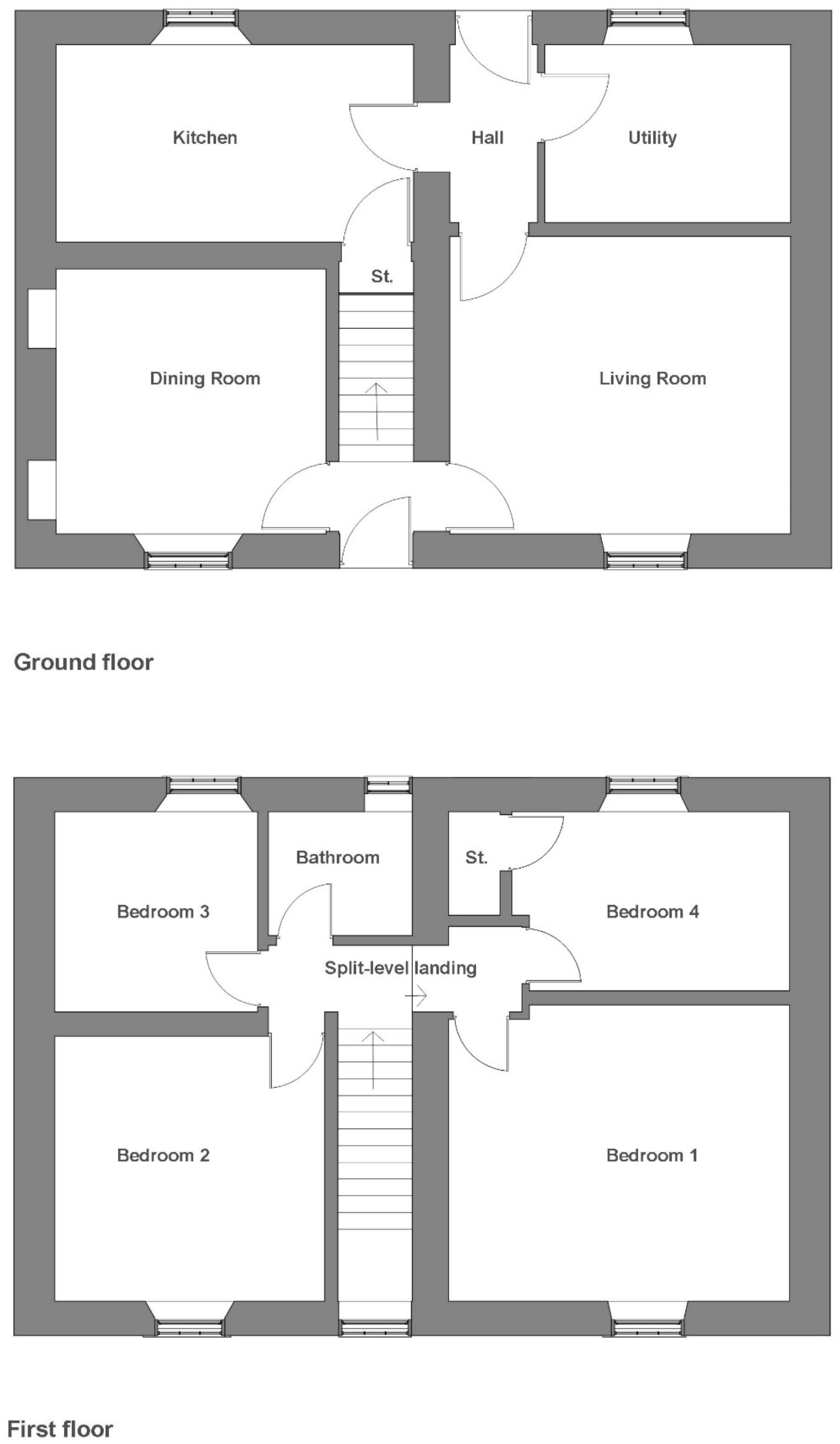
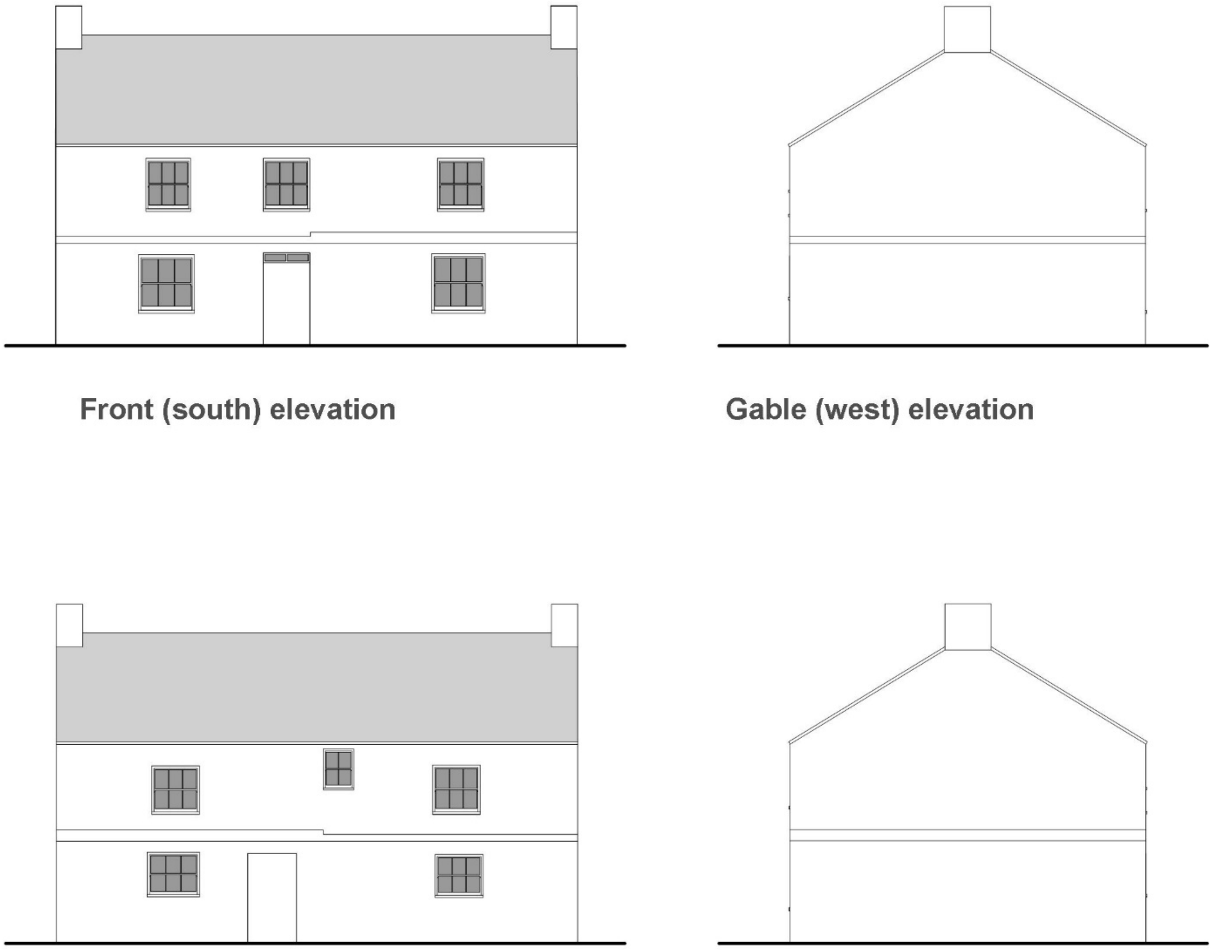


Figure 1-3 House floor plans



Front (south) elevation

Gable (west) elevation

Rear (north) elevation

Gable (east) elevation

Figure 1-4 House elevations

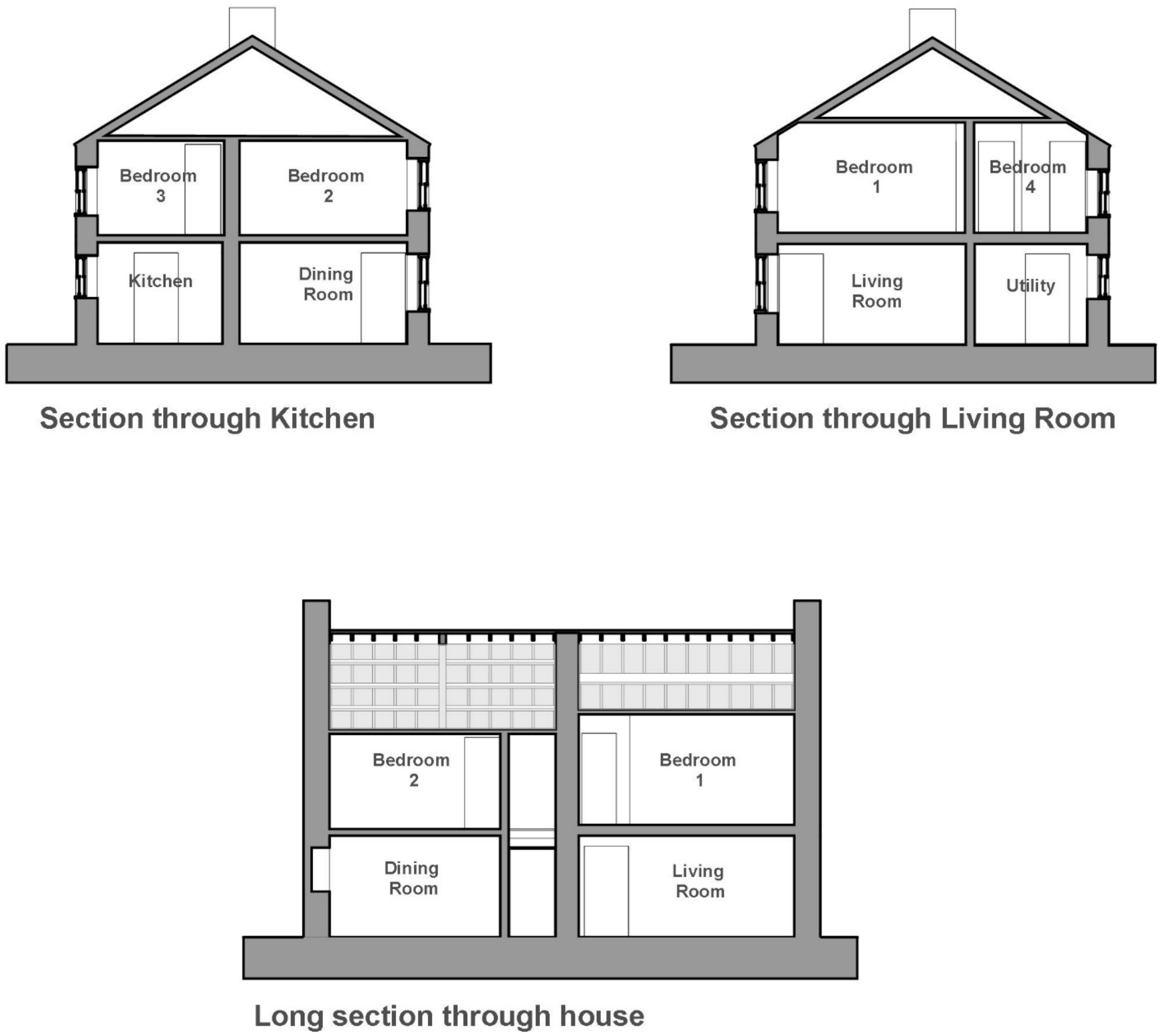


Figure 1-5 House sections

The dimensions of each element in the home are listed in Table 1-2 and are used to allocate heat losses as well as generate thermal models in RdSAP, BREDEM, and DSM.

Table 1-2 House dimensions

Detail	Measurement
Volume	325 m²
Total floor area	139 m²
Total heat loss area	294 m²
Solid ground floor	56 m²
Suspended timber ground floor	14 m²
External wall	139 m²
Loft	69 m²
Windows	11 m²
Doors	4 m²

Construction details are summarised in Table 1-3. There were no obvious defects with the building fabric in general and windows were in good condition with no signs of mould or condensation between the secondary and single glazing. However, the internal walls behind ground floor alcoves and first floor cupboards, built into the external solid stone walls, showed signs of damp and mould, presumably related to the walls being thinner and there being less air movement here as they were sunken into external walls. The main features to note are that the house has lots of exposed thermal mass, small windows, and secondary glazing.

Historic records for the property suggest that the east side of the house is newer than the west side. This is most pronounced in the loft, as the roof structure for the east and west sides of the house differs. This resulted in a small ‘skeiling’ (sloped ceiling at the eaves) in bedrooms 1 and 4, but not in bedrooms 2 and 3 or the bathroom.

The existing insulation present in each loft part differs. Above bedrooms 1 and 4, 200 mm of mineral wool was poorly laid across and over the ceiling joists. This should have been laid between joists and laid across the joists, as was found in the loft above bedrooms 2 and 3 and the bathroom, where there was 200 mm of sheep’s wool insulation.

1.4 Retrofit approach

The retrofit details and nominal U-value targets for each element are listed in Table 1-3. The target retrofit U-values listed have been calculated using 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 and the Combined Method detailed within BS EN 12524:2000 was used to account for repeat thermal bridges within each plane element calculation (e.g. floor joists).

Table 1-3 Construction and retrofit summary

Detail	Baseline construction	Retrofit[1]
Airtightness	7.56 $m^3/(h \cdot m^2)$ @ 50Pa	n/a
Floor type 1 (hall, utility, living room, front door hallway)	Uninsulated solid ground floor	Aerogel carpet underlay 10 mm 0.014 $W/(m \cdot K)$ Target U-value 0.37 $W/(m^2 \cdot K)$
Floor type 2 (kitchen and under stairs store)	Uninsulated solid ground floor	None (Landlord request for minimum disturbance to new kitchen flooring and units)
Floor type 3 (dining room)	Uninsulated suspended timber	Aerogel carpet underlay 10 mm 0.014 $W/(m \cdot K)$ Target U-value 0.45 $W/(m^2 \cdot K)$
External wall	510 mm uninsulated stone wall[2]	n/a
Roof type 1	200 mm sheep's wool insulation	n/a
Roof type 2	200 mm mineral wool insulation	n/a
Windows	Timber single glazed sash windows with secondary glazing	Timber single glazed sash windows with secondary glazing removed
Door	Timber	n/a

The sequence of retrofits is shown and illustrated in Figure 1-7 through to Figure 1-9. Building Performance Evaluation (BPE) tests, whole house energy modelling, and elemental thermal simulations were conducted at each stage of the retrofit. These quantified performance changes, with each separate intervention, and the potential for condensation risk. The specific methodologies for these are described in DEEP Report 2.01, DEEP Methods. The codes in Table 1-4 are shorthand to identify each retrofit stage to aid the discussion and presentation of results.

[1] Target U-values based on assumed construction details and may vary from Approved Document Part L maximums according to manufacturer recommendations or space limitations.
[2] Wall thickness varied between common and gable walls. Figure given here is an overall average.

Table 1-4 Phased retrofit stages

	Retrofit Stage	Code	Retrofit Dates
1	Baseline	00CS.B	January 2020
2	10mm aerogel floor insulation	00CS.F	October 2020
3	Removal of secondary glazing	00CS.F.G	November 2020

The ground floor insulation was not applied in the kitchen area since the landlord had recently replaced the flooring and kitchen units. This therefore allowed a comparison between the surface temperature in an insulated and uninsulated section of the ground floor in the same home toidentify if any surface condensation risks manifest on the areas that were left uninsulated. Hybrid floors are relatively common (part solid and part suspended timber). Thus, it is interesting to know how leaving a part of a ground floor uninsulated impacts performance and condensation risk.

Since secondary glazing was already installed in the home, the final step was to quantify the benefit that the secondary windows were providing. To do this, the secondary windows were removed for the tests during this stage as shown in Figure 1-6.

Figure 1-6 Secondary glazing removed for final test phase

The testing program was initially too short to include a glazing test, and the opportunity to perform a second test without the secondary glazing installed arose only later in the program, and after the floor insulation was installed. Thus, the baseline home had been tested with secondary glazing already installed.

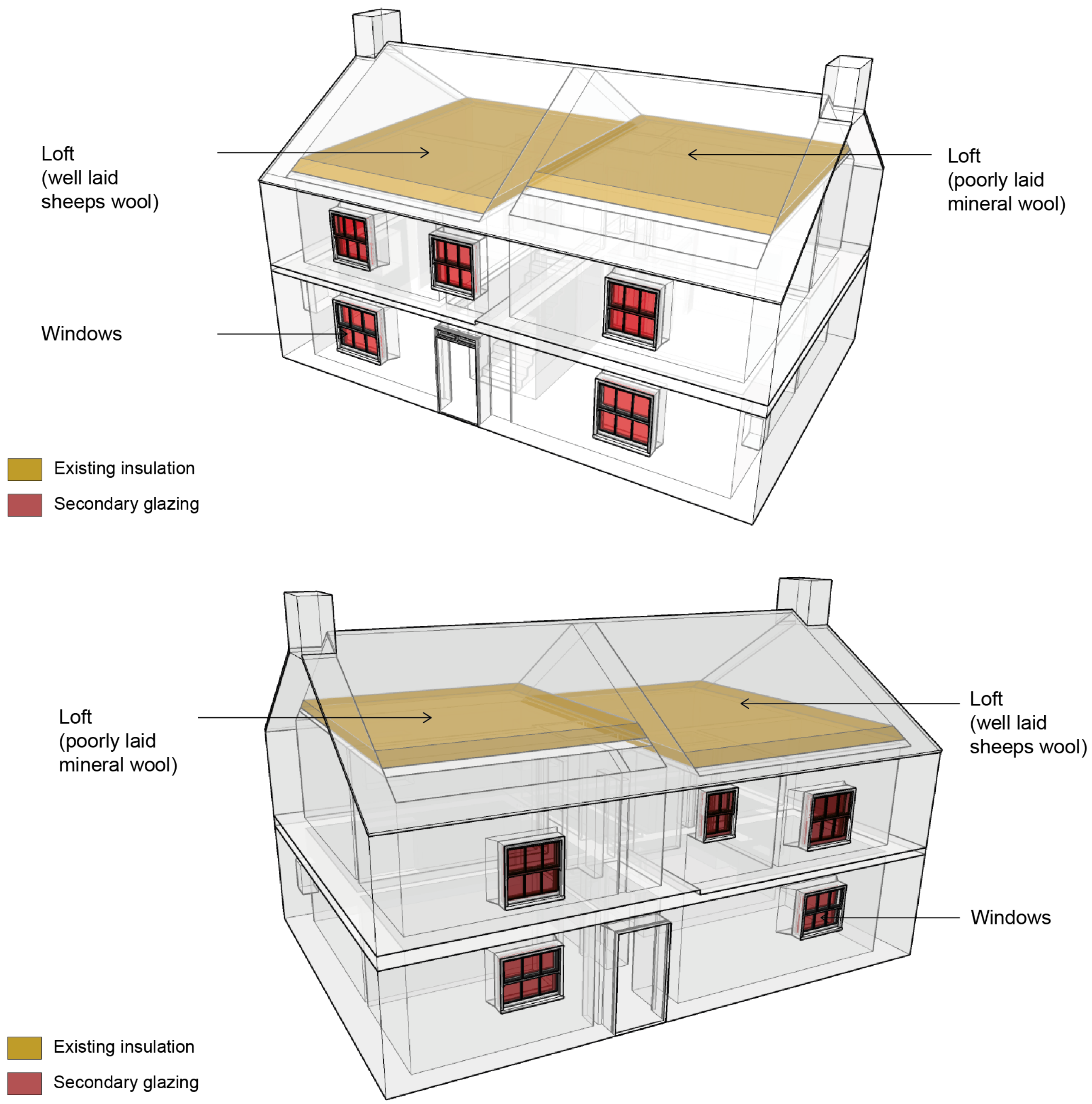


Figure 1-7 Stage 1: Loft insulation and secondary glazing already in the property prior to the retrofits (00CS.B). Front (south) and rear (north) elevations respectively.

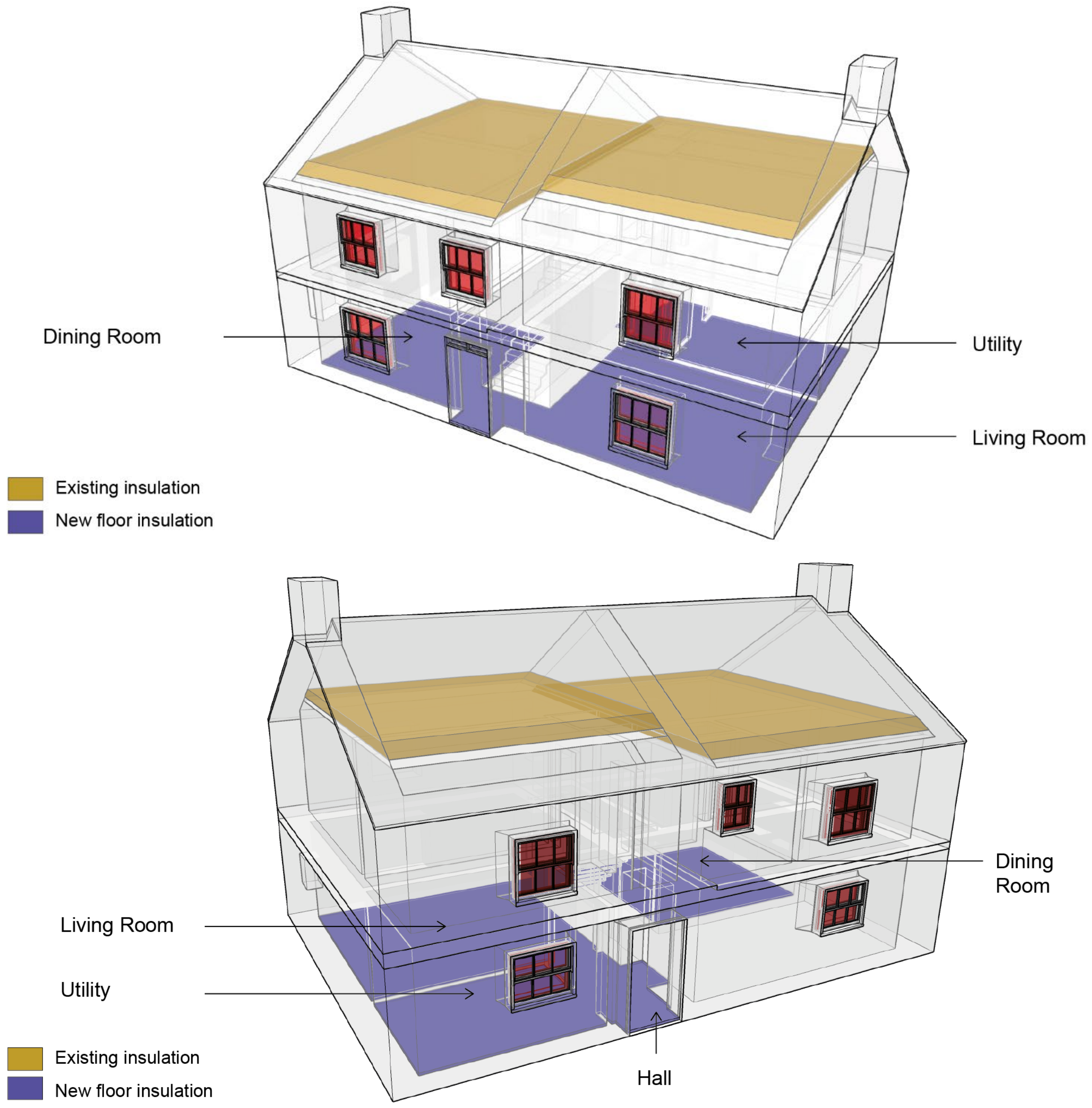
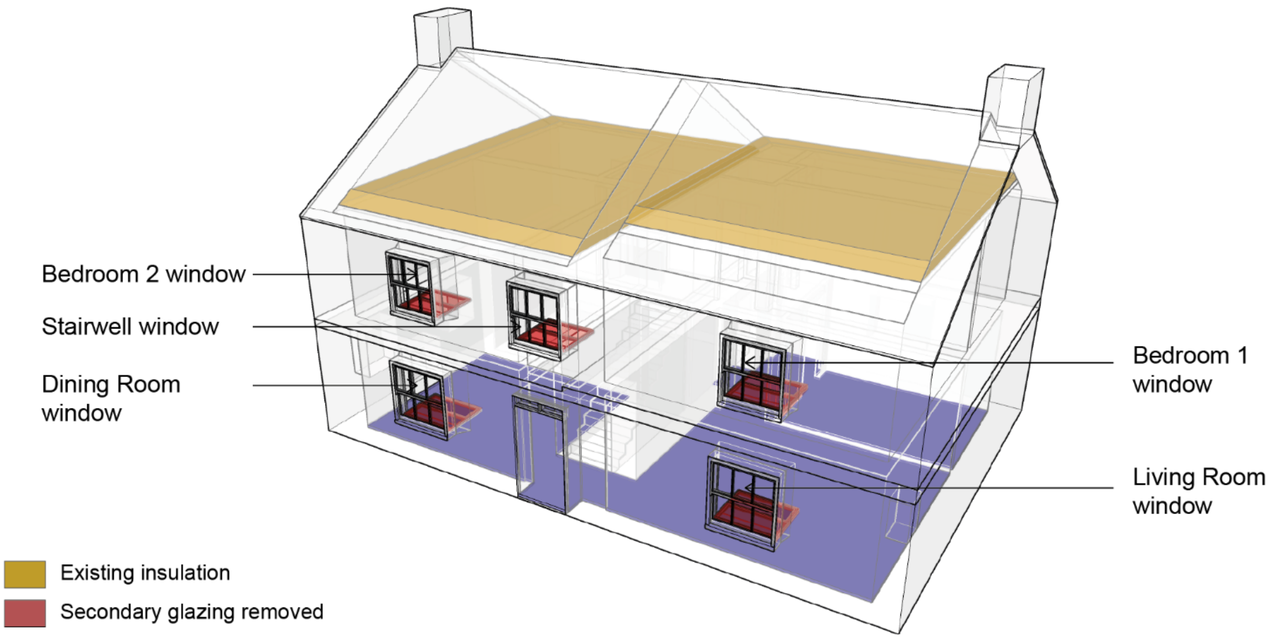


Figure 1-8 Stage 2: Floor retrofit to ground floor (except kitchen and under stairs store) (00CS.F). Front (south) and rear (north) elevations respectively.



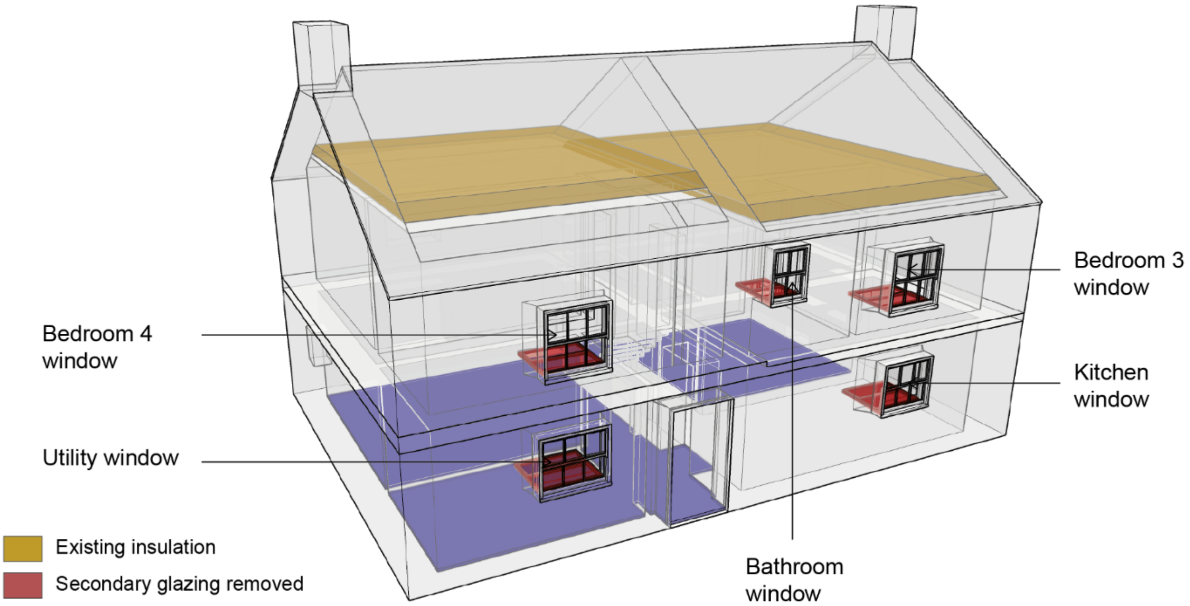


Figure 1-9 Stage 3: Airtightness retrofit to all windows – all secondary glazing opened (00CS.A). Front (south) and rear (north) elevations respectively.

Introduction summary

The 00CS case study provided an opportunity to collect performance data on two low disturbance retrofit measures: 10 mm aerogel carpet underlay and secondary glazing.

It also allowed an investigation into the implications of not insulating the entire ground floor area during floor retrofits, which may be a common scenario in UK homes where there are either mixed floor types or where kitchen and utility areas have been refurbished and it is not practical to remove the units.

It also provided an opportunity to investigate the implications of collecting building performance data from a historic dwelling with a high level of thermal mass.

2 Fieldwork and modelling methods

BPE tests and modelling activities were undertaken on 00CS at each retrofit stage in accordance with the methodologies listed in DEEP Report 2.01. This section outlines the specific implementation of these methods at 00CS, including any variations and additions.

2.1 Environmental data collection

Internal environmental data logging equipment is described in detail in the Methodologies Annex. Internal environmental data collected at 00CS included air temperature, Relative Humidity (RH) and CO_2 concentrations. External environmental data was collected via a Vaisala WXT536 weather station fitted with a Kipp & Zonen CMP3 pyranometer sited on the south-facing front façade of 00CS and included vertical solar irradiance, air temperature, relative humidity, and wind speed. This was positioned with the pyranometer mounted vertically and facing due south to allow a measurement of total solar irradiance for solar regression calculations.

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 through to Figure 1-5. 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. Finally, core samples of the walls were also taken to undertake lab analysis of the material properties and identify the construction layers, the method for which is described in the DEEP Report 4.

2.3 Airtightness and thermography

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

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

2.4 Heat flux measurement and U-values

40 Hukseflux HFP01 heat flux plates HFPs were installed on different elements in 00CS and the HFP locations are listed in Table 2-1. For context, the locations of these are visualised in Figure 2-1 and Figure 2-2. These were primarily installed to measure the improvements in in-situ U-values achieved by the fabric upgrades, and so 24 of these were installed on the ground floor (nine on the solid ground floor and 15 on the suspended timber ground floor).

Heat flux density from individual HFPs, along with internal and external air temperature data, was 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.

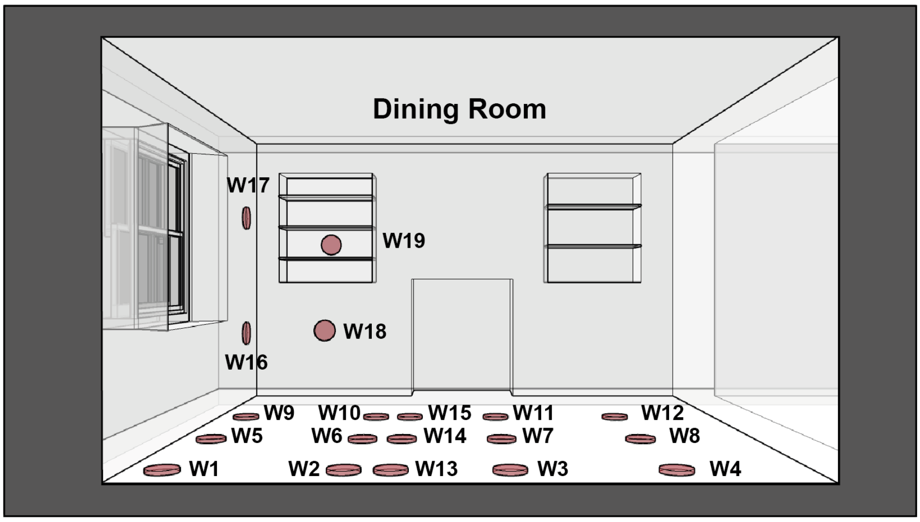
The in-situ U-values were based upon a limited set of measurements, so may not be representative of the performance of the element in practice. Similarly, where areas of thermal bridging may be expected, such as near corners, heat flux density measurements were taken to provide context to the whole fabric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

Table 2-1 HFP locations

HFP	Element	Room
G1-G4	Solid floor	Living room
W1-W15	Suspended timber floor	Dining room
W20	Solid floor	Front door hallway
S1, S2, S3, S5	Solid floor	Kitchen
W16-W19	External wall	Dining room
W19	External wall (thinner section)	Dining room
G5	External wall	Living room
I1, I2	External wall	Bedroom 4
J1, J2	External wall	Bedroom 3
I3	Skeiling (sloped part of ceiling)	Bedroom 4
I5	Insulated part of ceiling	Bedroom 4
I4	Ceiling edge (behind purlin)	Bedroom 4
J3, J4	Ceiling	Bedroom 3
J5	Ceiling	Landing
S4	Window	Kitchen

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

The U-values were used to calibrate energy and thermal models to estimate the heat loss due to the fabric (HTC_f) and compare this with the whole house HTC and disaggregation. Due to the layout of the dwelling, it was not always possible to place the HFPs in ideal locations, i.e., 0.5 m away from potential thermal bridges in geometric centres of rooms.



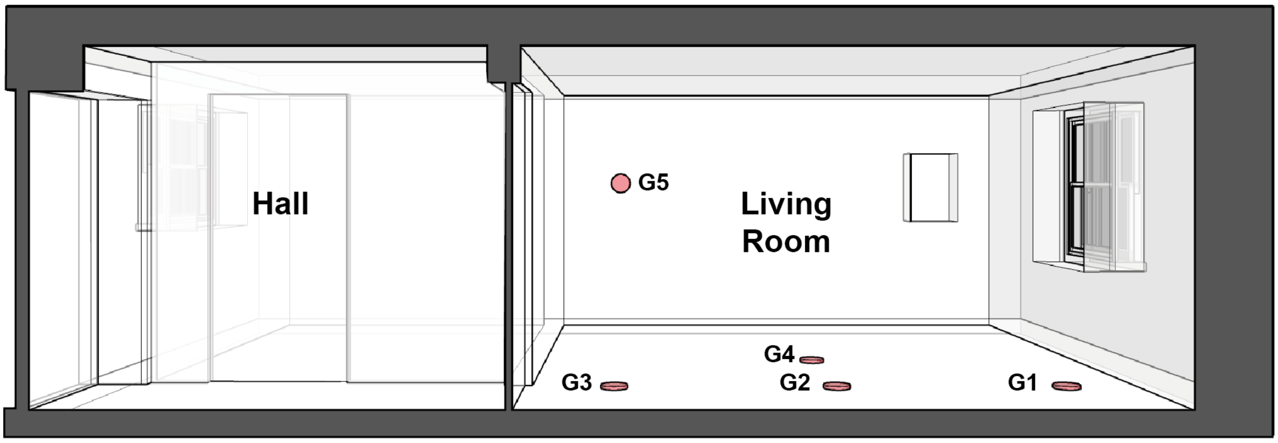
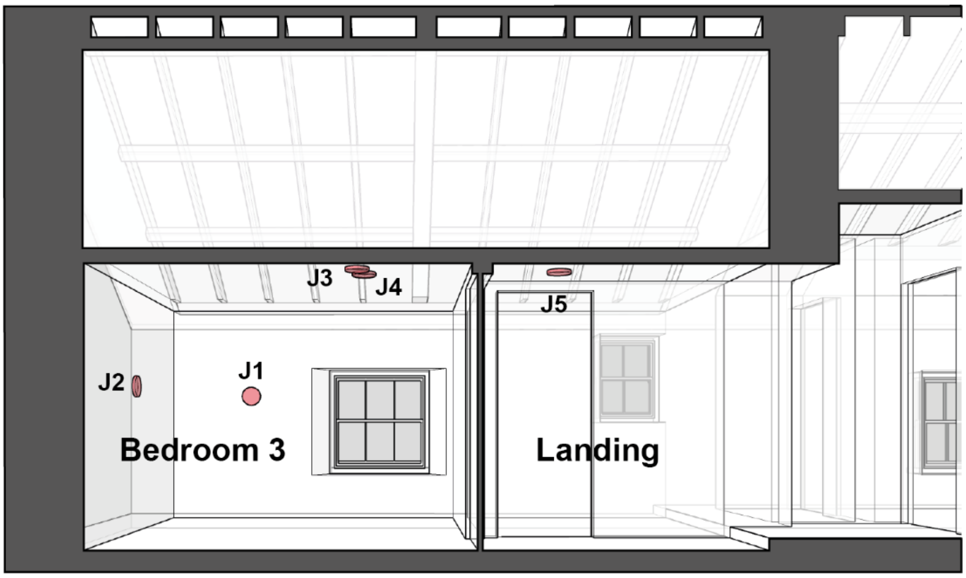


Figure 2-1 Ground floor HFP locations



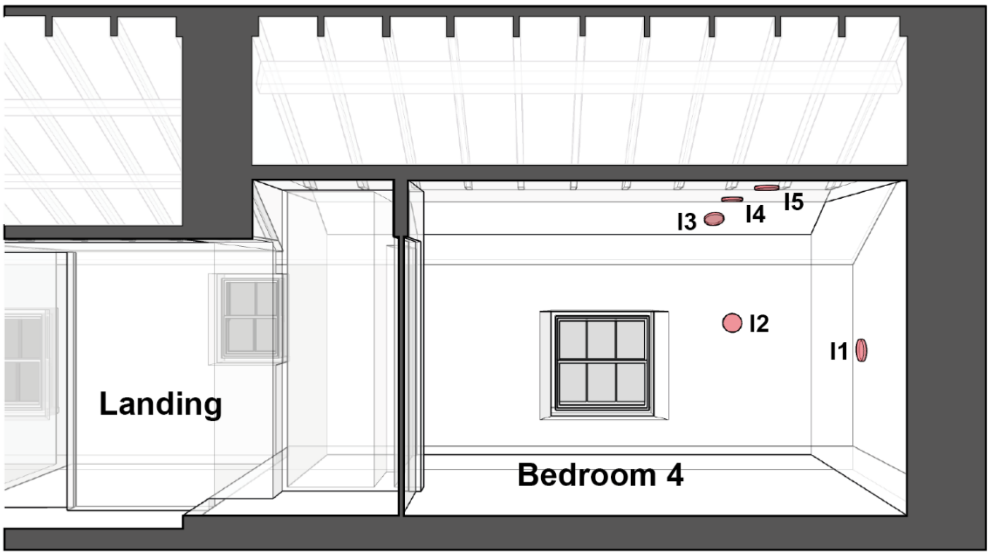


Figure 2-2 First floor HFP locations

2.5 Whole house heat transfer coefficient (HTC)

Coheating tests were performed at each retrofit stage to calculate the HTC. The uncertainty associated with these HTCs varied according to the test and the environmental conditions, and is presented in the results. QUB tests were also undertaken to investigate if it was possible to derive an HTC value in a home with a high thermal mass.

2.6 Surface temperatures and thermal bridges

The kitchen, which was left uninsulated, is of interest in 00CS where there could be a change in the risk of condensation following the insulation of the rest of the floors. Thus, surface temperatures were measured here to calculate the temperature factor (f_{Rsi}), which is used to assess surface condensation risk.

2.7 Whole building energy modelling

The modelling methodologies undertaken are explained in detail in the Report 2.01 DEEP Methods. DEEP first used the steady-state energy model, BREDEM, which generates EPCs for existing homes via the 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 [3]) 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 stages

Calibration step	Infiltration	U-values	Bridging
1	Default[3]	Default[3]	Default[4]
2	Measured[5]	Default[3]	Default[4]
3	Measured[5]	Calculated[6]	Default[4]
4	Measured[5]	Measured[7]	Default[4]

Additionally, the models predict annual energy demand, annual heating cost, carbon dioxide emissions, SAP score, and EPC band. The success of the retrofits against these criteria can therefore be evaluated and, along with the retrofit install costs, simple payback periods for each retrofit calculated.

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

[3] Provided by Appendix S RdSAP 2012 version 9.94
[4] Provided by Appendix K RdSAP 2012 version 9.94
[5] Derived from Blower door test
[6] Derived from BRE Calculator
[7] Derived from Heat flux plate measurements

Case study method summary

A deep dive into the 00CS retrofit case study was undertaken involving coheating tests, blower door tests, and 40 heat flux density measurements on fabric elements, taken before and after each of the retrofit stages.

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

These methods collectively investigate the energy performance and condensation risk associated with different approaches to retrofit, as well as the usefulness of the existing models to predict these.

3 Results

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

3.1 Airtightness improvements

The baseline air permeability value for 00CS was relatively low, 7.1 $m^3/(h \cdot m^2)$ @ 50Pa. For context, the average UK infiltration rate is estimated to be approximately 11 $m^3/(h \cdot m^2)$ @ 50Pa [4] and the maximum rate permitted under Building Regulations for new builds is now 8 $m^3/m^2.hr$ [5]. Thus, this case study house already meets the backstop value in the latest edition of Part L of the Building Regulations.

The case study dwelling is relatively airtight compared to the national average of 11 $m^3/(h \cdot m^2)$ @ 50Pa found by Stephen (1998) [6]. Stephen also found average infiltration rates of masonry dwellings pre 1900 dwellings was just over 12 $m^3/(h \cdot m^2)$ @ 50Pa based upon a sample size of 23 dwellings which is substantially higher than 00CS. More stone walled homes would need to be tested to understand if this level of air leakage is typical for these types of homes. However, characteristics, for instance, having a predominantly solid ground floor, wet plastered solid external walls and secondary glazing may be contributing to their superior performance.

The major air leakage routes identified were mainly around the historic timber front external door, as well as unsealed service penetrations and an unsealed loft hatch, as can be seen in Figure 3-1, Figure 3-2, and Figure 3-3 respectively.

Figure 3-1 Base case infiltration around front door during depressurisation

Figure 3-2 Base case infiltration through unsealed service penetrations attached to the boiler during depressurisation

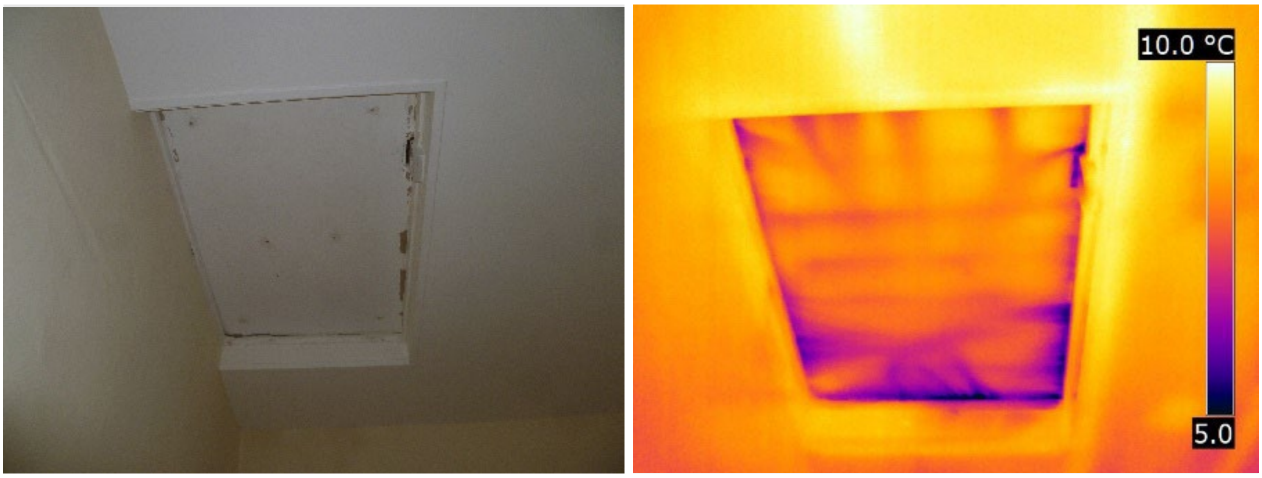


Figure 3-3 Infiltration via loft hatch during depressurisation

The dwelling is relatively airtight by UK standards, and it was not anticipated to be improved by the application of the ground floor insulation. However, removing the secondary glazing was expected to potentially reduce the airtightness of the house.

3.1.1 Summary of improvement in airtightness

The reduction in airtightness achieved by each retrofit is presented in Figure 3-4. The measured values are considerably below that assumed in RdSAP for a home of this type. The home, however, does not fall below the minimum threshold where continuous mechanical ventilation is recommended.

It appears that the airtightness of the house became worse after the ground floor insulation was installed, with mean air permeability increasing from around 7.1 to 8.5 $m^3/(h \cdot m^2)$ @ 50Pa . This may be because there were routine decoration works performed by the landlord between the two tests which involved repainting the timber windows. The difference is within the same order of magnitude as the upper end of the uncertainty in the test method; since the house was in an exposed position halfway up a valley side, it is possible that the test was subject to gusts (even when mean windspeed was at acceptable levels), which have affected the consistency of the tests.

The results also indicate that no measurable difference in airtightness was observed when the secondary glazing was removed. This is in contrast with one of the main reasons why homeowners install secondary glazing: to minimise draughts from the existing glazing system; and is suggestive of the good performance of the existing single glazing.

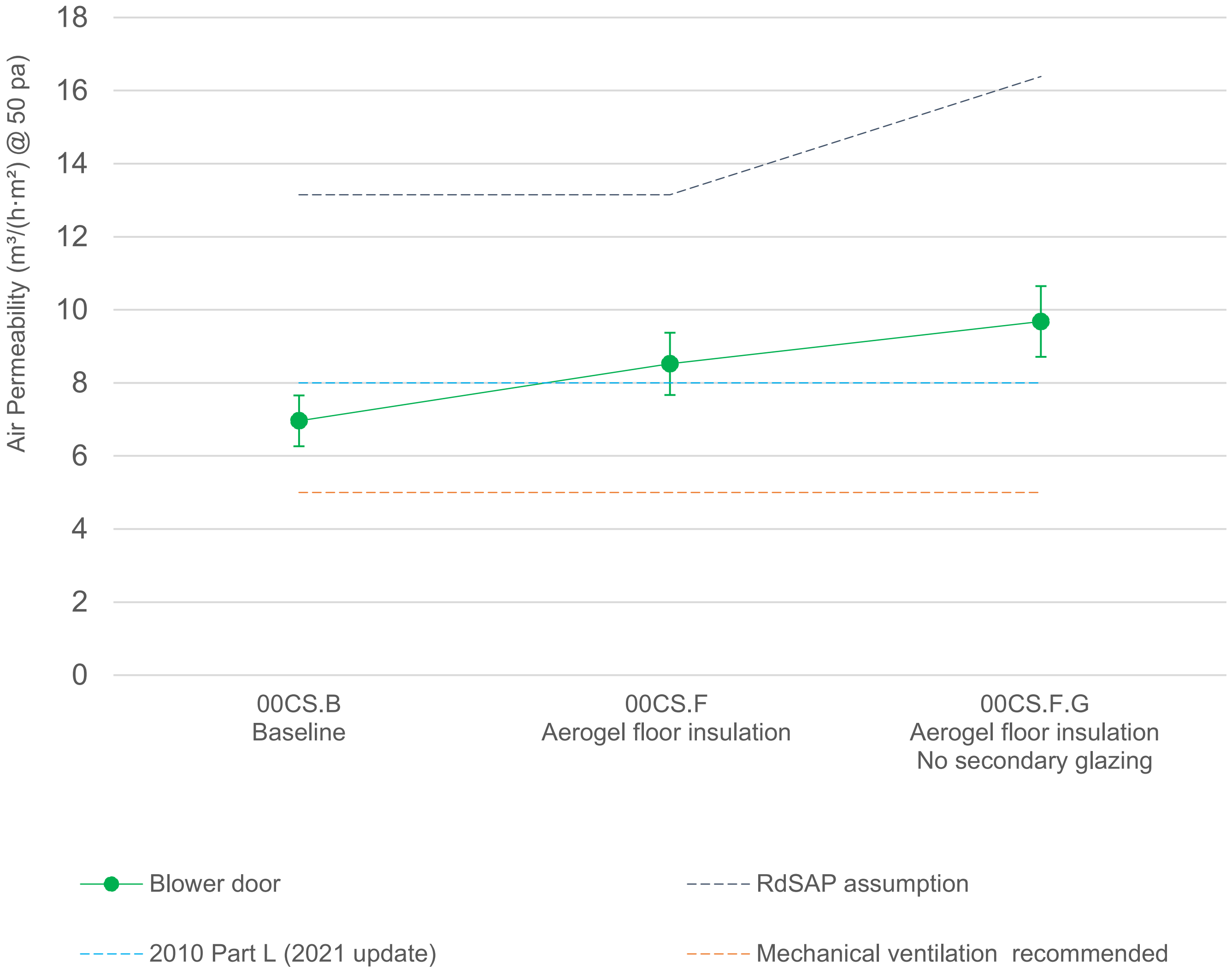


Figure 3-4 Air permeability at each retrofit stage

The excessive amount of dust that the aerogel blankets create meant the insulation had to be wrapped in a dust membrane before the carpets were refitted, as shown in Figure 3-5, which may have affected the insulation breathability.

This is an important point to consider if this measure is to be applied in a home, particularly if the occupants still reside there and suffer from respiratory problems. In addition, the requirement to add the dust membrane will also increase the time and cost associated with the refurbishment.

Although it is possible that the membrane may provide some additional airtightness benefits in homes with high air leakage rates through suspended timber floors, no improvement was observed in this house. Consequently, more data is needed to understand if this benefit would be experienced in other homes.

The removal of secondary glazing resulted in a marginal increase in air permeability, increasing from 8.5 to 9.7 $m^3/(h \cdot m^2)$ @50Pa, less than the 20 % improvement assumed in RdSAP. The Pulse test indicates a much greater increase in air permeability when the TM23 conversion is applied. This suggests that secondary glazing may be more effective at reducing air leakage in use than under blower door test conditions.

Figure 3-5 Aerogel ground floor insulation (left image) and dust membrane (right image)

3.1.2 Pulse tests and CO_2 decay tests

It was not possible to obtain reliable Pulse tests for the house as the algorithm identified the results as 'Invalid tests'. Results were obtained following the floor retrofit with secondary glazing closed, although accompanied with 'Warning' error messages, indicating that the house may have been too large for the Pulse unit with a single expansion tank.

These provided air permeability results of 2.3, 2.5 & 2.3 $m^3/(h \cdot m^2)$ @ 4Pa. Using the conversion to 50Pa from CIBSE TM23 (2022), this equates to air permeability values of 11.2, 12.2 & 11.1 $m^3/(h \cdot m^2)$ @50Pa, which are considerably higher than the 8.4 $m^3/(h \cdot m^2)$ @ 50Pa measured with the blower door method at the same phase.

CO_2 tracer gas decay was measured several times at each retrofit stage, though this did not result in meaningful findings. Following timed releases of CO_2 from release points in the centre of the house on the ground and first floor, the rate of concentration decay measured near the point of release suggested dwelling air change rates of >2.0 h^{-1}. This contradicts the blower door results: 8.0 h^{-1} @ 50Pa would result in an expected air change rate under natural conditions of <0.4 h^{-1}.

It is suspected that the size of the house, ~300 m^3, coupled with the location and orientation of the circulation fans inside it (installed to create isothermal conditions for coheating) meant that the released CO_2 was just being dispersed around the building rather than a decay rate representative of air exchange with outside.

Airtightness summary

The airtightness of the home was half that of the RdSAP predictions and was only marginally leakier than new build homes.

No significant improvement to airtightness was measured by either retrofit, which may be surprising in the instance of the secondary glazing, since single glazed timber windows are often considered to be a source of air leakage. However, the original single glazed traditional sashes were well-maintained, and draught proofed in this instance.

More investigation of secondary glazing and its impact on airtightness is needed in a representative sample of different homes with different window types and states of repair to understand its potential impact on the airtightness of the UK housing stock.

The relatively large building form by UK standards (139m^3, compared with an average of 89m^2) meant that the configuration of the CO_2 tracer gas equipment and Pulse technique used were not able to accurately measure the airtightness of the home. Consequently, more investigation to understand how this technique may be more successfully applied to homes similar to 00CS is needed.

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.

A summary of the before and after measured average in-situ U-values for the ground floor and the external windows are presented in Figure 3-6. Figure 3-7 shows the U-values for the other building elements that were not retrofitted.

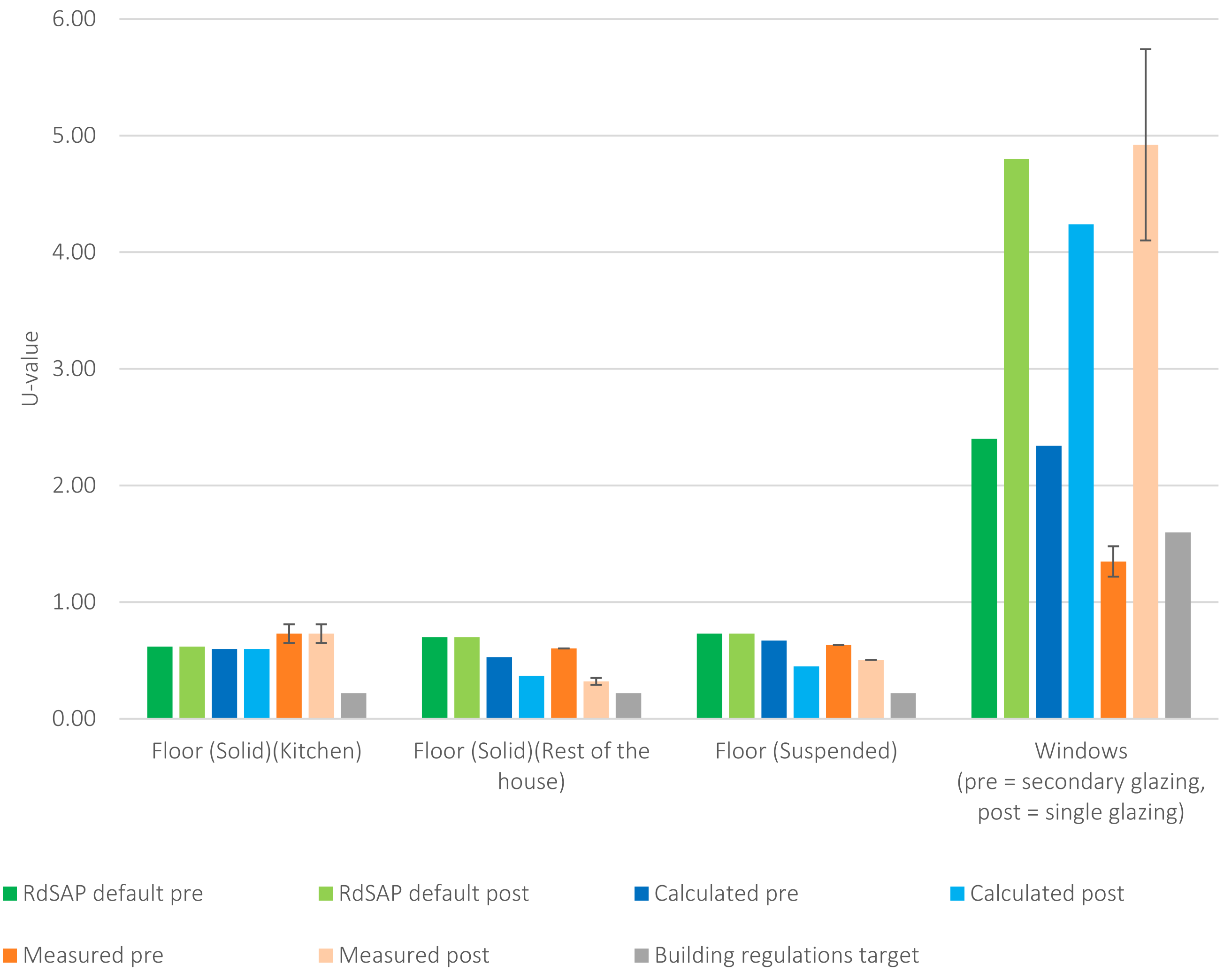


Figure 3-6 Measured, calculated, target, and assumed U-values of ground floor and windows

The RdSAP and calculated window U-values shown are whole window U-values (including the frame). However, the measured window U-value is only the centre pane value. Therefore, any comparisons should be treated with caution.

With secondary glazing, the in-situ measured window U-value is much lower, as may be expected. It is also lower than the RdSAP and BRE calculator predictions, as well as the Building Regulations limiting U-value for replacement windows. This confirms that secondary glazing can be an effective approach for reducing heat loss in homes where original single glazed windows need to be retained.

It was expected that the centre-pane U-value would be higher than the RdSAP values. However, the measured centre pane for the single glazed window is in line with the whole window RdSAP predictions and calculated values. It may have been assumed that the timber window frame would have lowered the window U-values, though there is a large uncertainty associated with the measurement.

The in-situ measured pre-retrofit ground floor U-values are roughly in line with that assumed in RdSAP and those calculated using the BRE calculator. The BRE calculator also predicts similar post-retrofit U-values to those that were measured in-situ. However, the aerogel insulation was too thin (10 mm) to be counted in RdSAP where the minimum allowable insulation thickness is 50 mm. This resulted in the post-retrofit RdSAP value for the solid ground floor in the rest of the house and the suspended floor being notably higher than that measured in-situ.

This highlights an issue associated with the adoption of any insulation material within RdSAP that has been designed to be installed in thicknesses less than 50 mm. As RdSAP currently stands, the insulation material will be assumed to provide no thermal benefit, so will result in no reduction in the dwelling's heat loss, and consequently no reduction in the home's EPC.

Although the aerogel provided a 47 % reduction in U-value of the solid floor, it did not quite achieve the current Building Regulations limiting U-value for upgrading the thermal performance of ground floors, for which a double (20 mm) aerogel blanket would be required.

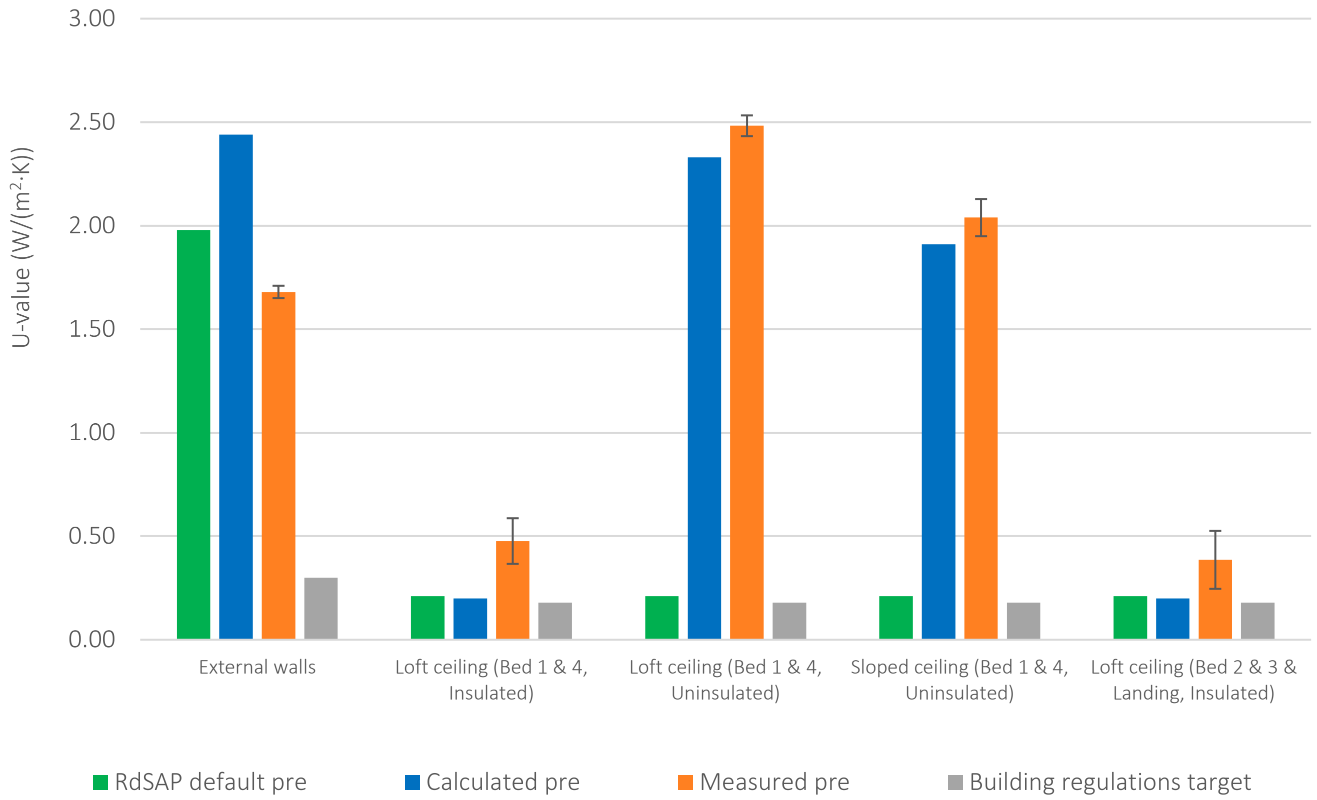


Figure 3-7 Measured, calculated, target, and assumed centre pane U-values of windows

Observations from the U-values of the elements that were not retrofitted are that the loft, which had 200 mm of insulation, appeared to be in good condition as shown in Figure 3-8. The in-situ measured U-values for the sections that were insulated were higher than the RdSAP defaults and calculated predictions.

Figure 3-8 200 mm sheep's wool loft insulation – view from loft hatch

However, there was a significant area of ceiling that was uninsulated, behind a large purlin (shown in Figure 3-9), and thus difficult to access from the loft. In addition, a large area around the loft hatch opening was also left uninsulated, presumably as it makes access to the loft space easier. The loft hatch needed to be lifted and placed on top of the existing loft insulation to gain access (see Figure 3-10). This highlights the need for a proprietary insulated loft hatch.

Figure 3-9 Purlin (left) restricting access resulting in no loft insulation being installed (right)

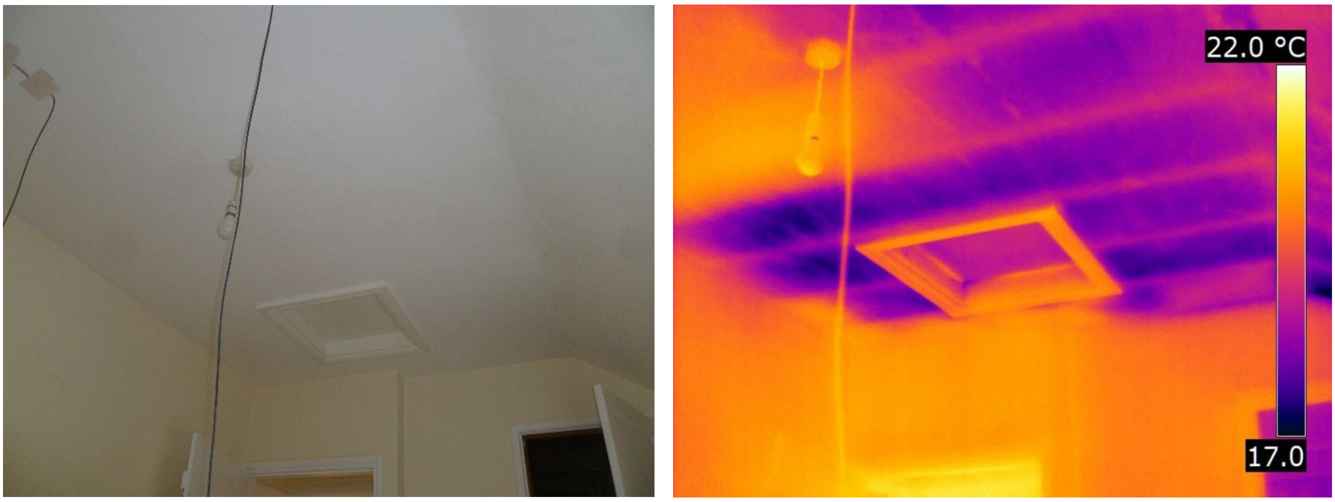


Figure 3-10 Uninsulated ceiling behind purlin and around loft hatch

Similarly, there was also a sloping section of ceiling in the bedrooms (skeiling) where loft insulation cannot be laid as standard, shown in Figure 3-11. These were uninsulated (Figure 3-13), despite the main loft area being well insulated. Therefore, these will constitute a significant thermal bridge in the home, resulting in lower surface temperatures (Figure 3-12) and therefore a potential risk of condensation and mould growth.

EPC assessors may assume lofts to be insulated homogenously based on a limited visual inspection of the loft from around the access hatch. It is feasible, however, that purlins and other obstacles could restrict views of certain areas in the lofts and that uninsulated sections may go unaccounted for in EPC assessments.

It is also known that there are other factors that can have a detrimental impact on the thermal performance of the loft space. Such factors include using the loft as a storage space, the installation of insulation around services including cold water storage tanks, and practical difficulties associated with installing insulation at the eaves.

Additionally, many homes in the UK have raked eave designs causing skeilings, which are not commonly insulated. EPC assessors cannot account for these areas of elevated heat loss from part of a ceiling in the current version of RdSAP. Thus, there is a danger that EPCs are overpredicting the effectiveness of loft insulation in homes, which means that the home may receive a higher EPC than it should, and result in the models underpredicting the impact that a loft top-up retrofit could have.

Figure 3-11 Uninsulated ceiling behind purlin (orange) and 'skeiling' (green)

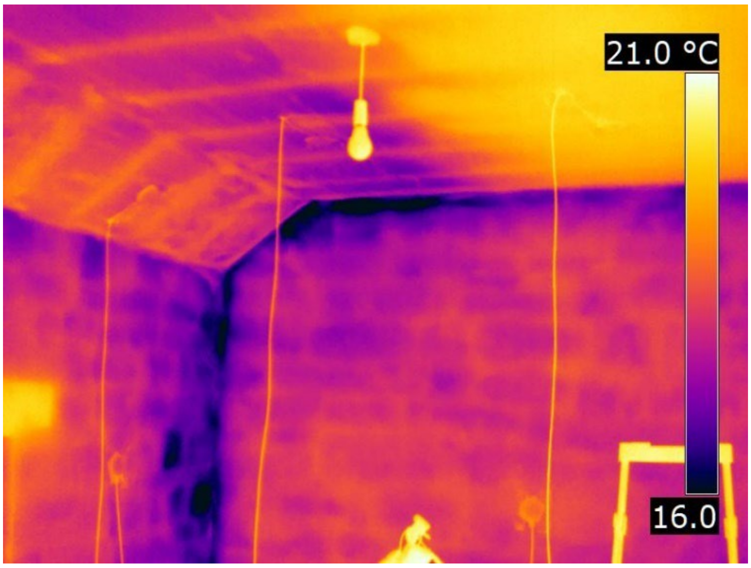


Figure 3-12 Colder surface on uninsulated skeilings and ceiling

Figure 3-13 Image showing no insulation in skeilings

Other interesting observations for 00CS were that the external solid walls have a RdSAP default U-value of 1.70 W/(m²·K), yet the calculated U-value in this case study was 2.40 W/(m²·K). The measured values were found to be lower than both these estimates at (1.68 ± 0.03) W/(m²·K). This is possibly due to the unknown internal makeup of the stone walls, which can often be rubble in homes of this age, and therefore some form of cavity or air pockets exists, providing some additional thermal resistance. The wall U-value of 1.68 W/(m²·K) represents an average of 27 individual HFP measurements of the external walls (9 installed HFPs, with measurements undertaken over 3 stages), which ranged from 1.22 W/(m²·K) to 2.77 W/(m²·K). The U-values for the inset recesses (built in cupboards) were not measured, though would be expected to have a higher U-value. However, as their area was a small proportion of the total wall area this is not considered to be a significant limitation.

This variability highlights the importance of collecting multiple HFP measurements. It suggests that while the RdSAP default will likely be incorrect for many stone properties, there is no guarantee that a calculated U-value where assumptions are being made about construction make up will yield more accurate values, especially for stone walls. Table 3-1 reports the U-values derived from the different approaches.

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

	Pre-retrofit			Post-retrofit		
	RdSAP Default	Calculated	Measured	RdSAP Default	Calculated	Measured
Windows pre = single glazing post = secondary glazing	2.40	2.34	1.35 ±0.13	4.80	4.24	4.92 ±0.82
Suspended timber ground floor	0.73	0.67	0.63 ±0.00	0.73	0.45	0.51 ±0.00
Living room solid ground floor	0.70	0.53	0.60 ±0.00	0.70	0.37	0.32 ±0.03
Kitchen solid ground floor	0.62	0.60	0.73 ±0.08	-	-	-
External walls	1.98	2.44	1.68 ±0.03	-	-	-
Loft ceiling (bed 4 insulated)	0.21	0.20	0.48 ±0.11	-	-	-
Loft ceiling (bed 4 uninsulated)	0.21	2.33	2.48 ±0.05	-	-	-
Sloped ceiling (Bed 4, uninsulated)	0.21	1.91	2.04 ±0.09	-	-	-
Loft ceiling (bed 3, insulated)	0.21	0.20	0.39 ±0.14	-	-	-

Small variations in the external wall U-values for detached homes can cause significant changes in energy performance. Describing performance over a range of U-values may be a way of overcoming the potential of selecting a single potentially erroneous value for stone buildings with unknown constructions.

Table 3-2 shows the change in U-value achieved by the retrofits, which also shows the potential performance gap and prediction gaps when using RdSAP specifically. A definition of the term 'performance gap' and 'prediction gap', within this context, is stated below:

RdSAP defaults prediction gap = difference between the RdSAP defaults for post-retrofit U-value Vs measured in-situ post-retrofit U-value

Performance gap = difference between as-built calculated post-retrofit U-value Vs measured in-situ post-retrofit U-value

As can be seen, a large negative prediction gap is observed for the ground floor insulation, i.e. it was measured to perform better than predicted. This is not surprising, as RdSAP in its current form is not capable of predicting any reduction in heat loss made due to the application of the aerogel carpet underlay, as RdSAP only allows a minimum insulation thickness of 50 mm to be specified.

The BRE calculator predicted an absolute reduction of 0.22 W/(m^2·K), but only a 0.13 W/(m^2·K) reduction was measured. Hence, a prediction gap of 0.09 W/(m^2·K). For the suspended timber floor, the BRE calculator predicted an absolute reduction of 0.16 W/(m^2·K) but a much greater reduction of 0.28 W/(m^2·K) was measured. More data on how the performance of insulation in different types of ground floors, and how they may affect moisture movement is needed.

The secondary glazing achieved a much larger reduction than was predicted by both the RdSAP defaults and the BRE Calculator, which is surprising given that the in-situ measured U-value is only for the centre pane.

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

Element	RdSAP default predicted reduction (W/(m^2·K))	BRE Calculator predicted reduction (W/(m^2·K))	Measured reduction (W/(m^2·K))	RdSAP defaults prediction gap %	as-built performance gap %
Living room solid ground floor	0.00 (0 %)	0.22 (30 %)	0.13 (47 %)	-31 %	12 %
Suspended timber ground floor	0.00 (0 %)	0.16 (33 %)	0.28 (20 %)	-54 %	-13 %
Windows	2.40 (100 %)	1.90 (81 %)	3.57 (265 %)	3 %	16 %

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

Figure 3-14 shows the impact the improvement in U-values may have had on fabric heat loss expressed as recorded by heat flux density measurements. This considers the U-values, coupled with the relative size of heat loss area of each element, to illustrate the implications of using default RdSAP, calculated or in-situ measured U-values:

- Walls overwhelmingly dominate the HTC_f in this home, meaning that large reductions to heat loss from other elements may only result in relatively small reductions in whole house HTC_f. Thus, appropriate, low risk IWI options (i.e. vapour open materials that achieve U-value improvements less than required in building regulations [7]) may be required to achieve material reductions to HTC in homes like 00CS.
- HTC_f is found to be highest when BRE calculator values are used and lowest when in-situ measured U-values are used, suggesting construction assumptions may be flawed.
- No change in heat loss resulting from the ground floor insulation is predicted when using RdSAP, since it cannot account for insulation thicknesses less than 50 mm.
- The in-situ measured U-values for secondary glazing were significantly lower than predicted, and when it was removed, the HTC_f increased by 40 W/K (11 %). However, as the windows only represented a small amount of the plane element heat loss and heat loss area in this dwelling, their impact on the overall HTC_f was minimal.
- There was only a 13 W/K (4 %) reduction in the measured HTC_f following the application of the ground floor insulation.

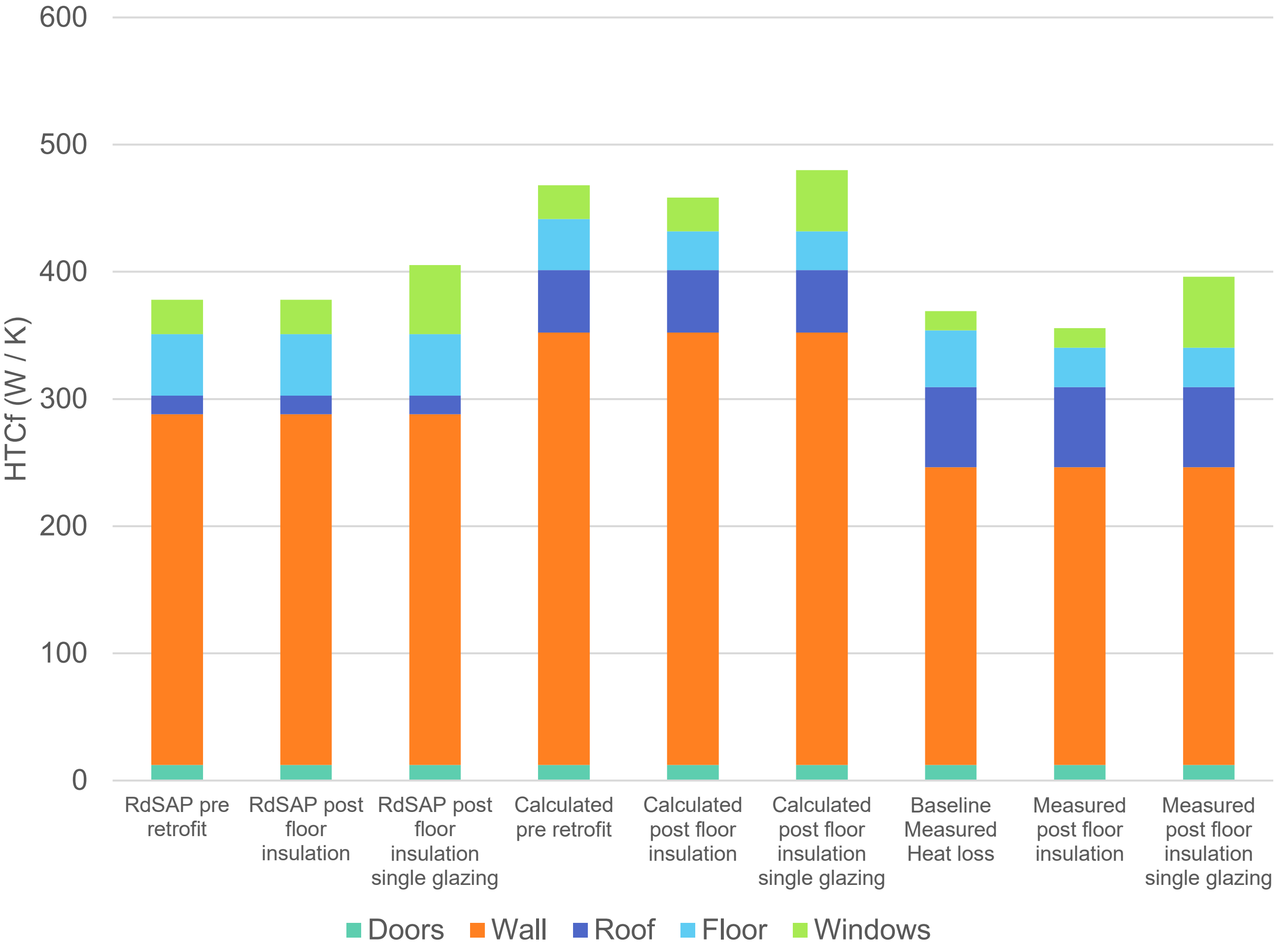


Figure 3-14 Heat loss of fabric elements pre and post-retrofit, as recorded by heat flux density measurements

U-value improvement summary

The 10 mm aerogel reduced the solid ground floor U-values by 0.28 W/(m^2·K) (47%), though only reduced suspended floor U-values by 0.13 W/(m^2·K) (20 %).

The savings measured in-situ were greater than those predicted by the BRE calculator for solid ground floors, but less than the prediction for suspended floors. The reason for this is not known, suggesting more research may be needed into ground floor heat losses in homes without modern foundations and with mixed floor types.

RdSAP did not consider any changes in heat loss or U-values for the ground floor retrofit, since the aerogel blanket was less than 50 mm.

The secondary glazing reduced the measured in-situ U-values by more than double, and although this case study home had a small glazed and heat loss area, removing the secondary glazing increased fabric heat losses (HTC_f) by 11 %.

The heat flux density measurements suggest heterogeneity of thermal resistance was found throughout the fabric. This is particularly the case for the external walls which are the most significant heat loss element in this detached home. Relying on point heat flux density measurements to estimate whole external wall U-values can be problematic.

3.3 Whole house heat loss (HTC) improvement

The total measured heat losses for i) the base case dwelling, ii) the dwelling with retrofitted ground floor insulation, and finally iii) the dwelling with secondary glazing removed, are shown in Figure 3-15. Figure 3-15. No significant change in HTC from the baseline was detected from either of the fabric changes.

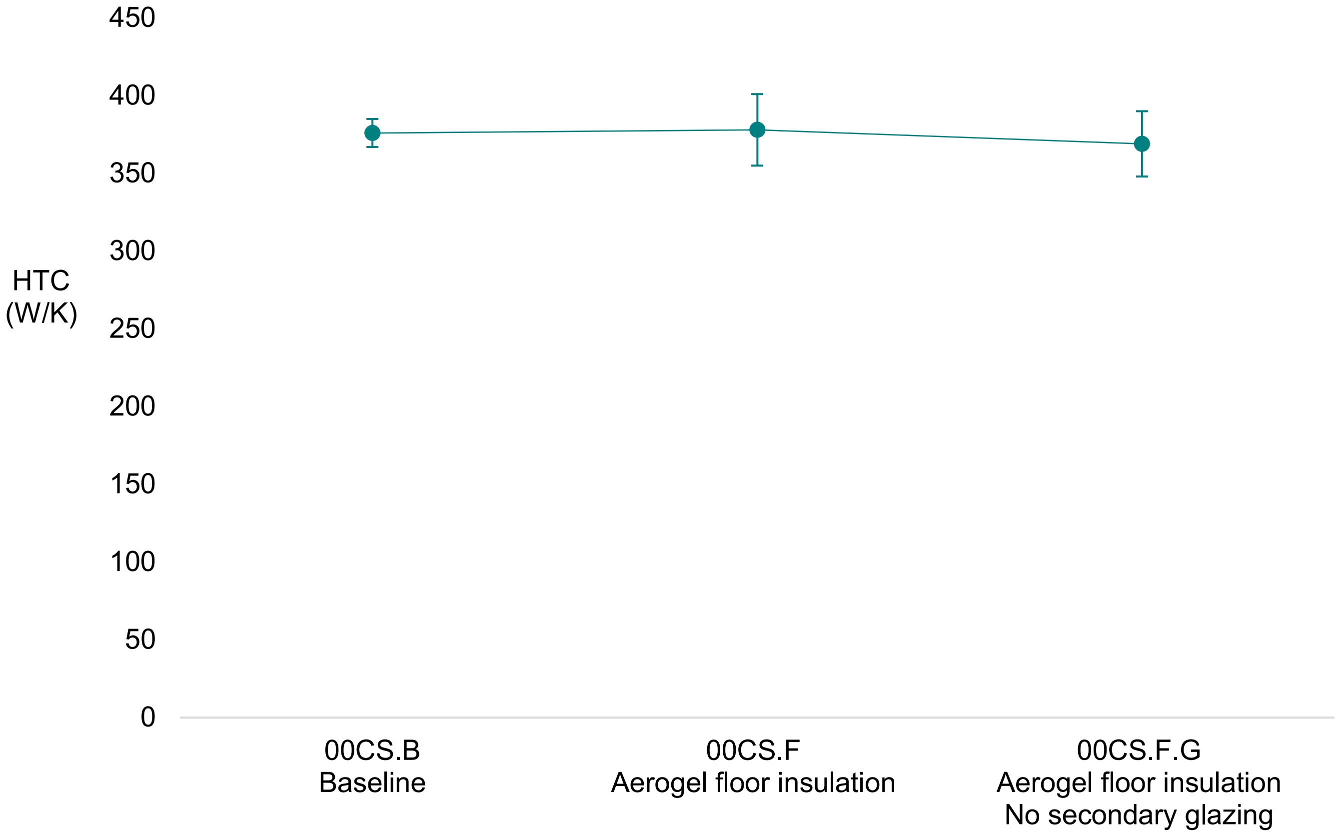


Figure 3-15 Coheating HTC at each retrofit stage

The lack of measurable difference to the HTC is perhaps to be expected, since the house has such a large absolute heat loss and the in-situ measured U-values suggest that approximately 87 % of the total heat loss was through elements that were not altered as part of the retrofit. Thus, even large heat loss reductions from the floor and windows result in relatively small changes in HTC.

Furthermore, the relatively high thermal mass of the building meant that measuring small changes via the coheating test was challenging. Table 3-3 shows the HTC uncertainty range for the home. Although relatively low in terms of the overall percentage of the total HTC, it is high in absolute terms (> 20 W/K) and is twice the improvement in heat loss measured by applying the ground floor insulation.

The in-situ U-value measurements suggested that the secondary glazing could have reduced the HTC by around 27 W/K. Thus, the coheating results suggest secondary glazing may not have as large an effect as had been indicated by the centre pane U-value measurements. Glazing was only 4 % of the total heat loss area of the home, thus, in homes like 00CS, glazing retrofits may not be a priority. More research into the effectiveness of secondary glazing at reducing heat loss, in different house types with different glazing ratios is needed to understand their potential for retrofits nationally.

The findings suggest the absolute uncertainty range in the HTC associated with a coheating test, not just the percentage uncertainty, can determine if one can successfully measure the impact of a particular retrofit measure.

The study also supports the proposition that for large, detached houses, with good levels of airtightness, where lofts have already been topped up, and which have a relatively small proportion of external window and heat loss area, meaningful reductions in total heat loss are only likely to be achieved if solid wall insulation (SWI) is installed. This is an important finding for national policy as it suggests that homes similar to this case study have very few alternatives to SWI to reduce their space heating demand.

Table 3-3 Test house HTC after each retrofit stage

Retrofit stage	HTC (W/K)	HTC Uncertainty	HTC Reduction (W/K)	Percentage reduction
00CS.B Base case	376 ± 9	2 %	n/a	n/a
00CS.F Ground floor insulation	378 ± 23	6 %	-2 ± 24	(-1 ± 6) %
00CS.F.A Ground floor insulation & secondary glazing removed	369 ± 21	6 %	9 ± 31	(2 ± 8) %

3.3.1 Thermal comfort benefit of ground floor insulation

The analysis has shown that the benefit of the ground floor insulation, in terms of reducing whole house heat loss, is minimal. It is important, however, to consider that ground floor retrofits can also have a positive impact on the thermal comfort of occupants via increased ground floor surface temperatures.

The ground floor retrofit did leave the kitchen uninsulated, which represents a likely scenario in homes where fitted kitchens have just been installed in homes with uninsulated floors, though the kitchen area was only 5 % of the heat loss area of the house.

To assess if this is indeed the case for 00CS, ground floor surface temperatures were recorded. Sensors were installed only during the last coheating test, meaning a comparison of thermal comfort before and after retrofit was not possible. However, sensors were installed on the solid kitchen ground floor, which was not insulated. This could act as an indicator for the pre-retrofit performance and used for comparison with the post-retrofit performance. Sensors were also installed in the solid ground floor utility room and the suspended timber ground floor dining room, all placed out of direct sunlight.

Using the surface temperature sensors, the temperature factor of the ground floor was calculated. Although temperature factors are often used to quantify condensation risk, they can be used to inform thermal comfort. The temperature factor is calculated from Equation 3-1.

Equation 3-1 Temperature Factor

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

Where T_{sur} is the surface temperature (°C), T_{ext} the external temperature (°C) and T_{int} the internal air temperature (°C). At a temperature factor of 1, the average surface temperature is the same as the average internal temp. At 0, the average surface temperature is at the external temperature. Thus, the higher the number, the warmer the floor surface.

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

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

Floor	Average internal air temperature (°C)	Average surface temperature (°C)	Difference (°C)	Temperature factor
Kitchen (uninsulated, solid)	20.34 ± 0.01	18.64 ± 0.04	1.70 ± 0.04	0.89 ± 0.02
Utility (insulated, solid)	20.24 ± 0.05	19.89 ± 0.8	0.35 ± 0.10	0.98 ± 0.01
Dining room (insulated, suspended)	20.18 ± 0.04	18.59 ± 0.09	1.59 ± 0.09	0.90 ± 0.02

The results did not observe statistically different ground floor temperatures between the test states. However, the solid ground floor with insulation displays a higher surface temperature and temperature factor than the solid ground floor without insulation. Thus, the floor in the insulated area is likely to offer greater thermal comfort.

However, occupant thermal comfort is affected by multiple factors including, amongst other things, air temperature, air movement, and surface temperatures. In this case, the solid ground floor slab was also heated to a consistently high temperature during the coheating test, higher than when the home is occupied and heated following normal heating profiles. Therefore, more holistic assessments, in a greater range of homes and retrofits, is needed to quantify how retrofits could improve thermal comfort.

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

It is also notable that the suspended ground floor performs worse than the insulated solid ground floor, at a comparable level to the uninsulated solid ground floor, both in terms of surface temperature and temperature factor. As no surface temperature data was available for the non-insulated suspended ground floor, it is not possible to quantify the impact of the insulation on thermal comfort in this area.

However, thermal images taken before the retrofit works and during coheating, when the internal temperatures were very similar, show lower surface temperatures than after. Thus, the addition of insulation likely improved the thermal comfort in the suspended ground floor as well. An illustration of the increase in floor surface temperatures is given in Figure 3-16.

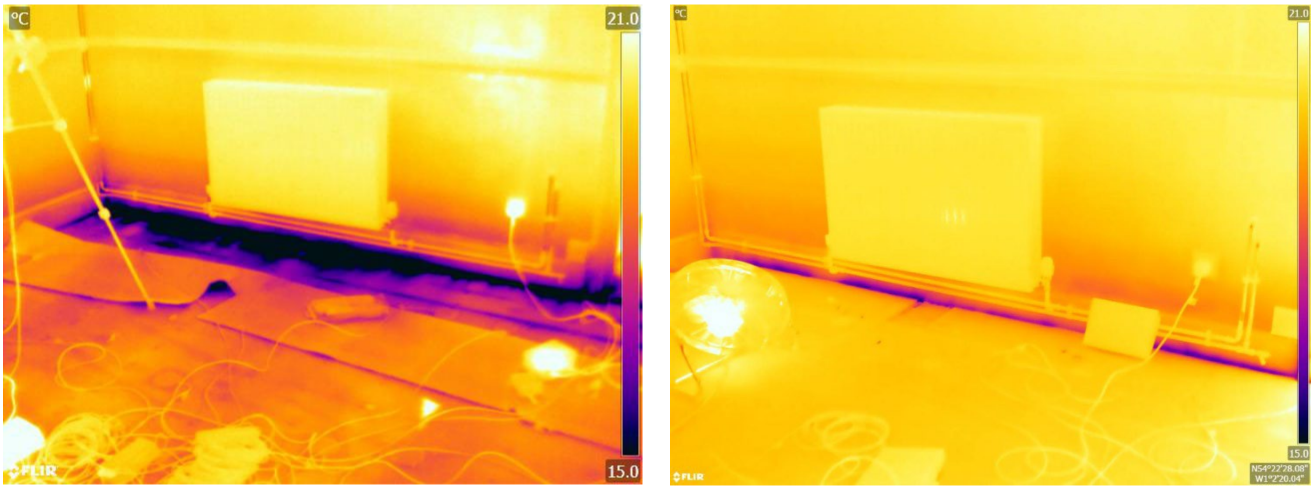


Figure 3-16 Cooler suspended ground floor temperatures when uninsulated (left) compared to insulated (right)

3.3.2 HTC QUB Measurements

An alternative method of measuring the HTC is to use the QUB method, as described in the Methods Chapter DEEP 2.0. This method was undertaken in the home for the baseline stage to compare against the coheating test.

In total, six QUB tests were performed on 00CS in September 2020 during the baseline retrofit stage. Of these, four were discounted based on the test α value (a ratio of power input, temperature difference, and the HTC of the property) being outside of recommended limit. The two remaining results gave HTC measurements of (262 ± 5) W/K and (290 ± 4) W/K for the baseline measurement. Not only was there some significant variation between the two remaining QUB tests, but more importantly, on average these tests were 26 % less than the coheating HTC measurement.

Losses through the solid ground floor could be a contributor to the large difference recorded between QUB and coheating measurements. The internal air – ground temperature difference and subsequent heat losses in the coheating test will be more significant than those occurring in the QUB test. This is a result of the higher internal temperature used in the coheating test of 21° C, compared to an average internal temperature of 14 °C throughout the QUB test. The internal temperature was much lower in the QUB tests due to the high heat loss of 00CS and no internal temperature control used between the QUB tests . Heat flux density measurements were not taken during the QUB tests so adjustments for these heat losses could not be completed. As a detached house there were no party wall considerations for 00CS.

Whole house heat loss improvement summary

The study confirms that it is possible to successfully measure the HTC of heavy weight buildings, using the coheating test, with relatively low levels of uncertainty.

Spotting absolute changes in HTC resulting from minor retrofits may not be possible and has implications for the development of methodologies to derive pre and post-retrofit HTCs.

The findings from this case study suggest that ground floor or glazing retrofits have not made a measurable improvement to the HTC of this building. This is likely to be because the HTC of the home was so large that smaller changes to the overall HTC were less easily observed.

Some evidence of improved thermal comfort was observed, in terms of the warm floor surface temperatures post-retrofit. The impact of the secondary glazing on thermal comfort was not assessed, though it was observed that it did not provide an improvement in the airtightness of the home since the single glazing seals were performing effectively.

This research highlights the challenge for improving the energy efficiency of large, detached homes which have loft insulation and minimal air leakage. Without SWI, the potential for retrofits to make major reductions in heat loss in these homes is limited.

This case study home had small areas of external glazing (4 % of heat loss area), thus more investigation into the effect of secondary glazing in different house types with different glazing ratios is needed to understand the potential for national retrofit policy.

A difference in measured in-situ U-value reductions achieved on solid, compared to suspended ground floors, was observed. It is not fully understood why this occurred, and more research into ground floor heat loss pre- and post- different retrofit approaches is required.

3.4 Measured and modelled retrofit performance

This section discusses how different modelling software can estimate the HTC reductions from each of the retrofits, and how their predictions can be improved via calibration.

3.4.1 Measured vs. modelled HTC calibration step 1

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

- The steady-state models predict a 30 % higher HTC than the DSM and greater HTC reductions resulting from the retrofits. This is mainly because DSM considers the thickness of internal walls when calculating the volume of the home, while the steady-state models do not. In this case study, the internal stone walls were substantial, in some places over half a metre thick. This means there is a 15 % lower volume of air to heat in DSM (273 m^3) compared to steady-state models (324 m^3), hence the HTC in the DSM is lower. When the DSM HTC is corrected for this, they are in alignment suggesting steady-state models should account for internal wall volumes.
- The models predict between 2 W/K and 16 W/K reduction in relative heat loss resulting from the ground floor retrofit. However, compared to the whole house heat loss, the saving is very small and only represents between 1 % and 3% of the whole house HTC. The U-value aggregation method suggests the saving was 13 W/K.
- The secondary glazing is predicted to have more of an impact than the ground floor insulation. Switching to single glazing was predicted to increase the HTC between 9 and 45 W/K, compared to the 40 W/K predicted via the measured U-values. Again though, as a percentage of total whole house HTC, this was a small increase (7 %).

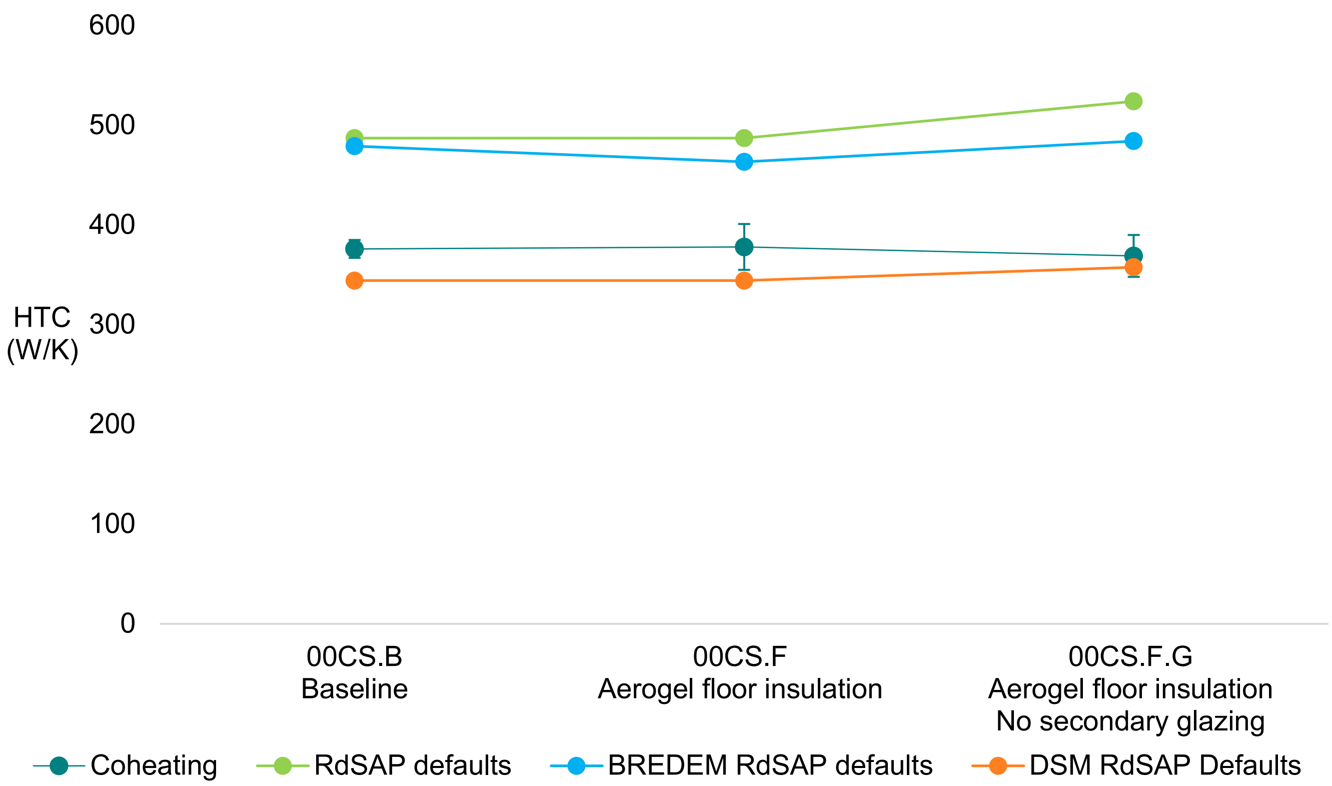


Figure 3-17 Measured vs modelled HTC calibration step 1: default data

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

In this first calibration step, the models used approximated infiltration rates derived from the blower door test, as this data is the most likely to be acquired and used in practice. The impact of this compared to the previous calibration stage can be seen in Figure 3-18:

- Introducing approximated infiltration rates based upon measured airtightness @ 50Pa into the models causes both the steady-state and DSM HTC reductions to fall, since the assumed airtightness value in RdSAP was higher than that which was measured.
- The steady-state estimate becomes closer to the measured value from coheating, while conversely, the DSM value reduces, getting further away from the measured result. Despite this, the results from DSM are still closer to the coheating measured result than the steady-state models.
- Again, the DSM predicts a smaller HTC than the steady-state models as it assumes a 15 % smaller volume due to the very thick internal walls.
- No RdSAP result is plotted since infiltration cannot be altered in the software.

2.06 DEEP 00CS

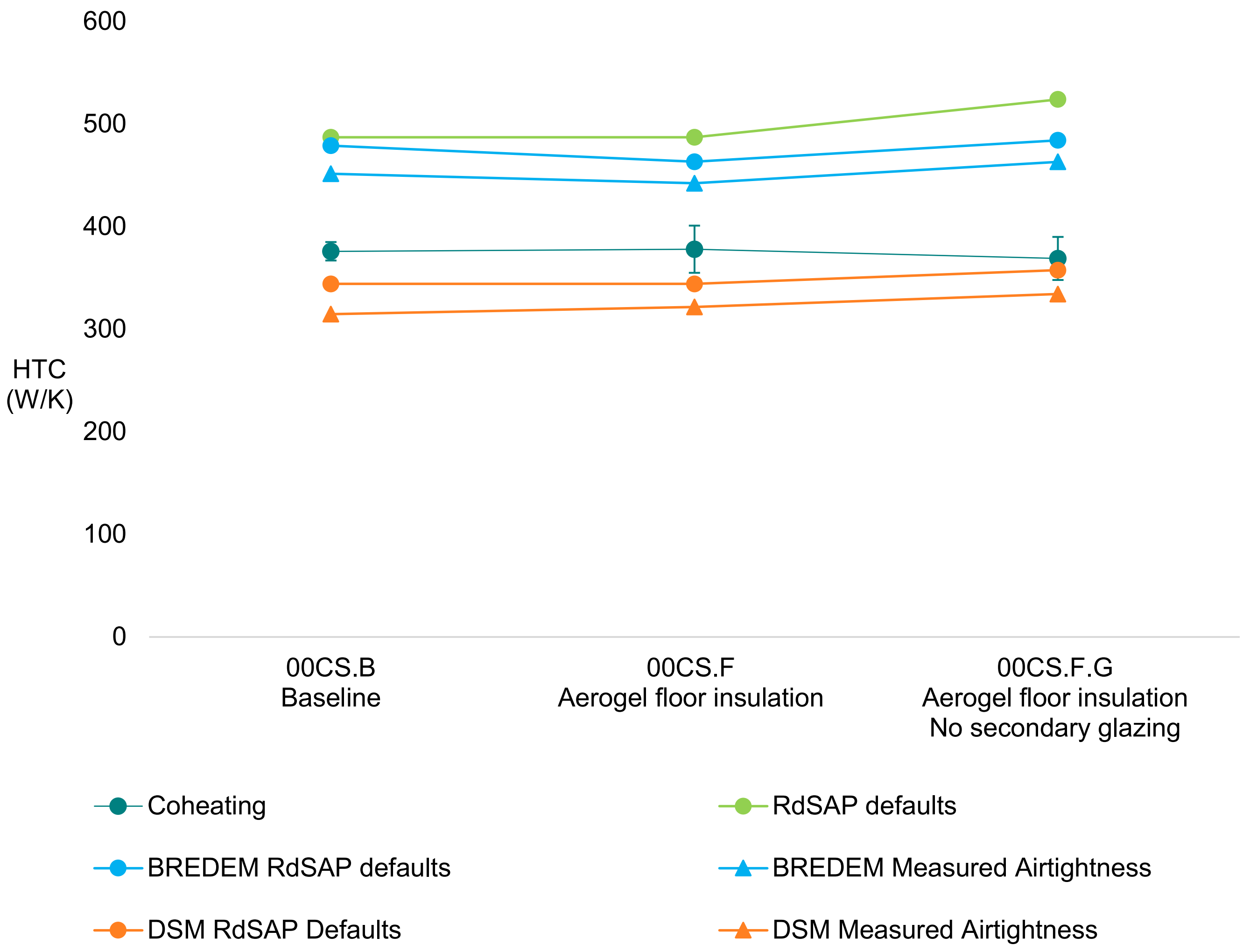


Figure 3-18 Measured vs modelled HTC calibration step 2: measured infiltration

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

In this step, the models included U-values calculated using the BRE calculator which requires more detailed surveys. It often needs 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 3-19:

- The introduction of calculated U-values increases the HTC predictions in both the steady-state and DSM models, effectively cancelling out the reduction obtained by inputting the lower approximated infiltration rates in calibration stage 2. This results in the DSM model matching the measured result for the coheating for each step of the retrofit, including the baseline. However, the steady-state models are now estimating a significantly higher HTC than the measured coheating result.
- The reason for the increase in HTC is due to the calculated U-values assuming a much higher external wall and loft U-value than the defaults.
- No additional RdSAP result is plotted as calculated U-values cannot be used in the software.

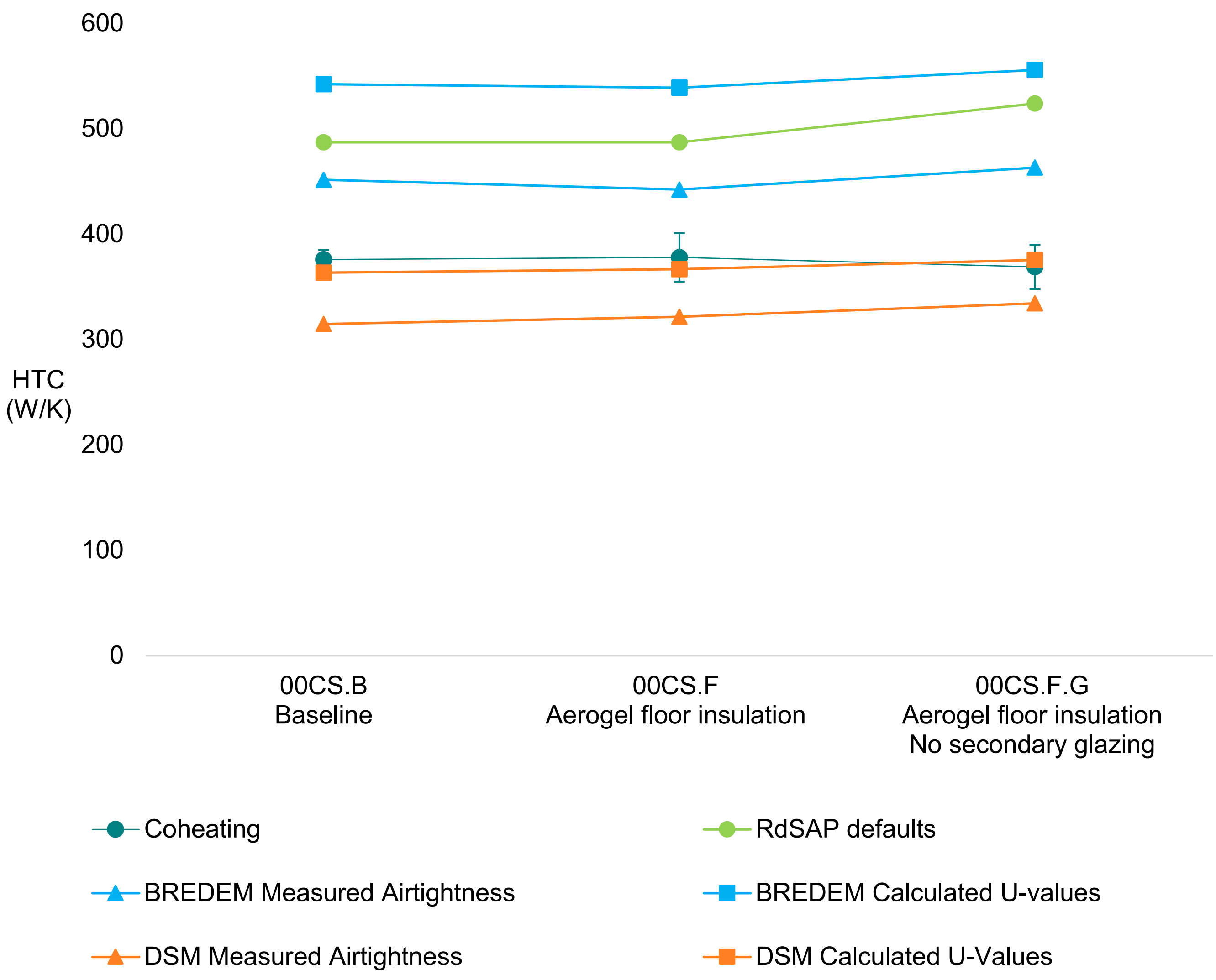


Figure 3-19 Measured vs modelled HTC calibration step 3: calculated U-values

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

In this step, the models used measured U-values which require resource intensive in-situ testing. The impact of this compared to the previous calibration stage is shown in Figure 3-20:

- Introducing measured U-values has the effect of reducing the HTC predictions in both the DSM and steady-state models, since the measured wall U-values were substantially lower than they were calculated to be using the BRE U-value calculator values. This results in the DSM HTC being over 40 W/K lower than that measured using coheating, compared to the steady-state models, which were over 80 W/K lower.
- The steady-state models still substantially overestimate the HTC compared to the measured coheating test result, even after the U-values and airtightness defaults are updated with measured data. This has important policy implications, as dwellings may receive a much higher EPC than they should. This may be because the default y-values used in models, to account for non-repeating thermal bridging, are not suitable.
- The steady-state BREDEM model predicts a lower HTC than the steady-state based RdSAP because it incorporates the measured ventilation rate. This indicates the impact that measured values can have on EPC accuracy, compared to standard defaults.

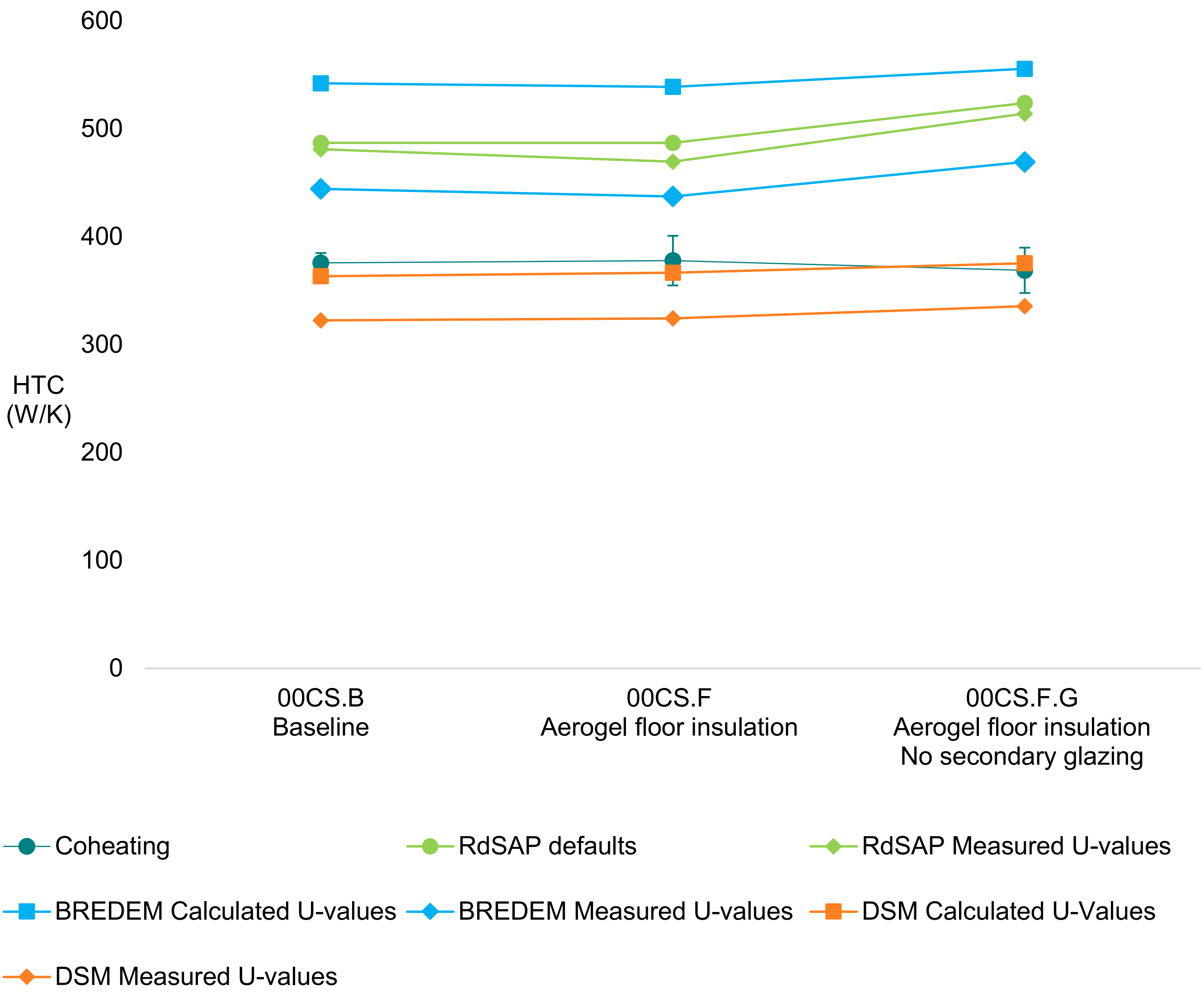


Figure 3-20 Measured vs modelled HTC calibration step 4: measured U-values

Measured versus modelled summary

Neither the ground floor insulation nor removing the secondary glazing achieved measurable changes in HTC according to the coheating test. However, the models predict the retrofits could achieve a 3 to 16 W/K (1 to 3 %) and 8 to 45 W/K (2 to 9%) reduction respectively.

More research may be needed to understand if homes with different proportions of ground floor and glazing areas achieve similar savings. For instance, the improvements made by the ground floor and window retrofits may have been measurable in homes where the ground floor and / or glazing area accounted for a more significant portion of the dwelling's overall heat loss.

The findings suggest that large stone homes similar to 00CS, with reasonably adequate levels of loft insulation, may struggle to substantially reduce their heat losses without the application of solid wall insulation.

The internal walls of this house were very thick and accounted for a significant proportion of the overall dwelling volume. This illustrated an important difference in the modelling approach; that only DSM takes the internal wall dimensions into consideration when calculating the heated volume in a home. Thus, as DSM had a 15 % lower volume, it predicted a 30 % lower HTC than the steady-state models. This suggests that it may be useful for the EPC assessor to be able to input the internal wall dimensions into the model, when these are substantial, to gain a more accurate internal volume.

Substituting the default background ventilation rate with an approximated value based on the blower door measurements for this house also resulted in a substantial reduction in the predicted HTC. In fact, this measure had as much impact on the overall HTC as the application of the secondary glazing. This implies that there may be merit in allowing approximated ventilation rates based upon blower door measurements to be used in EPCs, where they differ substantially from the defaults.

Using calculated U-values in this case study dwelling has not resulted in more accurate model predictions, since the assumptions that were made around the external wall construction appear to have been incorrect. Old stone walls with rubble fill may have a large degree of heterogeneity and consequently are more likely to have unpredictable and variable thermal performance. This means that using calculated, or even measured, U-values is not necessarily appropriate or representative.

3.5 Predicting EPC band, annual space heating and carbon emissions

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

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

Dynamic and steady-state models are fundamentally different. DSM calculates heat balances and demand at an hourly time step, whereas steady-state models such as BREDEM calculate these for a typical day of each month and extrapolate results for an annual prediction. Thus, the complex interactions between gains and heat demand that take place over a diurnal cycle are only captured in DSM. It is beyond the scope of this project to confirm which approach is more accurate, but it appears from this research that BREDEM consistently predicts 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 related default data were found to underestimate baseline EPC scores, and thus overestimate retrofit savings.

3.5.1 Potential reasons for differences in annual model outputs

Fundamental differences between steady-state and DSM models cause inherent discrepancies in the predicted heat loss and energy calculations for the DEEP case studies. The differences between the models are discussed in the DEEP Methods 2.01 Report, and 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 [8]) as discussed in the DEEP Methods 2.01 Report.

Differences specific to 00CS
For the 00CS baseline scenario, using measured infiltration rate and U-values, BREDEM predicts a space heating demand that is 8,742 kWh/year higher than DSM. As with all DEEP case studies, it is the HTC value that 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 to 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 the BREDEEM is 14,918 kWh, compared with the DSM estimate of 13,737 kWh, a difference of 1,181 kWh. The BREDEM calculations can be further normalised by using the DSM volume of conditioned space (51.04 m^3 less in the DSM model). Following this final adjustment, the BREDEM estimate is actually 1,170 kWh lower than the DSM output. This suggests that the cumulative impact of the other variables listed above have a relatively small impact on space heating demand when compared with the BREDEM calculated HTC and volume inputs.

3.5.2 Impact of retrofits on EPC bands

Several policy mechanisms set EPC targets, and the Government has set an ambition that all homes where practically possible will achieve an EPC band C by 2035 [9]. The impact of the retrofits on EPC in this case study is shown in Figure 3-21:

- Installing thin solid ground floor insulation did not achieve an EPC band C, thus appropriate, low risk IWI options may be required to achieve this.
- The secondary glazing has more impact on EPC score than the ground floor insulation.
- DSM predicts higher SAP scores, mainly as it excludes the internal wall volume from the model. DSM also considers the temporal nature of internal gains and cool-down rates between heating periods, meaning it has lower space heating demand than in EPCs.
- RdSAP allocates more SAP points than BREDEM, because:
    - RdSAP excludes any space heating between June and September.
    - BREDEM uses a known ‘Living Area’, which was larger than the assumed fraction defined in RdSAP. In addition, as living areas are allocated higher set points than other areas in BREDEM, the final monthly mean internal temperatures in BREDEM were higher, resulting in more space heating demand.
    - BREDEM has lower solar heat gains as the actual orientation of the dwelling is used, as opposed to the incremental orientation available in RdSAP, which can only use cardinal and ordinal directions.
    - A slight difference in total floor area inevitably exists since RdSAP ignores building features such as chimney breasts.
    - BREDEM assumes a lower volume of daily hot water requirement than RdSAP.
    - Higher internal heat gains from the hot water storage system are assumed in RdSAP.

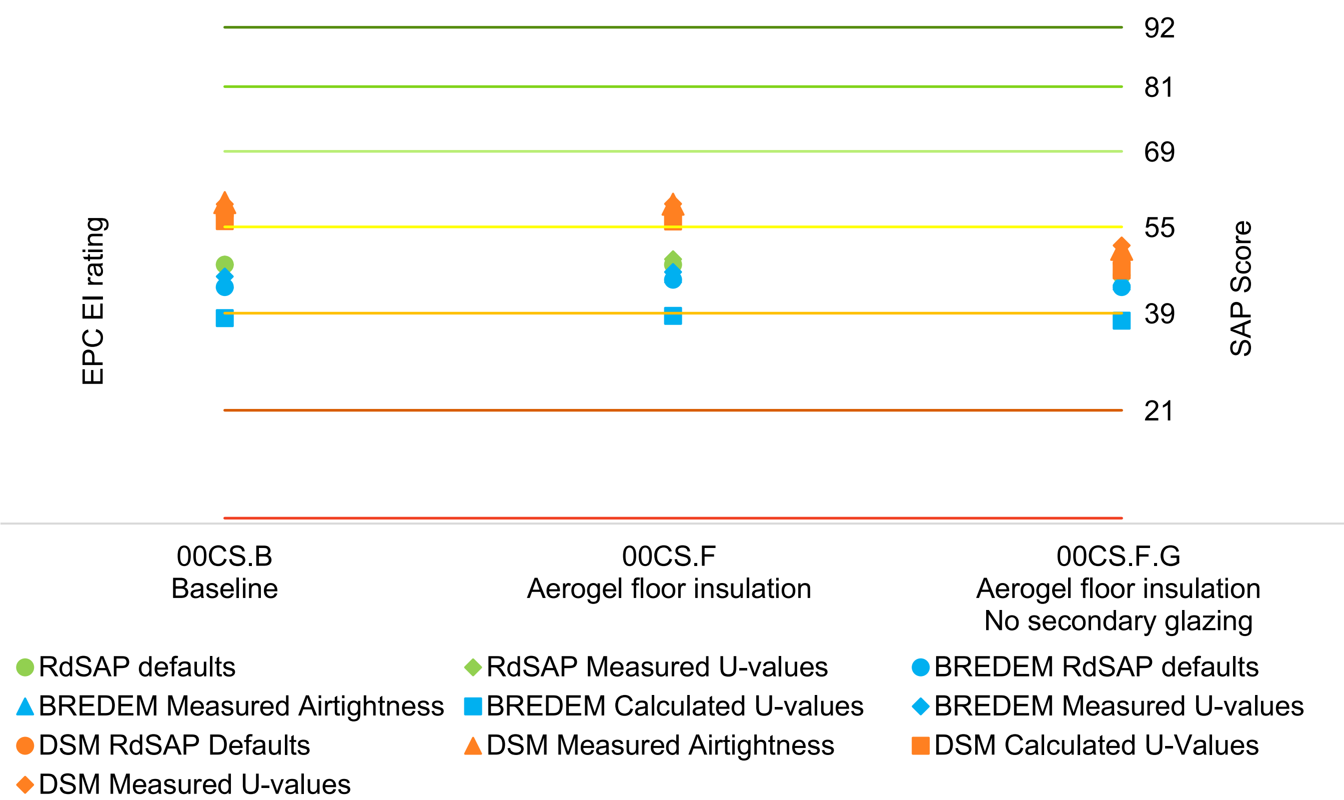


Figure 3-21 Predicted impact of retrofits on EPC band

3.5.3 Impact of retrofits on annual space heating

The Social Housing Decarbonisation Fund (SHDF) Wave 1 evaluates retrofit success by setting a target of 90 kWh/m²/yr for annual space heating for retrofits [10]. The predicted annual space heating demand for the retrofits undertaken in this case study are shown in Figure 3-22.

- Space heating demand is not materially affected by the retrofits in any of the models, since the space heating demand is dominated by the external wall heat losses.
- DSM has a much lower space heating demand than the steady-state models as it accounts for the internal walls, meaning it has a 15 % lower volume to heat.
- BREDEM has higher space heating demand than RdSAP for the reasons given in 3.6.1.
- The SHDF 90 kWh/m²/yr target is not met for this home in any of the models or retrofit scenarios.

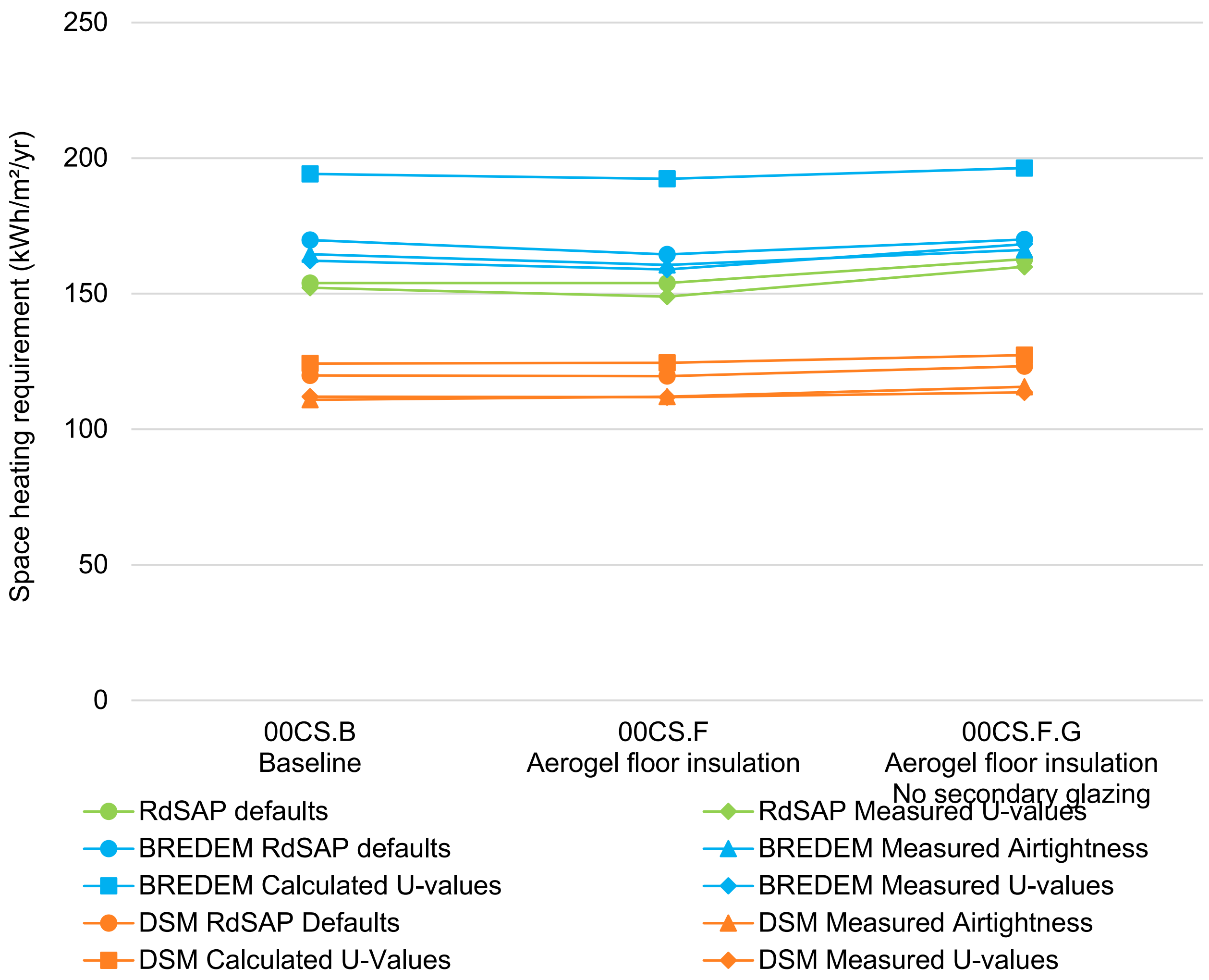


Figure 3-22 Predicted annual space heating demand

3.5.4 Impact of retrofits on CO_2 emissions

The space heating in homes is responsible for around 15 % of the UK's CO_2 emissions [11]. The predicted reduction in CO_2 emissions achieved by the case study's retrofits is shown in Figure 3-23.

- The removal of the secondary glazing results in a minor increase in emissions, regardless of which model is used, at most equivalent to 3 % of the whole house emissions.
- DSM generally predicts much lower changes in CO_2 resulting from the alterations, since it has a lower space heating demand as a result of assuming a lower internal volume.
- The changes in CO_2 emissions predicted for the ground floor insulation are larger in BREDEM as it has a higher space heating demand than RdSAP for the reasons explained in 3.6.1.
- No savings are shown for the ground floor insulation in the RdSAP defaults stage, since the software cannot account for insulation thinner than 50 mm.

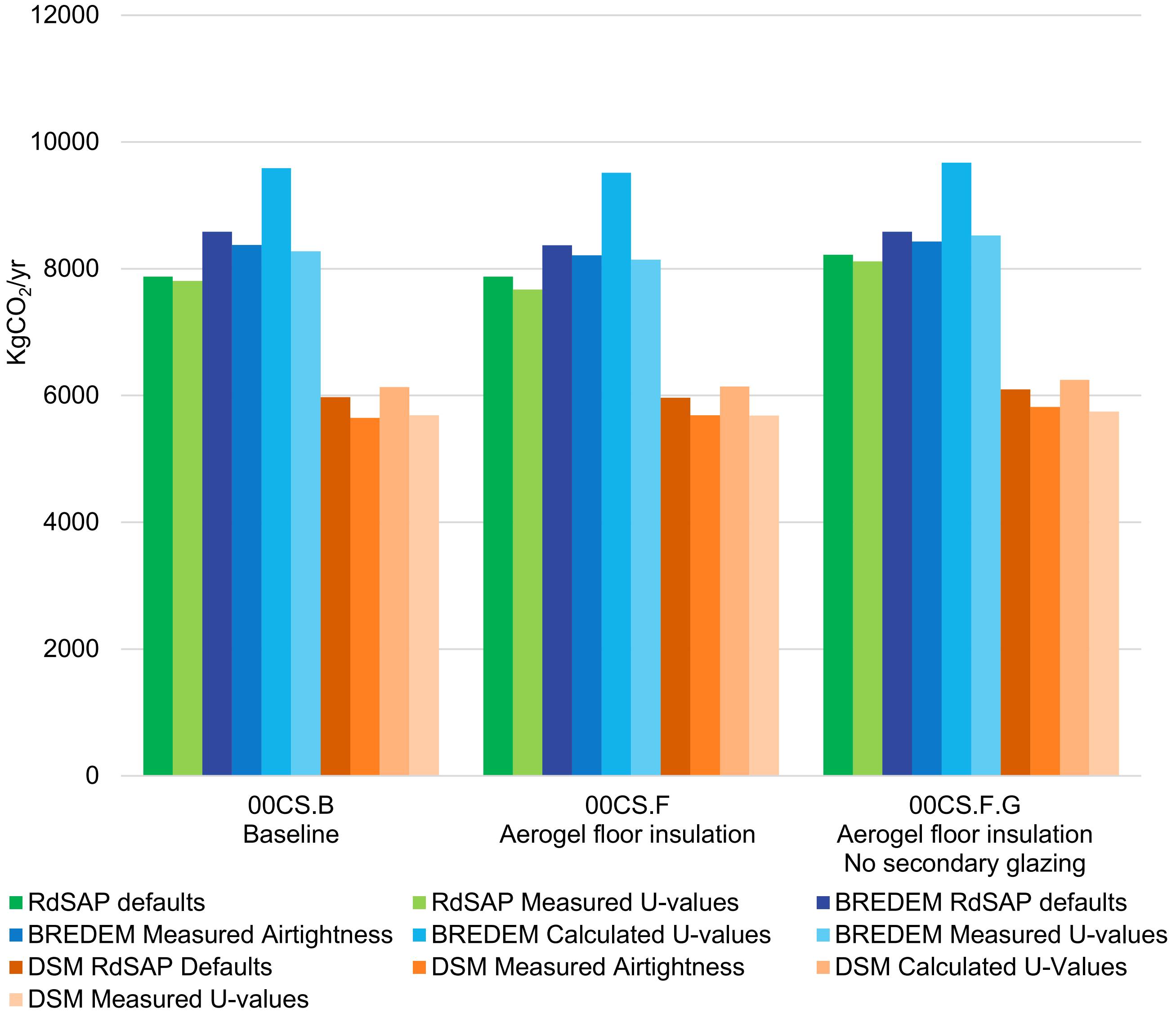


Figure 3-23 Annual CO_2 emission after each individual retrofit

Predicting EPC band, space heating, and carbon reductions summary

This section suggests that models may overpredict space heating demand when default data is used. In this home, inputting the measured airtightness, and accounting for insulation thinner than 50 mm results in a lower HTC than that predicted in the EPC model.

DSM predicts lower heat losses and a higher EPC score. In this case study, this is mainly because it accounts for the thickness of internal walls when calculating the home's volume. This is something that may be considered in future RdSAP updates, for homes like 00CS, since it can materially affect which EPC Band a home achieves and could be recorded on site.

It also identifies that by not accounting for internal walls when calculating the home's volume, steady-state models may substantially overpredict space heating demand fuel bills, and underpredict the SAP score of the home.

Achieving an EPC band C (or 90 kWh/m^2/yr policy target) in homes like 00CS, without installing external wall insulation, appears to be challenging.

3.6 Overheating risk of retrofitting

The overheating analysis in this section is complementary to this work and uses the overheating assessment method from CIBSE TM59, which is cited in the PAS2035 guidance [12]. This is used as a comparison to Loughborough's work, as it is the method used in current practice when following PAS2035. The openable windows and percentage opening area for 00CS are shown in Figure 3-24. All windows had secondary glazing that could be fully opened, in addition to the main sash window type. As these are a sash design, the models were set to include 90 % of openable area for all of the windows shaded in red.

Figure 3-24 Percentage of opening area for openable windows

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* [13]. 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 retrofit. Following the TM59 guidance, the 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. DSY1 represents a moderately warm summer, DSY2 represents a short, intense warm spell, and DSY3 a longer, less intense warm spell [8]. Assessment was also carried out for future weather scenarios, using the DSY1 files for the 2050s and 2080s high emission scenarios at the 50th percentile. Results for Criteria A are shown in Figure 3-25.

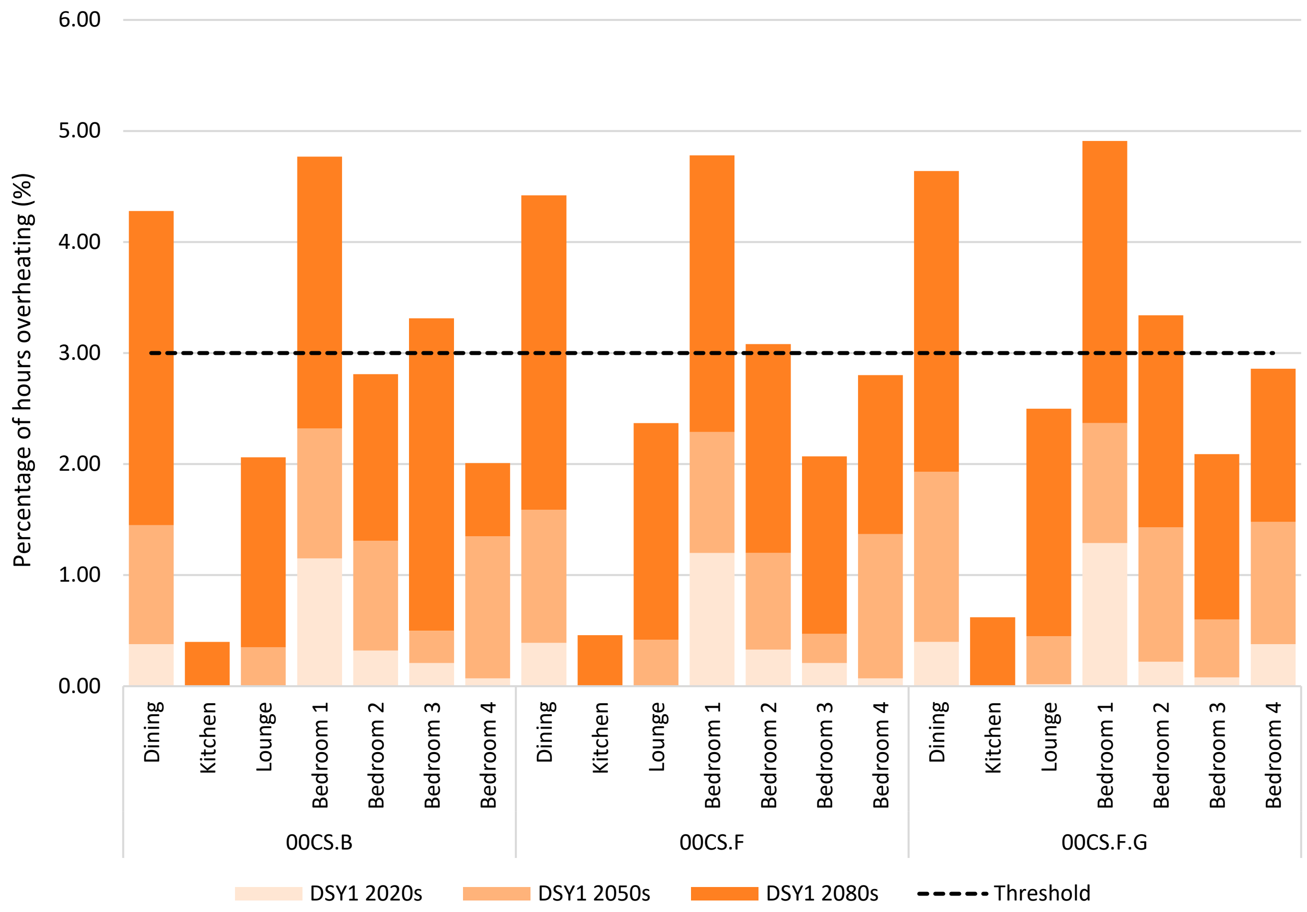


Figure 3-25 Modelled overheating under TM59 Criteria A

Cooling provided by natural ventilation in 00CS is aided by crossflow air movement, especially when internal doors are assumed to be left open during occupied hours, as per the TM59 modelling guidance.

It is only under the 2080s climate scenario that some, though not all, living spaces begin to experience excessive overheating under Criteria A. Although marginal, overheating does increase slightly following the floor insulation retrofit. The bedroom spaces in TM59 are also subject to assessment under Criteria B; the results are illustrated in Figure 3-26. Overheating could be mitigated through simple shading, however, the analysis presented here represents a worst-case scenario with no active shading included.

It is the two south facing bedrooms (1 and 2) that suffer from the greatest amount of overheating under Criteria B, although this is relatively low until after the 2020s scenario. Crossflow ventilation is reduced for night-time cooling, as TM59 guidance specifies that internal doors remain closed overnight. There are again very minor changes following retrofit, but not to the extent that they could be considered as unintended consequences of the retrofit.

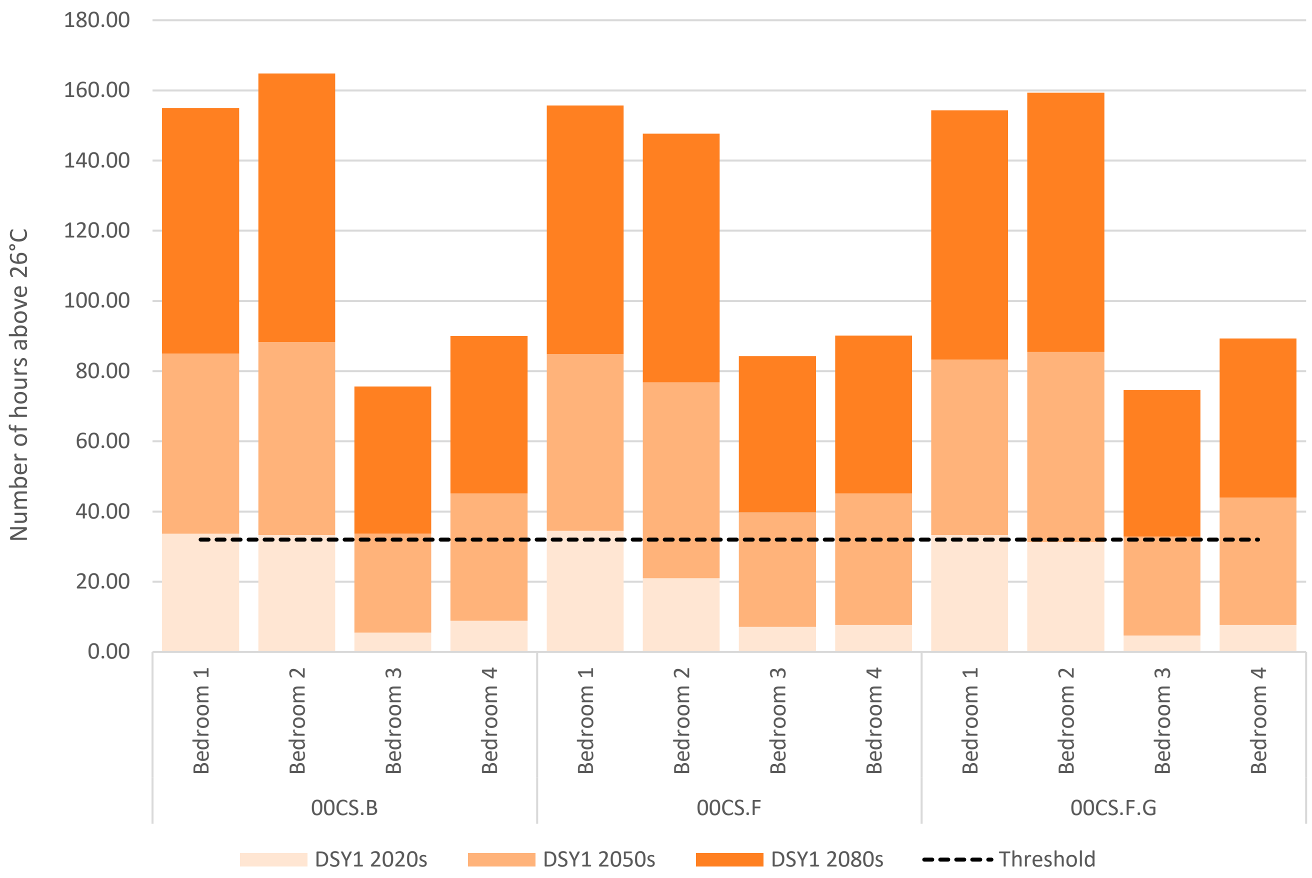
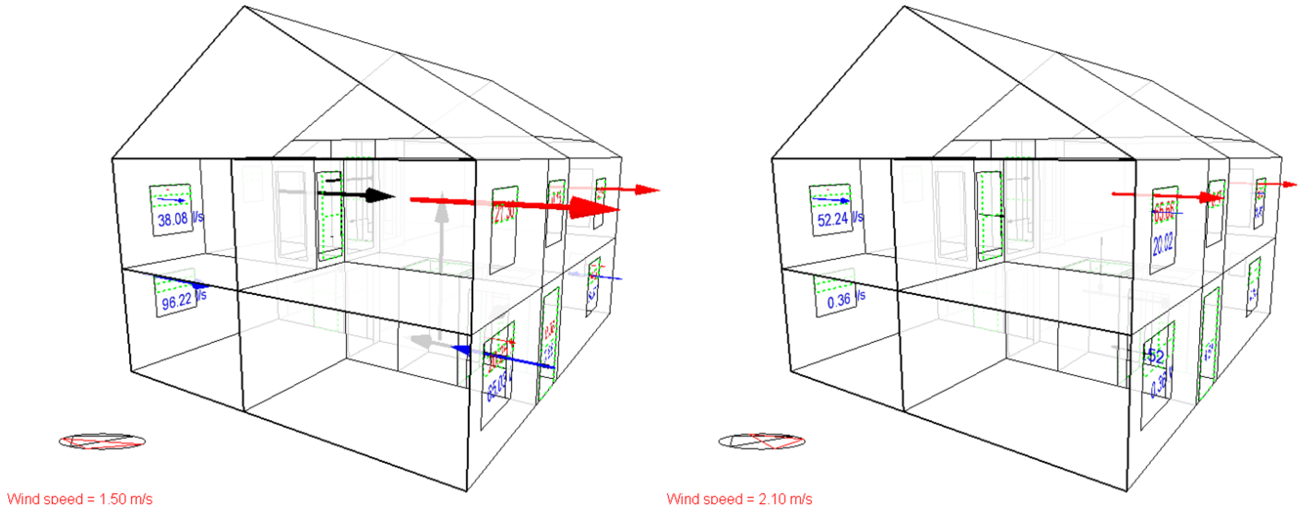


Figure 3-26 Modelled overheating under TM59 Criteria B

Visualisations presented in Figure 3-27 illustrate the importance of open internal doors in creating paths for crossflow natural ventilation. Both images show a section cut of the modelled dwelling. The first image (a) shows the air flow at 19:00 on 22nd July, when all internal doors are open on one of the hottest days of the year. The black arrows illustrate internal air flow between rooms, red arrows indicate the air that is leaving the building, with blue arrows indicating in-flowing fresh air. The second image (b) shows the reduced air flow due to the bedroom doors being closed at 04:00 on the next day, when the wind speed is slightly higher.



(a) 19:00 22nd July (b) 04:00 23rd July

Figure 3-27 Modelled air flow with bedroom doors open and closed (size of arrow indicates amount of air movement: red = hot air, blue = cold air, black = internal air)

Overheating risk of retrofit summary

Overheating during daylight hours does not represent a significant risk in 00CS, regardless of any retrofit actions.

When using the 2080 weather file, overheating becomes significant in south-facing spaces.

The comparison between results for Overheating Criteria A and Criteria B demonstrates the importance of crossflow air movement for naturally ventilated dwellings. Sufficient air movement is generated when internal doors are open during the day; however, they are required to be closed as part of Criteria B.

This results in the bedrooms experiencing more overheating, though this is not affected by the ground floor insulation or the secondary glazing.

3.7 Retrofit costs and payback

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

In this project, the costs of undertaking each retrofit were evaluated to be either i) enabling works that were linked specifically to getting the house ready for the retrofit (making repairs etc), or ii) the actual cost of the retrofit. The home was also remote, meaning travel time to the site would have been included. Therefore, labour costs for less rural properties (half a day travel time per day) could be expected to be lower. There was no cost for the secondary glazing, since this was already in-situ. The cost of floor retrofit is outlined in Table 3-5.

Table 3-5 Cost of retrofits

Retrofit	i) Retrofit activity	Retrofit costs	ii) Additional enabling work required	Enabling work costs
00CS.F 10 mm aerogel blanket	Remove existing floor covering Install aerogel underlay Install new or existing floor covering	£ 5,337	n/a	£ 0

Table 36 suggests that the costs of the 00CS floor retrofit may be as expensive as conventional mineral wool or XPS floor insulation, such as those undertaken in DEEP Case Study 2.09. This is because although there is no enabling work involved, such as removing or replacing the floorboards (which made up almost 40 % of the costs in the floor retrofits in DEEP Case Study 2.09), the material costs for the aerogel were very high (44 % of the cost).

To achieve the same U-value as conventional retrofits and to meet the Building Regulations limiting U-values, however, a second aerogel blanket (i.e. double the thickness) would be needed to make comparisons with conventional floor insulation. This would lead to even higher material costs. Innovation in the production of aerogel, or greater economies of scale, are therefore needed to reduce its material cost to make it competitive with standard insulation.

Fitting underlay to carpets and vinyl flooring requires less labour, disruption, time, and waste, compared with laying conventional solid or suspended timber floor insulation. There may be some benefits to the consumer in this approach, which are not captured in the financial calculations. This is inferred in Table 3-6, which shows that there were no enabling works for this retrofit, though the dust membrane was considered essential to install.

Avoiding enabling work is attractive as it provides certainty for installers and households when budgeting for retrofits, and certainty in the ability to predict the cost of retrofits. Aerogel floor insulation was the only retrofit measure installed in any of the DEEP Case Studies that had no enabling costs.

Table 3-6 Breakdown of cost of retrofits

Retrofit	Labour	Materials	Treated area (m²)	Cost per area (£/m²)	Benchmark (£/m²) [14]
00CS.F 10 mm aerogel blanket	56 %	44 %	55	£98	£38 - £92

3.7.1 Predicted fuel bill savings

The impact of the retrofits on household dual fuel bills is shown in Figure 3-28 using the SAP fuel prices of 3p per kWh gas and 5p per kWh oil. These values do not reflect current fuel prices and are shown only as an illustration.

- The change in response to both the floor retrofit and the removal of secondary glazing is relatively small because the absolute heating bills are very large and small changes are less obvious.
- The secondary glazing was around the same level of effectiveness at reducing fuel bill savings than double glazing in the other DEEP case studies.
- The marginal increase in air leakage measured post floor retrofit appears to have offset any savings achieved by the insulation.
- The thin amount of floor insulation did not yield substantial fuel bill reductions, suggesting that simply replacing flooring underlay with an insulation product may not be effective and more insulation is needed to achieve a significant reduction.

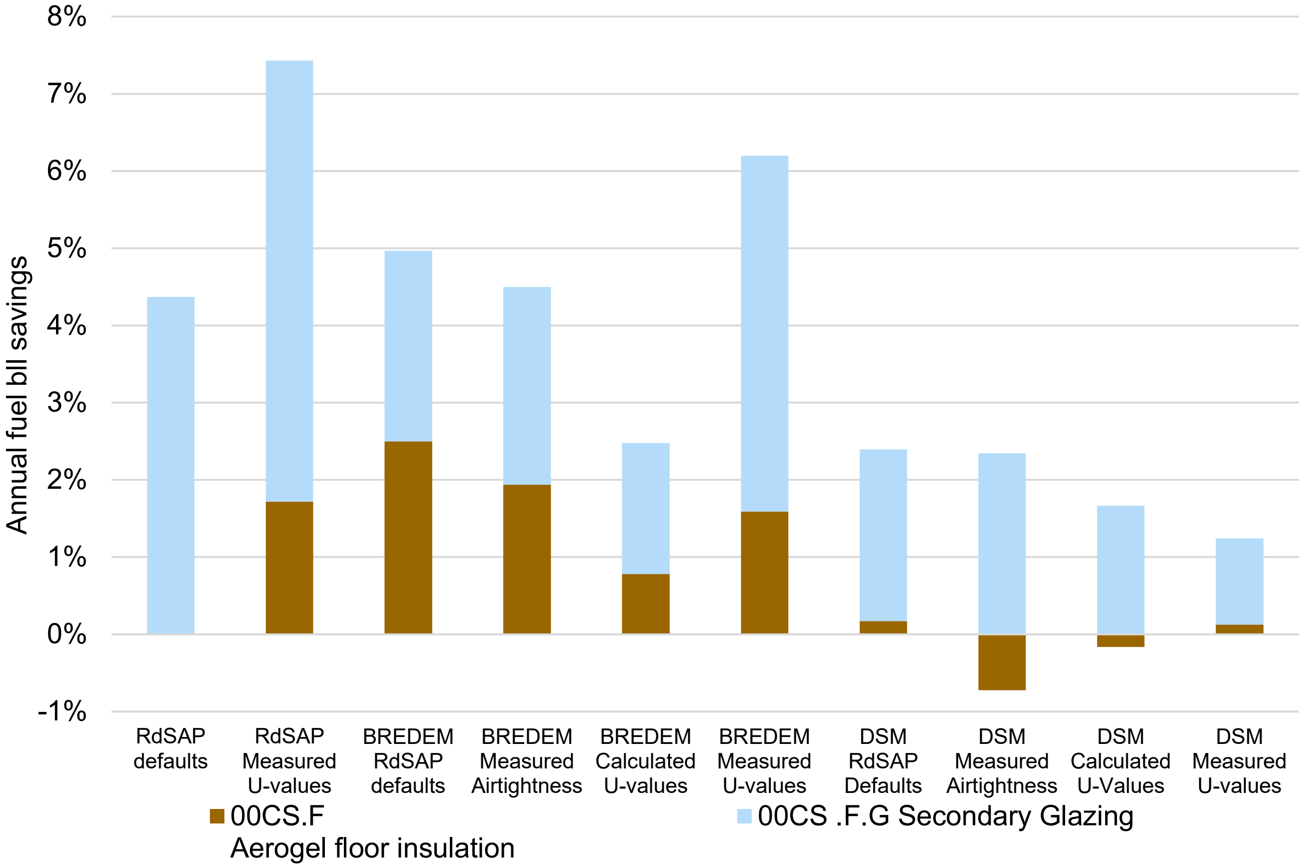


Figure 3-28 Annual fuel bill savings

Changes to fuel prices will directly impact the predicted savings shown here and have implications for payback periods calculated from these values.

There is much uncertainty over the future price of fuel and of retrofits themselves, making calculating a payback for this case study difficult. For instance, using the assumptions stated here, the ground floor retrofit would result in a payback over many hundreds of years. No payback for the impact of secondary glazing can be assessed as there was no retrofit cost for this since the glazing was already installed in-situ.

Retrofit costs summary

The retrofit costs of installing 10 mm of aerogel underneath floor finishes were equivalent to more conventional suspended timber floor retrofits. Although there were no enabling costs, the product itself is expensive. If the price of aerogel reduces, this will have implications for cost effectiveness.

The costs shown may also only be relevant for rural and remote dwellings, since the travel time (to and from the home, from the contractor’s base) was around half a day.

The dominance of the uninsulated solid walls on heat losses is masking the changes on fuel bill that were achieved by the secondary glazing and ground floor retrofit, as well as the impact of using different model input assumptions.

As with all the DEEP case study models, DSM predicts lower fuel bills. In this case study, this is mainly because it accounts for the thickness of internal walls, which in this case resulted in a 15 % reduction in the home’s overall volume.

Uncertainty over the cost of fuel and retrofits means that absolute values quoted here can only be representative of costs from when the project was undertaken, i.e. before the fuel price increases of the early 2020s.

4 Conclusions

This case study has identified important findings about retrofitting a large, detached, uninsulated solid stone-walled rural home of heritage value. Specifically, around the performance of ground floors with novel 10 mm aerogel insulation as carpet underlay, and of secondary glazing applied to single glazed timber windows. It also investigated the models used to predict performance. The main issues are discussed below:

Stone cottage with heritage value
The HTC of this home was very large, over 350 W/K, which is roughly twice that of most of the other DEEP case study homes. Over 70 % of this heat loss was due to the uninsulated stone external walls. Therefore, any retrofit that does not improve the performance of the external walls will only have a relatively small impact on the whole house heat losses. This case study has therefore been useful in exploring the options for homes like 00CS in the context of a future EPC band C policy target, where heritage value (in this instance being located in an AONB) means that making changes to the solid external walls and the original glazing may be difficult. Appropriate, low risk IWI options may be required for these types of homes to achieve desirable levels of energy efficiency.

Floor retrofit performance
The ground floor insulation achieved 40 % and 27 % reductions in in-situ measured U-value for the solid and suspended floors respectively. It did not achieve a measurable change in HTC measured using the coheating test. This resulted in savings between 1 % and maximum of 2 % on predicted fuel bills, depending on the energy model and input assumptions used.

The secondary benefits of the ground floor insulation on improved surface temperatures were measured, and it is likely this could improve thermal comfort. Additionally, this aerogel floor insulation was the only retrofit in the DEEP case studies that did not have any enabling costs. The material cost of the product, however, made its total installation costs comparable with mineral wool and XPS suspended ground floor insulation, which achieves perhaps double the U-value savings.

The case study shows there is potential for aerogel ground floor insulation to be used as a carpet underlay, but its material cost is a limitation. It may also need thicker products to achieve savings aligned with limiting U-values in the Building Regulations Part L1B. The findings also confirm that undertaking this retrofit in large, detached, stone homes, where most of the heat loss is through the external walls, is not likely to make substantial improvements to the whole house energy efficiency. They are therefore unlikely to be able to achieve the policy target of EPC band C.

Secondary glazing performance
An assessment was undertaken to understand the contribution of existing secondary glazing to the airtightness improvements and heat loss in the home. Secondary glazing is a common glazing retrofit for homes in AONB, conservation areas, or listed buildings, since it does not alter the external appearance of the home. The secondary glazing performed better than predicted, achieving a 73 % U-value reduction. This suggests that secondary glazing can have a significant impact on heat loss, which has implications for many historic properties in the UK. However, in this case study home, the external window area was relatively small compared to the external wall area, so there was no measurable difference in the HTC between the home with and without the secondary glazing.

There was also no measurable reduction in the air leakage of the house with or without secondary glazing according to the blower door test. This is in contrast with the data obtained from the models, which predicted that secondary glazing would reduce airtightness by 20 %. Infiltration around fenestrations is highly dependent on the condition of the windows and so more data is needed to understand the benefits that secondary glazing may have on different house window types.

Airtightness

This home had wet-plastered external walls, a mostly solid ground floor, and small external windows, relative to the home's size. A much better airtightness level was measured than the EPC predicted, at a level comparable with the new build target in the most recent version of Part L1A of the Building Regulations. It is interesting to note that older homes may in some instances be airtight, and that a building's characteristics, features, and condition may have more impact on its air leakage. The implication of this is that RdSAP substantially overpredicted the air leakage in the house, resulting in a worse EPC for the home. Allowing EPC assessors to input measured airtightness values for retrofits may improve the accuracy of EPCs, especially as these are often required for PAS2035. This suggests that there may be some merit in revisiting the calculation method for estimating airtightness of homes embedded in RdSAP software.

Loft Insulation observations

Although loft inspections found that 200 mm of loft insulation was installed at 00CS, further investigations revealed that there were discontinuities in the insulation. These resulted in cold surfaces on the bedroom ceiling, which may pose a condensation risk and excess heat losses. These were due to purlins in the loft which were difficult to insulate behind, but they were also hiding from view the uninsulated area, meaning an EPC assessor may not observe this where full loft inspections are not undertaken. The other area of uninsulated loft was the small area of sloped roof ceiling in the bedrooms ('skeiling'), where it is challenging to install insulation. Since this feature increases heat loss as well as the risk of condensation in homes, more research is needed to understand how common it is in the UK housing stock.

Overheating

The retrofits did not make any difference to the overheating risk in this home, which was assessed to be low. Only in 2080 might there be some risk of overheating. The home was heavyweight and had a relatively small external glazed area compared to external wall area, which contributed to its good performance.

Modelling inputs

As discussed, areas of inaccuracy in the EPC model relate to the airtightness of the home, which was overestimated, and the EPC's cannot account for insulation thinner than 50 mm. These limitations may be relatively simply addressed in future software and protocol updates.

Additionally, the case study highlighted that DSM predicted significantly lower HTC, space heat demand and fuel bills than steady-state models. This is because it accounts for the large internal walls (500 mm thick in places), resulting in a 15 % lower dwelling volume. The implication is that EPCs in homes with substantial internal wall volume are underpredicting the energy efficiency and allocating them lower SAP scores and EPC bands than they perhaps should receive. To improve the accuracy of EPCs, it may be worthwhile understanding how assessors can account for the thickness of internal walls during surveys, so that the calculations can reflect the actual volume of the homes where internal walls are substantial.

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