Department for Energy Security & Net Zero

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Demonstration of Energy Efficiency Potential (DEEP) Report 2.00

Case Studies Summary

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Executive summary

The DEEP case study retrofits provide compelling evidence on how a whole house approach to retrofit can reduce heat loss, surface condensation risk and overheating risks in solid walled homes. From the data collected, specific guidance is produced outlining how to install retrofits in solid walled homes more safely and effectively. Recommendations are provided on how to make measurements and modelling predictions of the technical performance of retrofits more accurate. The findings can inform evidence-led decisions at multiple levels to ensure retrofits in solid walled homes are safe and effective.

The project demonstrates that both fuel bills and risks are reduced via whole house retrofits. The case studies suggest that a large proportion (between 66 % and 89 %) of junctions in uninsulated solid walled homes can be at risk of surface condensation. Installing solid wall insulation (SWI) reduced this number to between 16 and 21 % in the DEEP houses, and when a whole house approach was taken, this dropped to <8 %. SWI was shown to reduce heat loss from the homes more than other retrofits, between 19 and 55 %, which could be equivalent to fuel bill savings up to 40 %. In most instances SWI also ensured the home received an Energy Performance Certificate (EPC) band C, achieved the social housing decarbonisation fund (SHDF) space heating target of 90 kWh/m² and was among the most effective retrofits for reducing overheating in homes. Airtightness improvements, loft insulation, room-in-roof retrofits, ground floor insulation and installing new glazing retrofits, were also found to reduce heat losses by varying degrees, most being responsible for fuel bill savings between <1 % and 8 % or HTC between 0 and 20 %, which was not usually enough to improve the EPC band, and savings were smaller than the uncertainty of the measurements in half of the retrofits.

The scale of savings achieved by the retrofit depended on the condition of the base case home, the retrofit specification, and the model inputs and assumptions that were made. The RdSAP model used to produce EPCs was generally not good at predicting the measured heat loss of the homes, overpredicting HTC by an average of 42 % across the case study homes, and therefore overpredicting retrofit savings, i.e., the prebound effect was observed. It was possible to improve predictions by incorporating measured and calculated values for air permeability, U-values and thermal bridging, though an average overprediction of 17 % was still observed. It is not usually practical to measure these performance attributes in homes. The accuracy of EPCs could therefore be improved by adopting a greater range of default values for assessors to select. In addition, convention around room-in-roof geometry was also found to overestimate heat loss in the EPC, which could be resolved in future software updates.

The DEEP case studies were generally one-off retrofit projects, which took place during a global pandemic and at a time of disruption in both the construction and energy markets. This makes the evaluations of the retrofits' cost effectiveness challenging. However, it can be surmised that retrofits generally have very long payback periods, usually many decades, although future supply chain and fuel costs may change this. Importantly the DEEP project identified that up to a third of the total costs of retrofits were spent on additional activities, other than the retrofit itself. This included enabling work for the retrofit (moving plumbing, utilities, etc.) but also maintenance and repair of the building itself (fixing leaks, fabric, etc.), which could be considered necessary maintenance costs outside the retrofit activity. Moreover, the non-financial benefits of the whole house approach were not captured in economic assessments, though these broader benefits should be factored in to achieve evidence based retrofit decision making.

1 Introduction to DEEP case studies

Solid walled homes are among the least efficient in the UK, meaning their occupants are more likely to be in fuel poverty. Retrofitting solid walled homes can address fuel poverty, support net zero goals and contribute to the decarbonisation of heat. However, solid wall insulation is among the highest risk, technically difficult and expensive to install. To reduce the risk of unintended consequences, a "whole house approach" is recommended, in which the interaction of various retrofits is considered.

Solid walled homes come in many varied constructions, meaning the default input values used in energy and hygrothermal modelling are not always appropriate. This can affect the accuracy of energy performance predictions or moisture risk assessments, as well as predictions of fuel bill reductions resulting from retrofits taking place. The issues above have long been ill-understood [1-4]. The Demonstration of Energy Efficiency Project (DEEP) was designed to shed some light in this area through 14 retrofit case studies. The 6 aims of DEEP specified in the invitation to tender for the project can be summarised in three specific goals:

1) investigate the energy saving of individual and multiple retrofits in solid walled homes.
2) investigate the causes and severity of unintended consequences and risks associated with retrofitting via a piecemeal or whole house approach.
3) assess the appropriateness of input default assumptions used in energy, thermal and hygrothermal models, and the impact of updating defaults with measured values.

A description of the building performance evaluation (BPE) methods used to collect data for case studies can be found in the DEEP Report 2.01, *Case Study Methods*. A range of field tests were undertaken to measure performance before and after individual and cumulative retrofits. Models of the homes were created for comparison to the measured values, to understand the scale and causes of any discrepancies (i.e., performance gaps).

The field trials included coheating tests, heat flux density measurements, airtightness testing, leakage detection, thermography, and surface temperature monitoring. The energy modelling included the Reduced Data Standard Assessment Procedure (RdSAP), the algorithm used to generate Energy Performance Certificates (EPCs) in existing homes, the Building Research Establishment Domestic Energy Model (BREDEM) and dynamic simulation modelling (DSM). Thermal modelling of junctions was carried out to identify localised areas with high heat loss (i.e., thermal bridges) and internal surface condensation risks.

Detailed analyses of each of the 14 case study homes are in the individual DEEP case study Reports 2.02 to 2.12[1]. These reports present the key findings, considering the collective results from all the case studies. Section 2 identifies the main findings related to individual retrofits. Section 3 presents findings which have implications for modelling retrofit performance and risk. Section 4 considers the cost effectiveness of retrofits. Section 5 discusses the findings which relate to the importance of the whole house approach to retrofit. Section 6 comments on lessons for BPE tools and, Section 7 draws final conclusions and recommendations.

[1] Three reports describe two homes each, as the homes were adjoined in these cases.

1.1 DEEP case study homes

Fourteen case study homes were recruited via social and private landlords over the course of three winters from 2019/20 to 2021/22. The requirements for selection were that the houses were vacant for the entire testing period (typically four months for a single measure but up to 18 months for multiple retrofits), had no known major pre-existing retrofits, large extensions, or any structural or other health and safety concerns. An overview of the successfully recruited homes is presented in Table 1-1 and images shown in Figure 1-1.

Table 1-1 DEEP field trial case study homes

House code	Age	Wall type	Building form	Party walls	Bedrooms	No. Stories	Floor area (m²)
17BG	1890	Brick	End-terrace	2	2	3	65
56TR	1920	Brick	End-terrace	1	3	2	91
01BA	1910	Brick	End-terrace	1	2	2	70
55AD	1940	Brick	Semi-detached	1	3	3	78
57AD	1940	Brick	Semi-detached	1	3	3	78
04KG	1960	No Fines	Semi-detached	1	3	2	79
52NP	1900	Brick	Terrace	2	4	3	94
54NP	1900	Brick	Terrace	2	4	3	94
27BG	1890	Brick	Terrace	3	2	3	66
08OL	1930	Non trad	Semi-detached	1	3	2	67
07LT	Pre-1890	Brick	End-terrace	1	3	3	150
09LT	Pre-1890	Brick	Terrace	2	4	3	153
19BA	1890	Brick	Terrace	2	4	3	132
00CS	Pre-1890	Stone	Detached	0	4	2	139

The homes also needed to exhibit a range of technical requirements specific to the testing programme. For instance, preference was given to homes with fewer neighbours (so that party wall influences could be minimised), were north facing (to reduce the impact of solar radiation) and were within commuting distance for fieldworkers based in Leeds. These requirements, in addition to the Covid-19 pandemic and associated restrictions, necessarily limited the availability of homes for the study.

A range of end and mid-terraced, as well as semi-detached homes were recruited. Only one detached home was included. The main solid wall type was brick (the most abundant building material in the UK), though one stone, one concrete “no fines”, and one non-traditional walled home were also recruited. The age of the properties ranged from pre-1890 to 1960 which captures most solid walled homes in the UK. Homes were typically located in urban areas within Yorkshire. However, one rural home situated in the North Yorkshire Moors was included, alongside two semi-detached urban properties in Leicestershire.

Figure 1-1 DEEP case study homes, left to right:
Top; 17BG, 56TR, 01BA, 19BA,
Middle; 57AD (left) & 55AD, 00CS, 27BG, 07LT (left) & 09LT (right),
Bottom; 04KG, 52NP, 54N, 08OL

While every effort was made to obtain a representative sample, the sample could not be fully representative of all the varied UK solid wall home archetypes. There are therefore limitations to the ability to generalise from the findings in these homes, and extrapolations of the findings should be considered with some care. Nonetheless, the range of homes in the DEEP sample allowed for a wide-ranging investigation into the potential and implications for retrofitting a variety of solid walled homes and non-traditional house types. The sample included a mix of building forms and attachment, floor types, construction age and materials, as well as a range of existing fabric insulation levels.

1.2 DEEP case study retrofits

Forty-two retrofits were undertaken in the fourteen case study homes, as outlined in Table 1-2. The specification of each retrofit is described in the individual case study DEEP Reports 2.02 to 2.12, though they were generally designed according to the Part L 1B Approved Document [5] and the whole house approach identified in PAS 2035. Decisions on which retrofits would take place were taken in the context of the research questions posed in the DEEP invitation to tender. Specifically, the research was required to investigate the potential for ground floor and airtightness retrofits in solid walled homes, and so these were among the most common retrofits to take place in the DEEP case studies. Additionally, investigating multiple measures installed via a “piecemeal approach”, where measures were installed in isolation, versus a “whole house approach” was required, and so a subsample of the homes had multiple measures installed.

Where time allowed, the measures were installed individually and BPE tests were undertaken to identify the benefits of each measure. The order in which the measures were generally installed is shown in Table 1-2, with stage 1 being first and stage 8 last. In some instances, a retrofit may have included several measures combined to fit in with the research schedule. This was done to reflect the most likely order in which homes undergo piecemeal retrofits in the UK, as well as considering upfront costs. Airtightness (draughtproofing) improvements were made at stage 1, as they are relatively cheap to undertake, while solid wall retrofits were the final fabric retrofit installed, at stage 6, since these are expensive. Similarly, most of the homes had loft insulation and double glazing installed over the last few decades, but most had not installed ground floor insulation. Stage 7, the whole house approach, is a step that was introduced to investigate the difference between installing multiple measures into homes in a piecemeal versus a whole house approach. Thus, in this stage, homes had an additional retrofit that was specifically aimed at tying together the previously installed piecemeal retrofits. Mechanical Ventilation and Heat Recovery (MVHR) is stage 8. This is not a common measure and so is not incorporated in this summary report, instead, it is discussed separately in the case study report (04KG).

Table 1-2 DEEP retrofits (tick in parentheses shows retrofit took place without BPE tests)

Retrofit stage	17 BG	56 TR	01 BA	55 AD	57 AD	01 ST	04 KG	52 NP	54 NP	27 BG	08 OL	07 LT	09 LT	19 BA	00 CS
1. Airtightness improvements	✓						✓	✓	✓			✓	✓	✓	
2. Loft insulation		✓	✓	(✓)	(✓)										
3. Room-in-roof insulation	✓											✓	✓	✓	
4. New glazing and dDoors			✓	(✓)	(✓)		✓								✓
5. Ground floor insulation	✓	✓	✓	(✓)	(✓)		✓	✓	✓	✓ ✓	✓				✓
6. Solid wall insulation	✓	✓	(✓)	(✓)	✓										
7. Whole house approach	✓	✓	✓	✓											
8. MVHR							✓								

2 Measuring the impact of retrofits

Forty-one of the retrofits installed in the 14 DEEP case study homes were fabric improvements, meaning most homes received a mix of retrofit measures. Codes were used to identify the specific home and retrofit that a test refers to and these are outlined in Figure **2-1**. For instance, code *17BG.WH* refers to test house 17BG, and the whole house (WH) retrofit stage. In the following sections the impact on heat losses that were achieved by each retrofit measure is discussed.

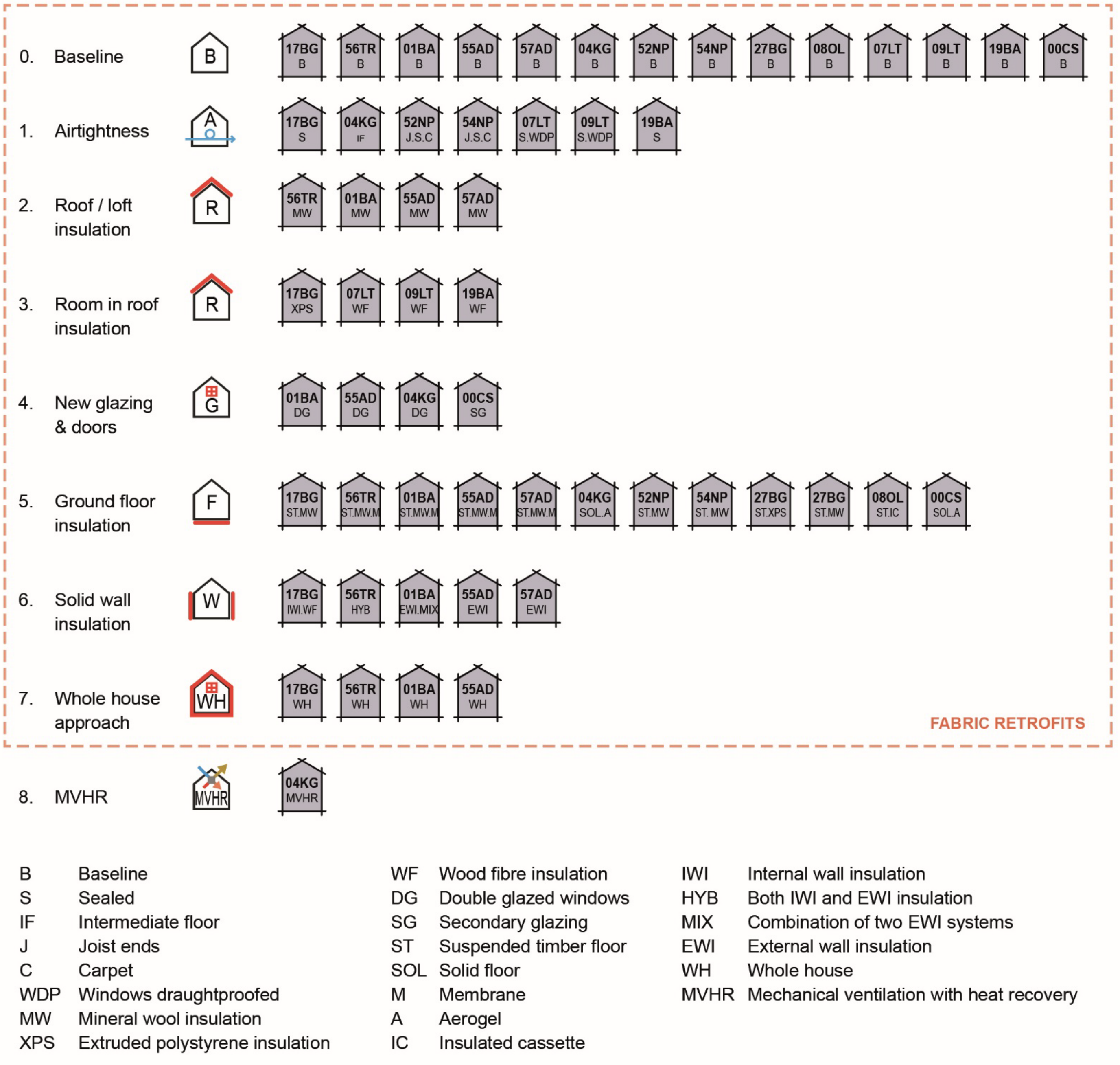


Figure 2-1 **Overview of case study retrofits**

2.1 Airtightness improvements

Airtightness improvements in the DEEP cases targeted *background ventilation*, often called infiltration (air entering) and exfiltration (air leaving). This contrasts with *purpose provided ventilation,* which is deliberately included in homes to bring in fresh air directly from outside for occupants, and to purge stale, humid air from inside. Background ventilation is unwanted air leakage which can travel from outside via indirect pathways thought the fabric before it eventually enters the living space, thus it may not be fresh, cannot be controlled, and may cause unwanted circulation between spaces (e.g., transporting warm moist air into unheated spaces where it may cause moisture issues). PAS2035 ensures adequate provision of purpose provided ventilation in homes, however, while improving the airtightness of homes can be beneficial, care must be taken in naturally ventilated homes to ensure sufficient fresh air.

The airtightness retrofits undertaken in DEEP reflect common approaches to draughtproofing currently in use, i.e., using silicon to seal cracks and gaps internally, fitting draughtproofing strips to windows and doors and replacing leaky “boxing in” of services. More advanced airtightness tapes and membranes, which create a continuous primary air barrier, were not included, since this approach represents significant disruption (removing and replacing wall and floor coverings, replastering, etc.), and is rare outside low energy retrofits. Where possible, draughtproofing activity was undertaken one at a time to study the impact of each approach.

Figure 2-2 illustrates that the success of airtightness improvements is highly context specific, and it is difficult to predict their outcomes, which depend on the specific condition of the home. General sealing of homes was not particularly effective in many instances. This was often due to the fact that homes had many indirect air leakage pathways (i.e., entering suspended ground and intermediate floor voids, or boxed-in services) and sealing these often redirected, rather than removed the air leakage. Sealing of direct inside to outside air leakage was more effective, for instance sealing around penetrations in walls, though sealing around windows in 07LT and 09LT had little impact. Installing carpets in 52NP and 54NP had the largest impact across the case study homes. This has potential implications for social housing where carpets are often removed for hygiene reasons when new tenants take possession. If the new tenants do not fit carpets, their homes may lose excessive heat via infiltration causing higher fuel bills.

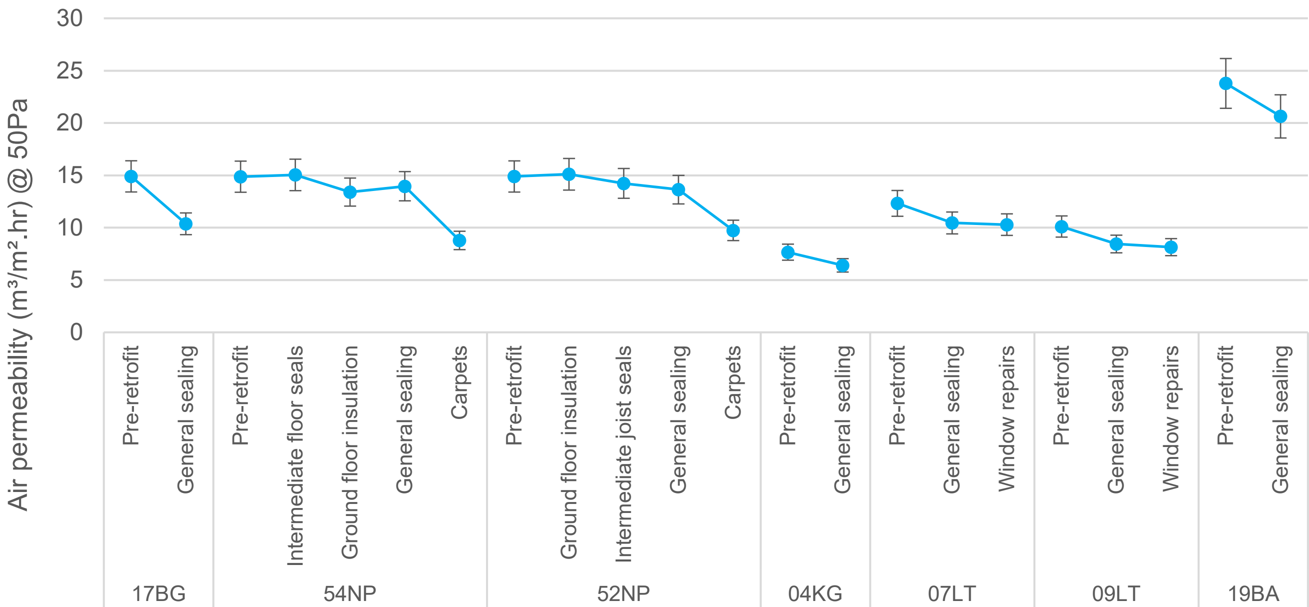


Figure 2-2 Airtightness changes in each home

Figure 2-3 shows the measured heat transfer coefficient (HTC) reduction achieved by air leakage reductions (negative reduction is represented by increases in HTC) as measured by the coheating test, which ranged between 0 and 27 %. Where the error bars cross the “0” axis, this means the change in HTC is not statistically significant. HTC reductions for 07LT and 09LT are not shown as these were combined with room-in-roof retrofits, while 52NP and 54NP HTC reductions are not shown as these were combined with suspended timber ground floor retrofits. These findings illustrate that savings from draughtproofing is very variable and dictated by specific air leakage pathways in the homes. 19BA and 17BG are similar constructions, pre-1910, brick-built, terrace homes with cellars (17BG is also an end terrace and back-to-back, so both have two external walls and two party walls). Yet, despite similar approaches to draughtproofing, they had very different outcomes. A reduction of around a quarter of the home’s heat loss was measured in 17BG, but no significant reduction was recorded in 19BA.

04KG was an altogether different house type, a 1960s concrete home with solid floors (also with external wall insulation (EWI) installed). No improvement was measured resulting from the additional sealing that took place (which included installing plywood over the intermediate floors), even though the blower door results suggested that a reduction in air leakage was achieved. Figure 2-3 shows the modelled HTC savings predicted for the draughtproofing. No EPC reduction is shown for the homes, since RdSAP infiltration default assumptions cannot be altered in EPCs, even when the air permeability rate has been measured. BREDEM replicates the RdSAP model, although it allows input variables, including airtightness levels, to be altered. The findings suggest the predictions do not always match the measured HTC reductions. Similarly, DSM models are not always able to predict the measured HTC savings resulting from draughtproofing. This indicates that the way in which the models account for background ventilation heat losses should be further explored.

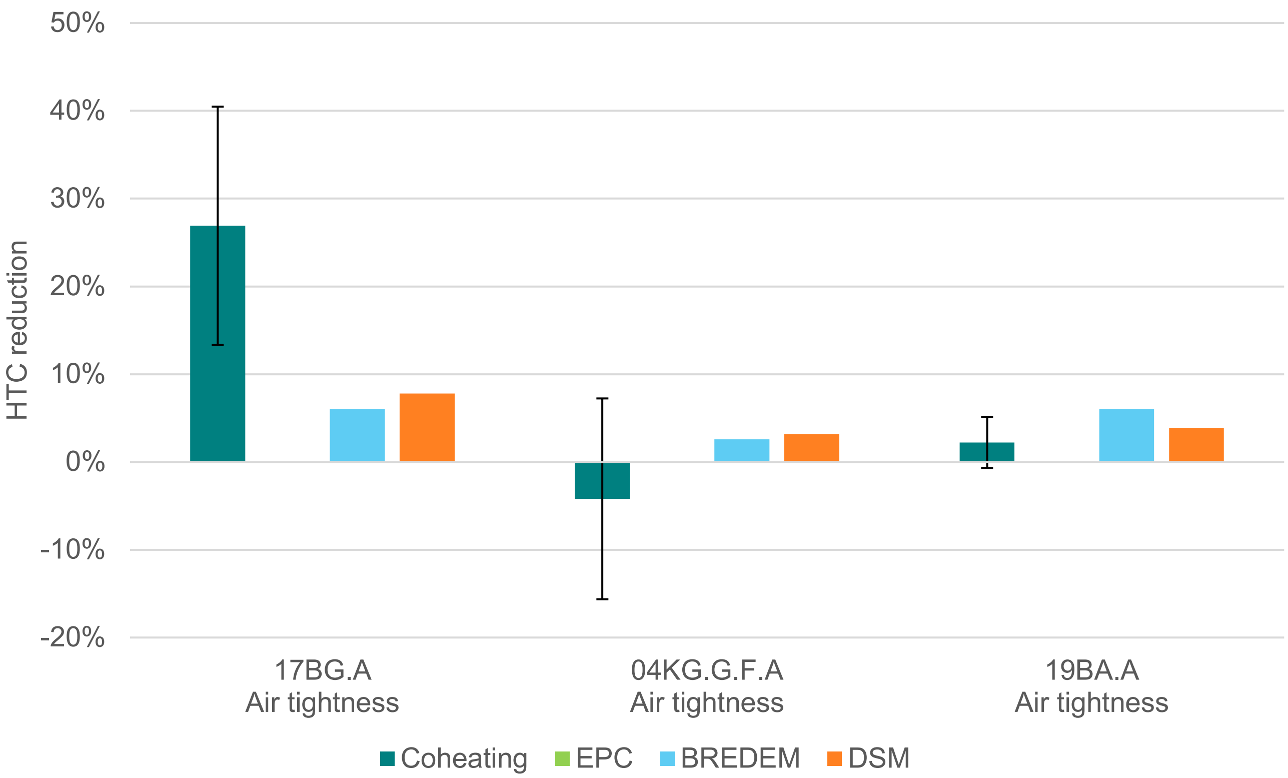


Figure 2-3 Reduction in HTC due to airtightness measures

2.2 Loft insulation

Loft insulation is among the most common retrofits in UK homes, though the amount of insulation installed, and the quality of installation or degree to which it has been disturbed since it was installed, varies greatly. The potential energy savings that can be achieved by topping up or replacing loft insulation in UK homes is relatively unknown. Loft inspections in 114 homes as part of the DEEP Energy Efficiency Surveys described in DEEP Report 3.00, suggest that three quarters of the homes had less than 250 mm and many were disturbed, and therefore may not have been performing to their potential. To explore this further, four DEEP case study homes, which already had some level of loft insulation, underwent loft insulation retrofits. Two were undertaken at the same time as other retrofits (55AD and 57AD), and two were stand-alone retrofits with pre- and post-HTC measurements (01BA and 56TR). 55AD and 57AD had 100 mm and 150 mm of existing insulation, respectively. 01BA also had 150mm, while 56TR had 270 mm, though it was missing in parts. 55AD and 57AD were retrofitted to 300 mm of loft insulation, while 01BA and 56TR received 420 mm of insulation.

The impact on measured U-values is displayed in Figure 2-4**Error! Reference source not found.**. The shaded region indicates the absolute reduction in U-value achieved. In every instance the loft retrofit achieved a U-value reduction (improvement) in the range of 0 to 0.5 W/(m^2·K). Pre-retrofit, all U-values were between 0.2 and 0.3 W/(m^2·K). Post-retrofit, the worst performing was 55AD. 55AD received less insulation than 01BA and 56TR, but received the same amount of insulation as 57AD, yet 57AD performed better. The only noticeable difference between the two was that 57AD received a loft top-up, while in 55AD, the old insulation was replaced. This suggests there may have been some issue with the installation technique in 55AD, but also indicates that topping-up loft insulation, which is much cheaper than removing and replacing old loft insulation, can be more effective since, the U-value of 57AD also outperformed 56TR, which received more insulation. The findings suggest that the quality of a loft retrofit can be more important than the quantity of insulation installed, and that loft top-up retrofits, in homes where the loft has some incumbent insulation, are beneficial.

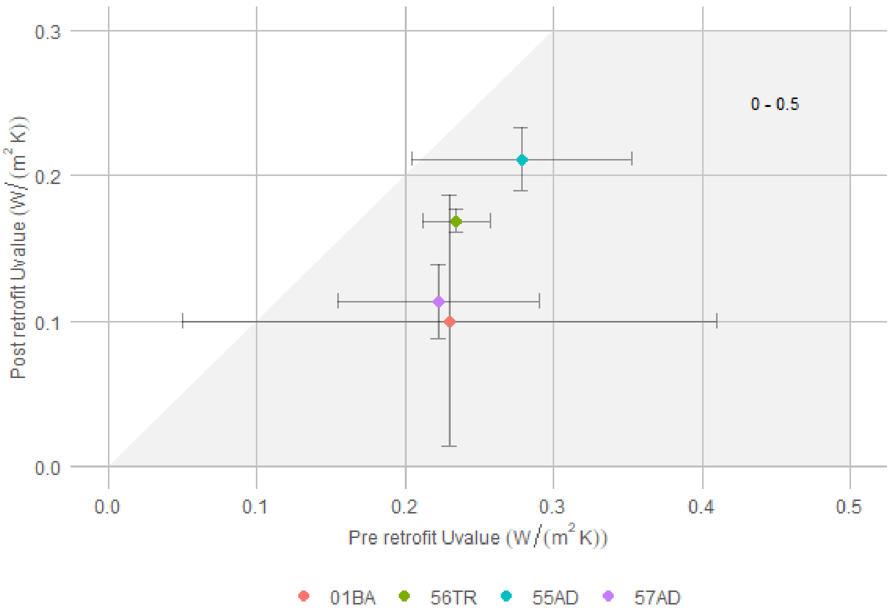


Figure 2-4 U-values of loft elements pre- and post-retrofit. Colours represent the elements; shaded area indicates an absolute reduction in U-value achieved of between 0 and 0.5 W/(m^2·K)

For 01BA and 56TR, a coheating test assessed the impact of the loft insulation on the HTC and the results of these are shown in Figure 2-5, ranging between 5 % and 8 %. For 55AD and 57AD, since their loft insulation was done as part of a multiple measure retrofit, there was no separate coheating test to assess the individual impact on HTC. Figure 2-5 also shows the savings predicted by the three models. The HTC predicted by the RdSAP model used to create EPCs for the homes is shown, as well as the BREDEM and DSM models in which the default inputs for airtightness and U-values were updated with measured values, and, in the case of 56TR, where the default thermal bridging heat loss was replaced with calculated values.

The loft retrofit in 01BA was measured as achieving a reduction in HTC of (19 ± 15) W/K. This was substantially higher than the models assumed would be the case. This shows that while there may be real energy savings that can be achieved by topping-up or removing and replacing loft insulation in homes, these savings may not be translated across to the models. This may be because the models assume that the existing loft insulation performs perfectly, and so only marginal savings are predicted.

No statistically significant reduction in HTC was measured at 56TR (as a reduction of zero lies within its test uncertainty). This may have been because the home already had 270 mm of loft insulation which was performing relatively well. However, the BREDEM and DSM models did predict a large reduction. In this instance, this was because these models factored in a large thermal bridge, caused by the original loft insulation which left a large stretch of uninsulated loft space which was difficult to access behind a roof purlin. This was insulated by the DEEP retrofit, highlighting another potential benefit of retrofits, resolving existing underperformance issues. The resulting reduction in thermal bridging heat loss was captured by the BREDEM and DSM models, which is why greater savings are predicted than in the EPC since thermal bridging heat loss in RdSAP is fixed and so only plane element heat loss savings achieved by changes in assumed U-values are shown. The coheating saving measured was not as significant as the predictions. This suggests perhaps that the retrofit did not fully resolve this bridge, or that it was not as extreme as calculated, or that there were other installation issues with the retrofit meaning that the loft retrofit did not achieve its potential.

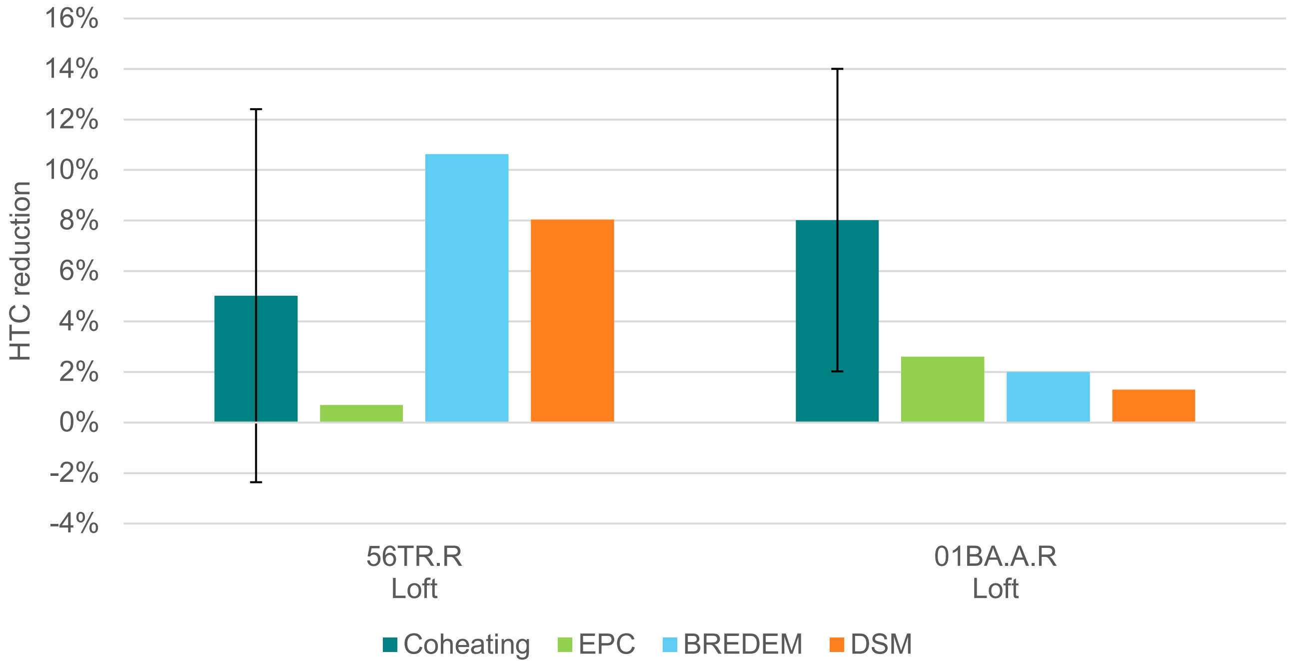


Figure 2-5 Reduction in HTC from loft retrofits

2.3 Room-in-roof insulation

Many solid walled homes in the UK are built with rooms-in-roof or have had cold roof spaces converted into habitable rooms. These rooms tend to have complex geometry, multiple junctions between elements and inconsistent levels of insulation. This makes them particularly prone thermal bridges as well as excessive air leakage, heat loss, and summertime overheating. Indeed, these traits were all found in the DEEP case homes with rooms-in-roof. In total, four room-in-roof retrofits were undertaken in the case study homes. This involved stripping back fabric to the structure for each heat loss element (typically knee walls, sloped ceilings, and dormer elements) and adding new insulation. These were disruptive and messy retrofits, which required enabling work such as moving plumbing, and often substantial additional work such as fixing roof leaks and repairing woodwork in the roof.

Figure 2-6 shows the before and after U-value measurements for each of the seven main room-in-roof fabric elements. The shaded regions indicate the absolute reductions in U-values achieved, with larger savings represented by darker areas. The pre-retrofit U-values were very variable, from around 0.25 to over 2.7 W/(m²·K) highlighting that these rooms were susceptible to heterogenous heat loss. This suggests that, when conditions are appropriate, condensation may be localised, exacerbating damp and mould risks. Some elements were relatively well insulated, specifically the ceilings behind the knee walls since these tended to be easily accessible and simply insulated with mineral wool. More inaccessible or complex elements such as dormer windows were often, but not always, the worst performing, indicating that sometimes elements had received insulation, but sometimes they had not. Often, it was not obvious whether an element was insulated until a thermographic or destructive survey was undertaken, meaning it may not have been discovered until the retrofit commenced. This made planning and designing the room-in-roof retrofits challenging.

Loft hatches achieved the greatest U-value improvement, indicating they are typically poorly performing elements. Although these are small areas, and improvements may not significantly affect whole house heat loss, benefits may be achieved in reduced condensation risk.

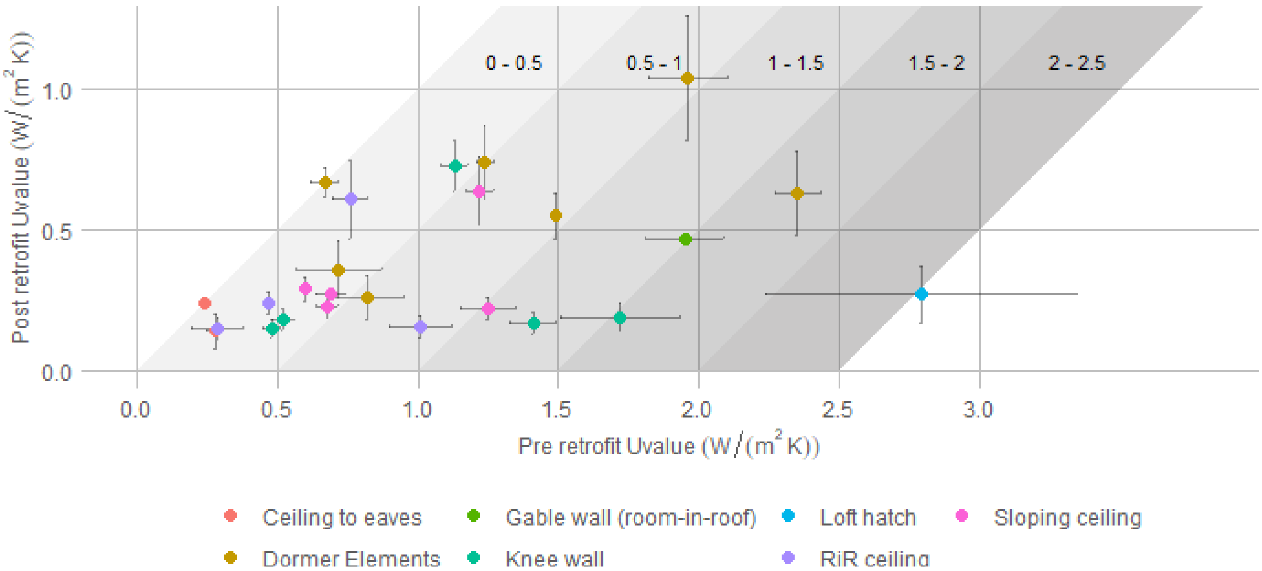


Figure 2-6 U-values of room-in-roof elements pre- and post-retrofit. Colours represent the elements; shaded areas indicate absolute reductions in U-value, with larger savings represented by darker areas

The HTC reductions achieved by the room-in-roof retrofits are shown in Figure 2-7 and range between 5 % and 9 %. For most homes, no statistically significant reduction in HTC was measured (i.e., a reduction of zero lies within the test uncertainty). Only one of the retrofits (07LT) achieved a change in HTC detectable by the coheating test. Additionally, although the 07LT and 09LT retrofits were similar, 09LT is a mid-terrace, while 07LT is an end terrace, so internal wall insulation (IWI) was also installed on the gable wall.

The savings may not have been significant in three of the homes because they were large, and the room-in-roof represented a relatively small proportion of the whole house heat loss. This made any reduction in room-in-roof heat loss difficult to detect via HTC measurements. Additionally, they already had some insulation pre-retrofit which made the potential for improvement smaller and more difficult to measure. Despite this, room-in-roof retrofits do reduce heat loss and therefore fuel bills, as well as resolve the problem of different elements having different heat losses which may cause cold spots and increase the risk of surface condensation.

It is notable that the reductions predicted from EPC assessments were significantly higher than the savings measured, and much higher than the other models predicted. This was due to the simplified default inputs used in the RdSAP around room-in-roof geometry and fabric heat loss, as an uninsulated U-value of 2.3 W/(m²·K) was assumed for all elements. This was not realistic, as the measured U-values in the DEEP case study homes were much lower, i.e., better performing. This over prediction of room-in-roof heat losses may cause homes to be awarded lower EPC bands than they merit, and substantially overpredict the retrofit savings that may be achieved by (i.e., the prebound effect). The BREDEM and DSM predictions, which considered the measured U-values, provided predictions that were more realistic, and these were more similar to the coheating test measurements.

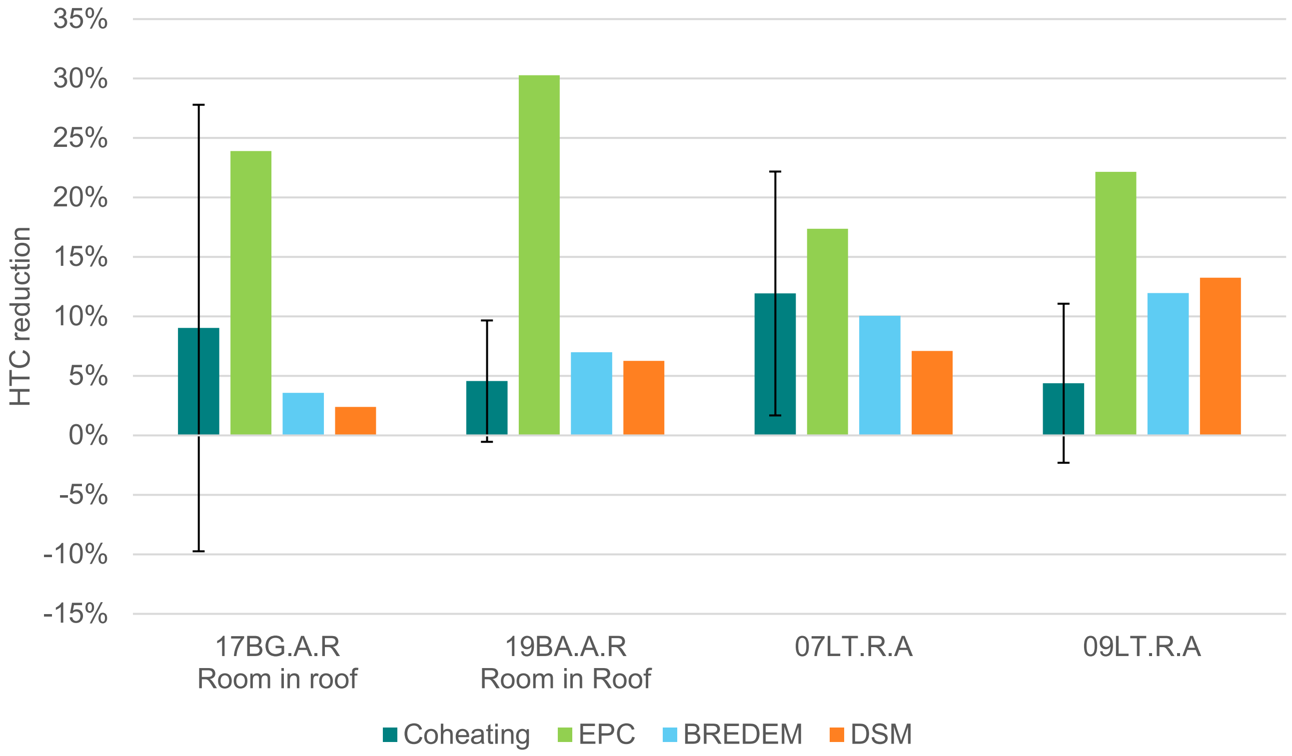


Figure 2-7 Reduction in HTC from room-in-roof retrofits

2.4 Suspended timber ground floor insulation

Millions of UK homes are built with suspended timber floors, including many solid brick homes. Suspended timber floors are traditionally considered locations of air leakage, though the impact of insulating suspended timber floors on whole house heat losses is less understood.

Eight suspended timber floor retrofits were undertaken on seven of the DEEP case study homes, most with either mineral wool or extruded polystyrene (XPS) foam affixed between floor joists, with target U-values of 0.22 W/(m²·K). The two exceptions were 08OL, in which the entire suspended floor structure was removed and replaced with 173mm of EPS insulation in a composite plastic cassette (target of 0.16 W/(m²·K)), and 00CS in which only one room had a suspended timber floor over which 10 mm aerogel product was laid (target of 0.45 W/(m²·K)).

The measured U-value changes are displayed in Figure 2-8. The shaded regions indicate the absolute reductions in U-value achieved, where larger savings are represented by darker areas. It is notable that the U-values prior to any retrofits showed considerable variability across the homes, with values between ~0.4 and ~1.1 W/(m²·K) recorded. It is relatively well understood that heat transfer through suspended timber floors is heterogenous, for instance affected by the presence of air bricks (sub-floor ventilation rates) and edge effects. The U-values reported here are average values derived from multiple spot heat flux density measurements, however, it cannot be known if the values derived were representative of the entire floor, and this could be behind some of the variation in U-values observed.

Neither mineral wool or XPS foam insulation had a significant performance gap. The composite plastic cassette appears to have fallen slightly short of its target, achieving a value of (0.27 ± 0.07) W/(m²·K) compared to its target of 0.16 W/(m²·K). However, this product had the largest associated uncertainty, indicating there may have been some issues with the test conditions. Likewise, the aerogel product did not quite reach its target of 0.45 W/(m²·K) though all products substantially improved the floor U-value. Note that the uncertainty on the U-value for the aerogel insulation was extremely small, as 15 heat flux plates were used to obtain an accurate assessment.

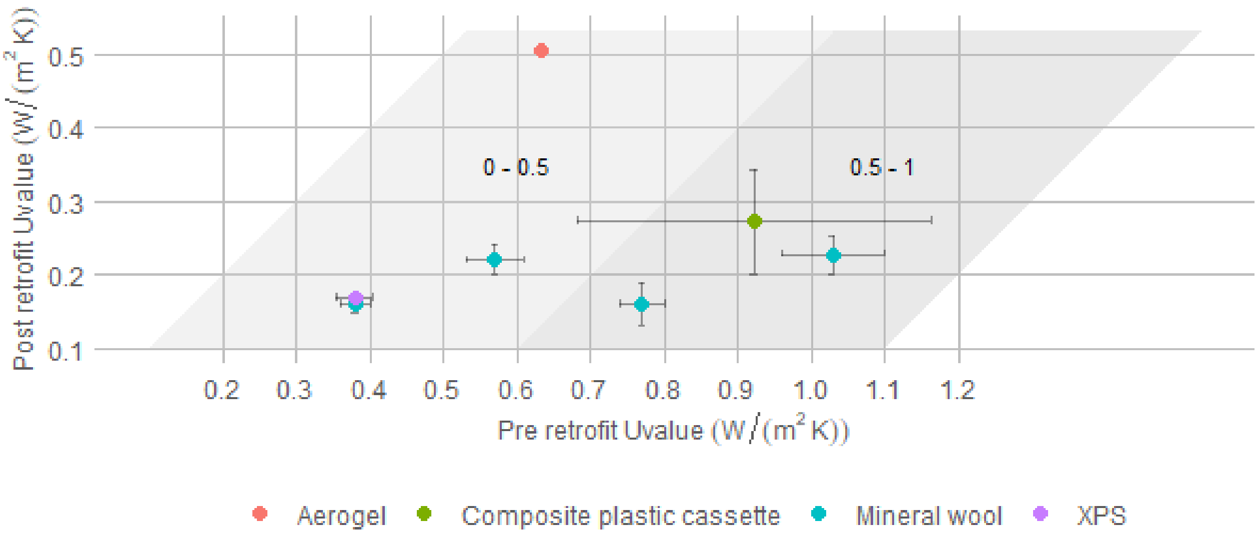


Figure 2-8 U-values of suspended floor retrofits pre- and post-retrofit. Colours represent the elements; shaded areas indicate the absolute reductions in U-value achieved, with larger savings represented by darker areas

Despite the substantial measured reductions in U-values, Figure 2-9 shows HTC reductions ranging between 0 and 11 %, and that statistically significant reductions in HTC were detected by the coheating tests (i.e., a reduction of zero lies within the test uncertainty for most homes) in only three homes. HTC reductions are not shown for 52NP or 54NP since draughtproofing was undertaken at the same time as the floor retrofit. A significant reduction was only seen in 08OL, despite not quite meeting its target U-value. This retrofit required the entire floor to be removed and replaced with an insulated composite floor. No retrofit which involved a traditional approach to installing insulation between the floor timbers achieved a significant (measurable) reduction in HTC. In 27BG and 56TR the homes experienced slightly worse air leakage after suspended timber ground floor retrofits (not directly linked to worsening floor air leakage, as other fabric element airtightness performance was observed to deteriorate), which may have offset the savings achieved by the floor insulation.

Since the U-value reductions were sizable, but the HTC reductions were not, this suggests more investigation is needed into measuring ground floor heat loss. One reason for the lack of measurable improvement may be that ground floors are relatively small heat loss areas in homes, thus, measuring a whole house improvement from ground floor retrofits is challenging. Furthermore, in 01BA, 56TR and 08OL the ground floor was part solid (usually the kitchen), which was not insulated as part of the retrofit, meaning the area insulated was smaller still. Despite no measurable reductions in HTC, the EPCs predicted HTC reductions between 4 and 9 % for the traditional ground floor retrofits. This suggests that EPCs may have overpredicted the savings achieved by suspended timber floor retrofits or that more investigation into ground floor heat flow during coheating test conditions is needed.

Suspended timber ground floor retrofits are one of the only retrofits which RdSAP assumes make an incidental improvement to the airtightness of homes, and so part of the reported saving in EPCs was linked to this. However, the airtightness of the homes, was not significantly improved by the suspended ground floor retrofits. The BREDEM and DSM predictions, which considered measured U-values and airtightness rather than the default RdSAP values, were more variable, suggesting a more complex relationship between suspended ground floor retrofits and whole house heat loss reductions. It should be noted that, although many retrofits did not result in detectable HTC reductions, improving ground floor U-values resulted in increased floor surface temperatures in the DEEP case studies, suggesting improved thermal comfort levels in the homes.

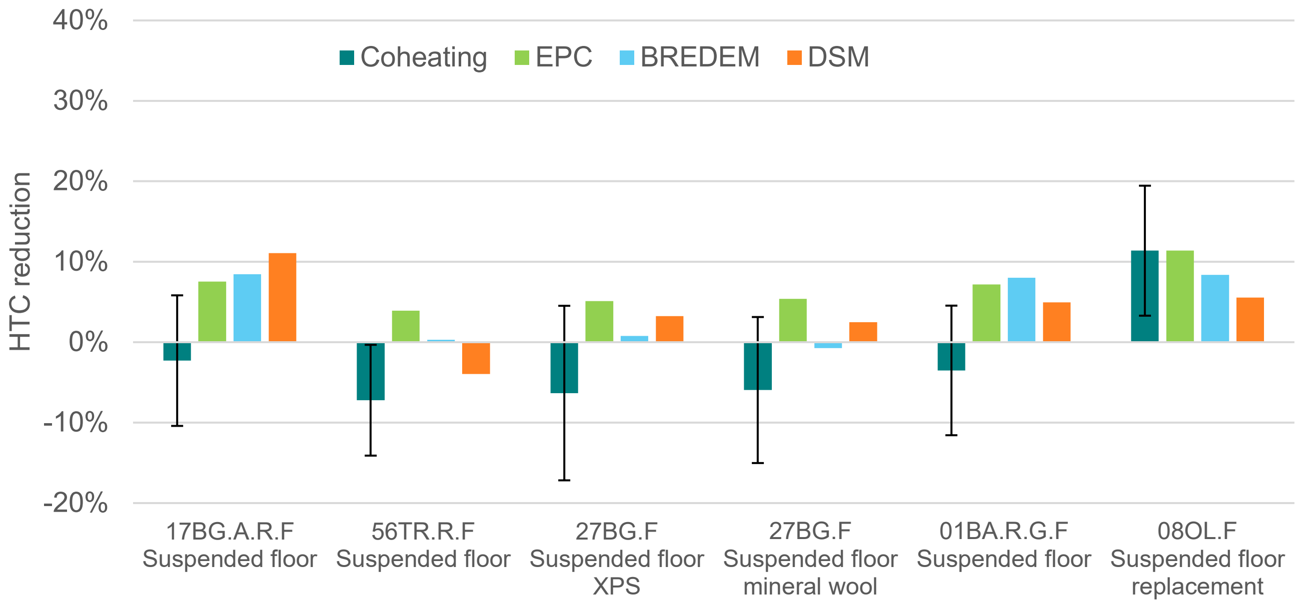


Figure 2-9 Reduction in HTC from suspended floor retrofits

2.5 Solid ground floor insulation

Retrofitting solid floors can involve digging up the concrete ground floor slab, laying insulation and repouring a screed over the top. This is extremely disruptive and not a common approach to retrofitting homes, so was not considered for this project. An alternative approach was adopted in DEEP and two solid floor retrofits took place in the case study homes. Both involved laying a thin aerogel product directly over the ground floor slab to act as an insulated flooring underlay. Two thicknesses were trialled, a 10 mm blanket in 00CS, and a 20 mm aerogel blanket bonded to a 3 mm plywood board in 04KG.

As shown in Figure 2-10, both retrofits outperformed the manufacturers' target U-values of 0.37 W/(m^2·K) and 0.32 W/(m^2·K), respectively, though a thicker blanket would be required to achieve the Part L limiting U-value of 0.18 W/(m^2·K). The uninsulated U-values differed substantially in the two base case homes. This is not surprising given their differing constructions; 00CS was a pre-1890 stone cottage in the North Yorkshire Moors, which had a worse U-value than 04KG, which was a 1960s concrete "no fines" home in urban North Yorkshire with a more conventional poured concrete ground floor slab. Both U-values were area weighted based on multiple spot heat flux density measurements to account for edge effects and other heterogeneous heat flow taking place across the floors.

The aerogel retrofit is a low disruption option for solid, or suspended, ground floors since it does not require removal of the existing slab, though currently, the high cost of aerogel offsets the cost savings of its less disruptive installation.

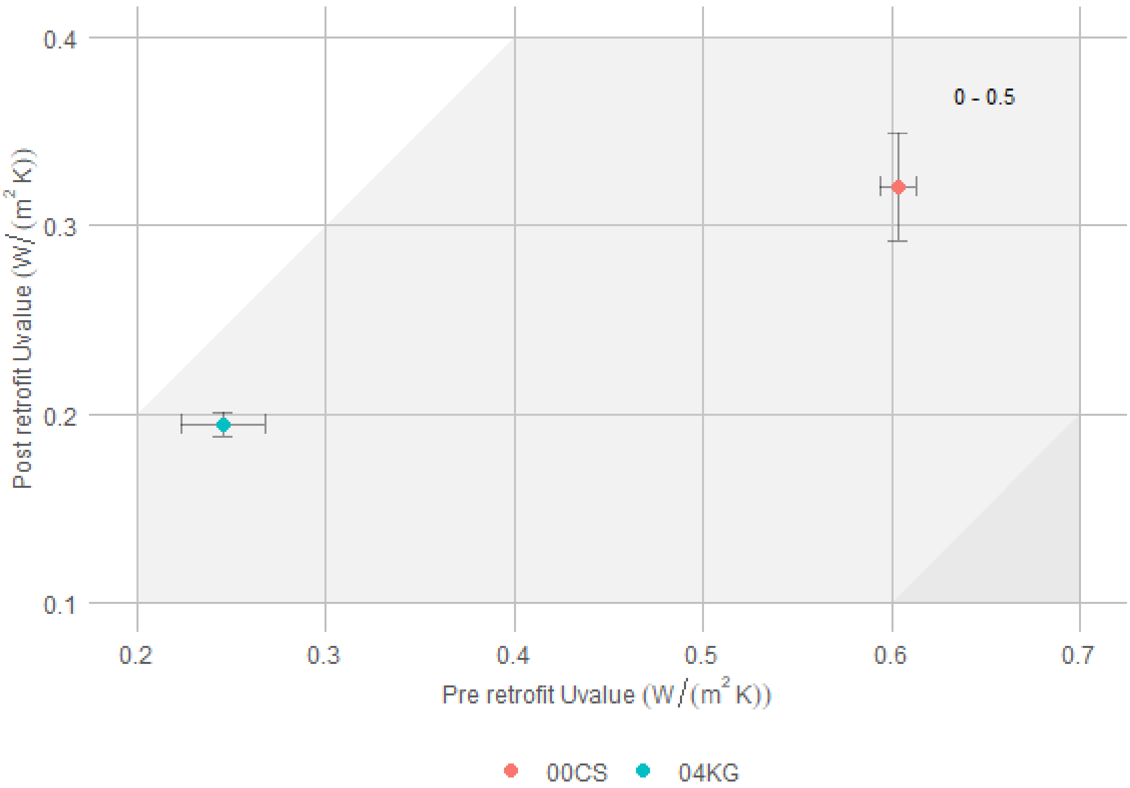


Figure 2-10 U-values of solid floor retrofits pre- and post-retrofit. Colours represent the elements; shaded areas indicate the absolute reduction in U-value achieved, with larger savings represented by darker areas

Figure 2-11 shows the retrofit reductions in HTC to be between 4 % and 20 %. In 00CS the insulation did not achieve a measurable reduction in HTC. Here the aerogel blanket was only 10 mm and, since the home was a very large, detached cottage with uninsulated stone solid walls, the floor represented only a small proportion of the whole house heat loss making any savings difficult to measure. In 04KG the insulation thickness was 20 mm and a reduction in HTC was measured. This was aided by the fact that the walls were already insulated with EWI, meaning the ground floor was a relatively larger proportion of the whole house heat loss and therefore it was more likely that any saving could be accurately measured. No EPC predictions are shown in Figure 2-11, since only insulation thicker than 50 mm is considered in RdSAP. Interestingly, BREDEM and DSM, which can consider insulation of any thickness, did not predict meaningful HTC reductions even though the insulation considerably improved measured U-values.

One reason for this may be that the models assume insulation only reduces plane-element heat losses. However, pre-retrofit thermography in 04KG suggests that there was a thermal bridge at the ground floor to external wall junction, where the EWI did not extended below the damp proof course (DPC). A heat flux plate (HFP) placed on floor at this junction measured heat flux equivalent to (2.13 ± 0.32) W/(m^2·K) before the ground floor retrofit. Post-retrofit this reduced to (0.36 ± 0.02) W/(m^2·K) indicating a large reduction in this thermal bridge, which contributed to the HTC reduction measured by the coheating test. It is possible that the reduction in thermal bridging was partly responsible for the significant reduction in measured HTC. Thermal bridging calculations are required to confirm the magnitude of this reduction for inclusion in models, since the RdSAP thermal bridging heat loss is assumed in the models, which, as previously mentioned, are fixed and identical pre- and post-retrofit.

As with the suspended floor insulation, higher ground floor surface temperatures were measured post-retrofit, indicating that thermal comfort may be improved and condensation risks may be reduced with this approach to solid floor retrofits, especially in homes which have EWI which does not extend below the DPC.

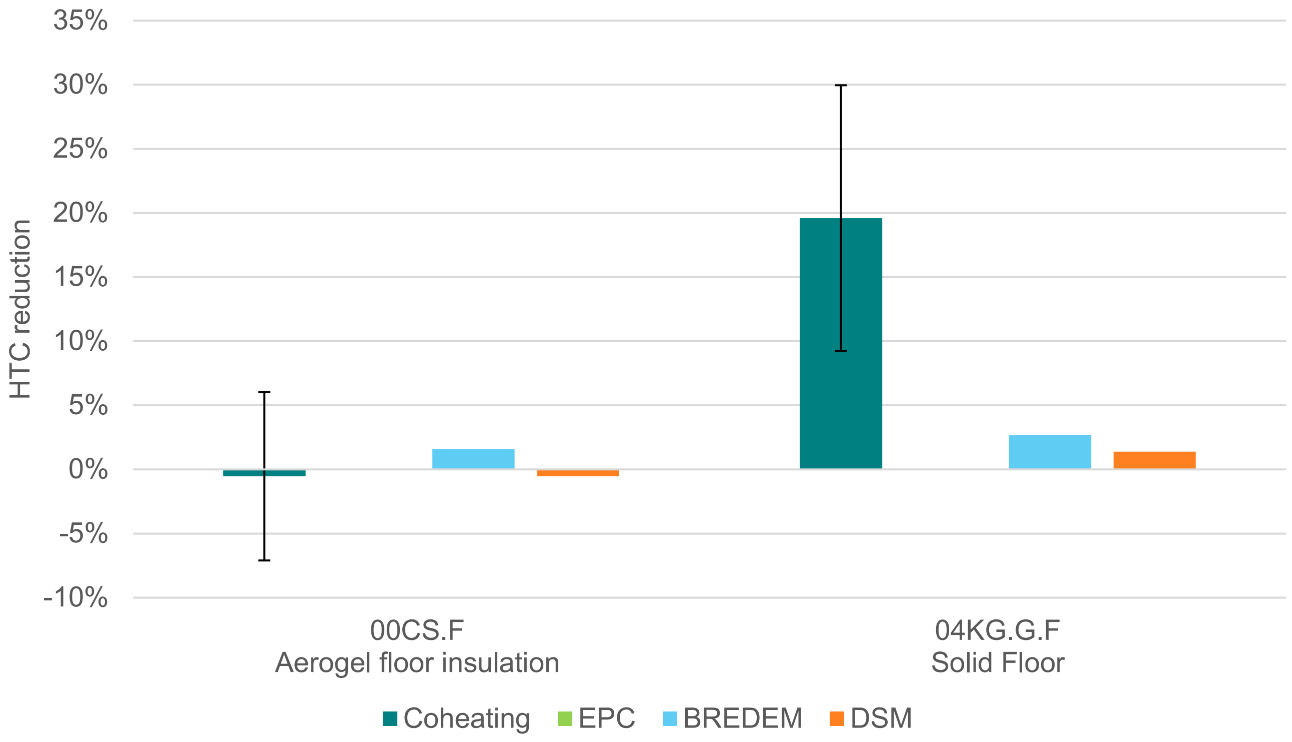


Figure 2-11 Reduction in HTC from solid floor retrofits

2.6 Fenestration replacements

Double glazing and, to a lesser extent, insulated external doors have been installed in UK homes for decades. Early double-glazing units were not built to the same performance standards as newer double glazing and seals around units can fail after several decades in situ. The benefit of upgrading existing double glazing and external doors is not well understood. Although triple glazed windows are commonly installed in high performance homes, they are not common retrofits, and so were not included in the DEEP case studies. Double glazing and external doors were replaced in three DEEP case study homes, 01BA and 04KG (as separate piecemeal retrofits) and in 55AD (as part of a wider suite of multiple retrofit measures). Additionally, secondary glazing is a relatively common measure installed in heritage buildings, and the opportunity to test the efficacy of secondary glazing arose in case study 00CS, which had a detachable secondary glazing system fitted to the inside of its original single glazing. As there was extra time in the test programme for 00CS, the secondary glazing was temporarily removed to study its impact, i.e., the benefit of the secondary glazing was assessed by how much the HTC dropped when the secondary glazing was removed.

Whole window U-values must include both the frame and the glazing. Additionally, glazed external door U-values need to consider all the door elements. It is only practical, however, to measure the heat loss through the window centre pane in field trials. The pre- and post-retrofit centre pane U-values for windows and the glazing in external doors for the DEEP case study homes are shown in Figure 2-12. The shaded regions indicate absolute reductions in U-value achieved, with larger savings represented by darker areas. Note that the uncertainties in these U-value measurements tend to be much larger than for other elements. This is due to the more variable temperatures typically experienced by the glass or door which affects the stability of heat flux density measurements.

Upgrading the existing double glazing in windows and external doors showed a modest improvement in U-values. Benefits were also found to both airtightness and overheating risk, as described in sections 3.4 and 3.9, respectively. Interestingly, the results for 00CS show that secondary glazing achieved centre pane U-values equivalent to double glazing. In properties where windows cannot be changed (e.g., listed buildings), this offers a promising path by which heat loss might be reduced considerably, especially as without the secondary glazing the single glazed window U-values were exceptionally poor.

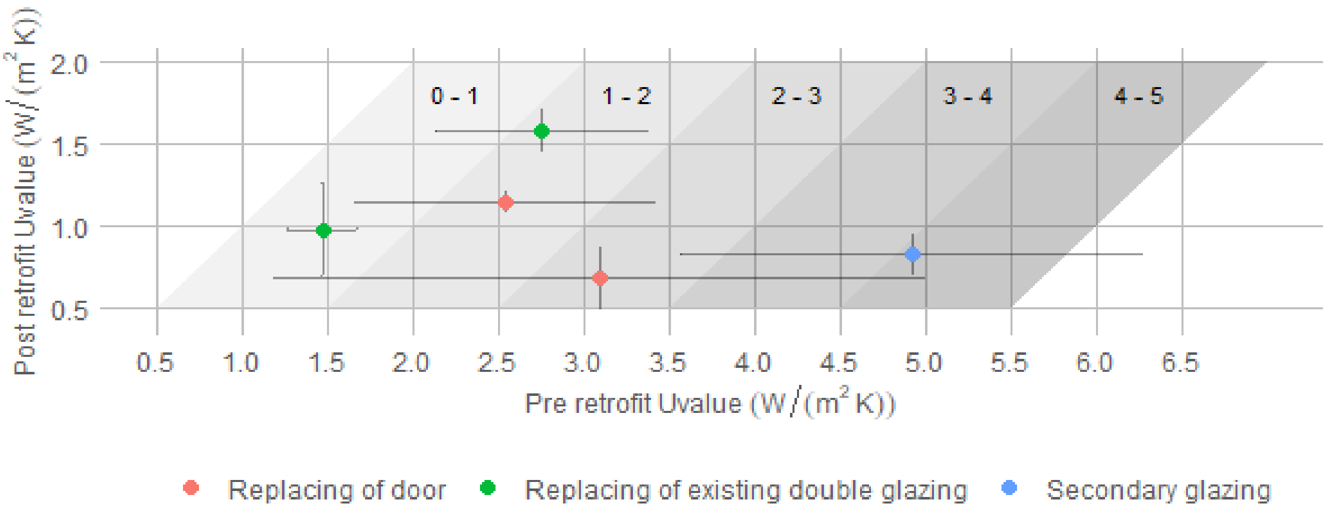


Figure 2-12 U-values of fenestration retrofits pre- and post-retrofit. Colours represent the elements (pre-retrofit secondary glazing = single glazing); shaded areas indicate the absolute reductions in U-value achieved, with larger savings represented by darker areas

The reductions in HTC achieved by upgrading the glazing and external doors are shown in Figure 2-13 to be between 0 and 5 % for the three homes (00CS, 01BA and 04KG) that underwent piecemeal fenestration retrofits, and therefore have before and after HTC measurements. The benefit of the secondary glazing is shown as a negative change, i.e., how much worse the HTC got when the secondary glazing was removed. The benefit of the new windows in 55AD cannot be shown as this was part of multiple retrofits installed together.

No significant change in HTC was detectable from the coheating tests for any of the glazing upgrades (i.e., a reduction of zero lies within the test uncertainty) and there are several possible reasons for this. In the case of 00CS, it may be because the windows did not constitute a large heat loss area. 00CS is a rural detached pre-1890 stone cottage which was built with small windows on only the North and South elevations, as is traditional for this type of home. It therefore had a very low window to wall area ratio and, furthermore, the original timber external doors were not upgraded.

For 01BA and 04KG the existing windows were already double glazed, thus the scope for improvement was reduced and this made it difficult to measure the improvement with statistical significance, though the U-value improvement indicates the upgrades to the windows and doors did reduce heat losses. The models also predicted an improvement; however the size of reduction was determined by the condition and U-values of the incumbent windows, which was not usually possible to determine pre-retrofit as the manufacturers' details were not often available. The installation of the new windows, doors and secondary glazing also coincided with small reductions in air leakage, which may be expected as seals may have been worn or failed, and because the secondary glazing offered a second air barrier. However, the savings were not significant for the installation of new double-glazed windows. This may be because the openings were severely damaged, requiring costly additional plastering work to be undertaken to ensure that airtightness was achieved.

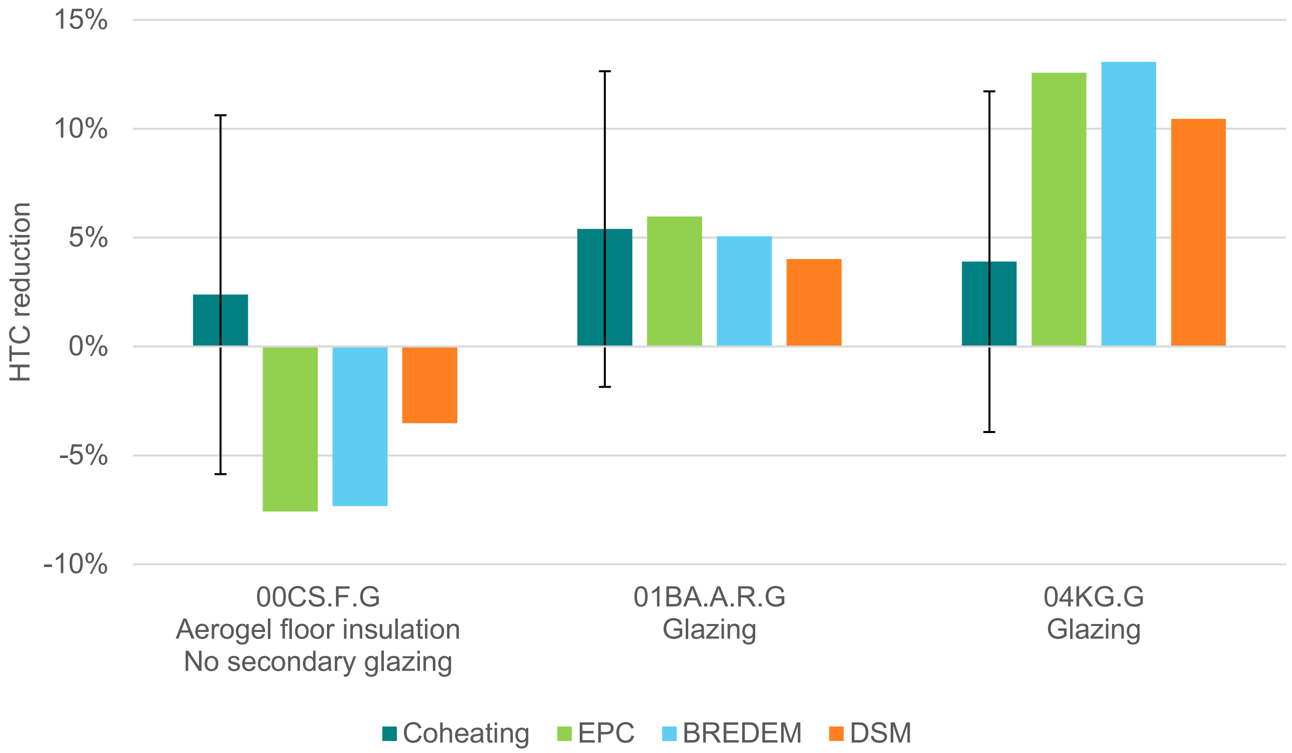


Figure 2-13 - Reduction in HTC from fenestration retrofits

2.7 Solid wall insulation

Insulating solid walls is one of the most effective ways to reduce heat losses in solid walled homes, but it is less commonplace, since it is complex and costly to install. In the DEEP case studies, five homes were given new SWI retrofits. Three of these used EWI, one used IWI, and one home used a hybrid of EWI and IWI. The effect these products had on U-values is shown in Figure 2-14 with shaded regions indicating the absolute reductions in U-value achieved (larger savings are represented by darker areas). All the retrofits achieved a significant improvement in U-values, although most did not reach their intended performance. Additionally, some measured pre-retrofit wall U-values indicated the presence of existing IWI at the baseline stage, specifically polystyrene backed plasterboard. This was previously installed in several of the DEEP case studies, indicating that many homes already had some IWI, (which limits the potential savings from SWI). However, it was noted that the insulated plasterboard used had often been installed with an unventilated cavity (usually due to a dot and dab installation method), which has been found to cause interstitial condensation risks. Thus, although the potential energy reductions from the new SWI retrofit were smaller in these homes, it was an opportunity to remove this potential risk from the homes.

EWI retrofits outperformed IWI for heat loss reduction, because IWI tended to be thinner to reduce risks of interstitial condensation. Installing IWI reduces the temperature of the bricks behind the insulation and so manufacturers design IWI systems to have a higher U-value (0.56 $W/(m^2 \cdot K)$) than the Building Regulations target of 0.3 $W/(m^2 \cdot K)$, i.e., they trade off energy savings for a lower risk design. Minimising risk is a driver of the whole house approach to retrofit; thus, whole house approach IWI retrofits may not achieve as large HTC reductions as piecemeal IWI retrofits. Conversely the EWI systems, which do not have similar moisture accumulation risk (since they keep the bricks warm), can target lower U-values ranging between 0.27 and 0.31 $W/(m^2 \cdot K)$.

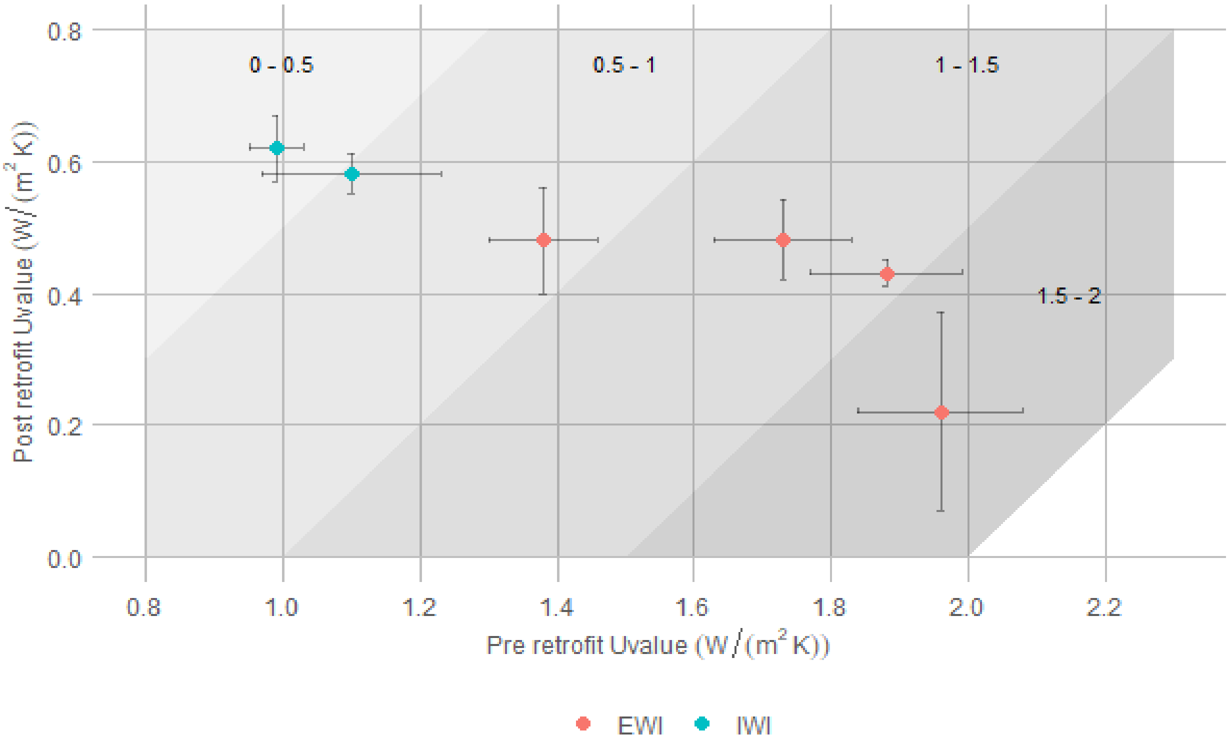


Figure 2-14 U-values of wall retrofits pre- and post-retrofit. Colours represent the elements; shaded areas indicate the absolute reductions in U-value achieved, with larger savings represented by darker areas

The reductions in HTC achieved by SWI are shown in Figure 2-15 and range between 19 % and 55 %. While all five retrofits are shown, the HTC improvements for 55AD and 57AD are not shown as EWI was installed alongside multiple retrofits at the same time. Uniquely for the DEEP case studies, every SWI retrofit achieved significant reductions in HTC. The IWI and hybrid homes had lower savings than the EWI homes. This was expected, because, as previously discussed, IWI targets higher U-values, but also because of the law of diminishing returns, since both 17BG and 56TR already had some thin IWI installed pre-retrofit (which was removed during the IWI retrofit to remove interstitial condensation risks). Additionally, 17BG had a smaller heat loss area insulated, as only two external walls were insulated compared to the three for the other homes.

Interestingly, there was relatively good agreement between the measured and predicted HTC reductions, even between models when default inputs for airtightness, U-values and thermal bridging heat loss were included. It is notable that EPCs tended to over predict the savings for IWI since they did not account for any pre-existing IWI installed in the homes thinner than 50 mm. However, the EPC tended to slightly underpredict the savings achieved by the EWI retrofits, perhaps because the uninsulated walls in these homes had starting U-values higher than the default 1.7 W/(m^2·K) assumed in the EPC.

The reason for the generally better agreement in reduction in HTC between measurements and models, is that external walls form the dominant heat loss element in these homes and the relatively high level of certainty around insulated wall U-values means that whole house heat loss predictions in models are more reliable.

It is noteworthy that, compared to other retrofits taking place in the homes, SWI alone achieved greater savings than the other retrofits combined. It was also the only single retrofit measure which could increase the EPC to band C on its own and achieve the SHDF target space heating demand. It also successfully increased surface temperatures to improve comfort and reduce surface condensation risks and was the most effective fabric measure to reduce overheating risks. Thus, SWI was the most impactful retrofit for solid walled homes, making them healthier (reducing condensation and overheating risks) and reducing heat loss.

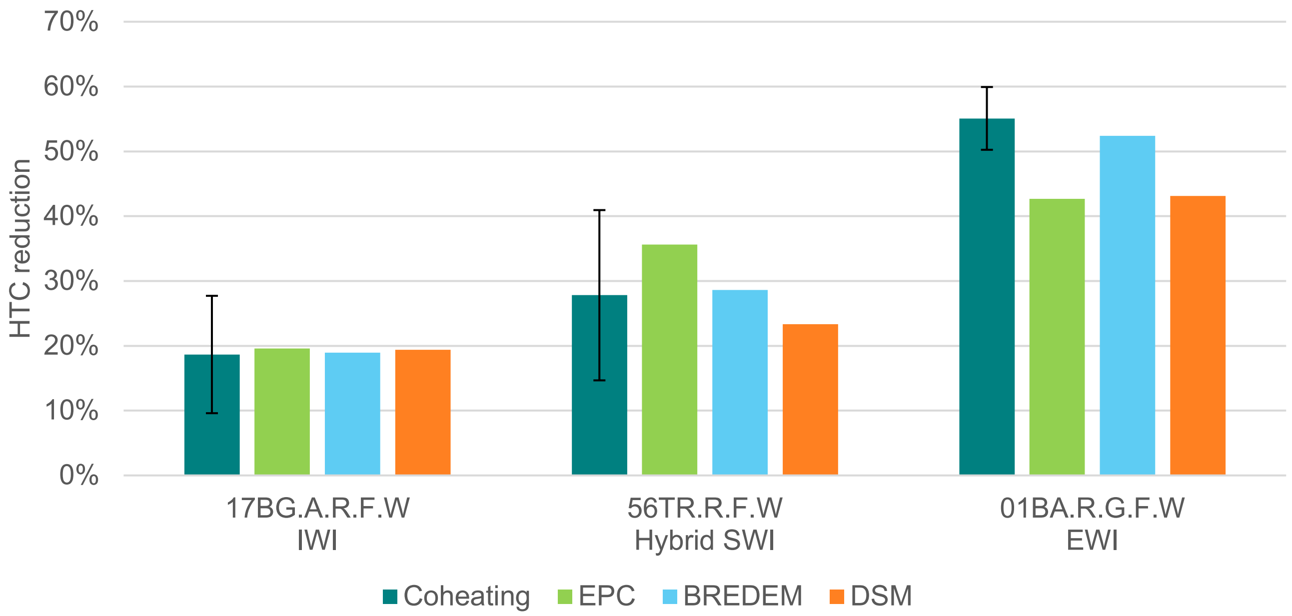


Figure 2-15 Reduction in HTC from wall insulation retrofits

2.8 Multiple measure retrofits

In six homes the benefits of multiple retrofits were only measured via single aggregate pre- and post-retrofit coheating tests. The cumulative benefits of these multiple measure retrofits are shown in Figure 2-16. The details of these retrofits can be seen in the relevant DEEP case study reports. In 54NP and 52NP suspended timber ground floor insulation was installed in combination with draughtproofing and the installation of new carpets. In 57AD EWI, new loft insulation and suspended timber ground floor insulation was installed via a piecemeal approach. 55AD was identical to 57AD but also had bay roof insulation, new windows and external doors. In 07LT and 09LT room-in-roof and draughtproofing was undertaken.

In all but one case these multiple retrofits achieved measurable reductions in HTC (i.e., the error bars did not cross the zero-saving line). The retrofits that incorporated EWI were the greatest. U-value measurements suggest that the solid walls represented 77 % and 70 % of total HTC reductions for 55AD and 57AD, respectively. This also suggests that combining less costly retrofits can collectively reduce heat loss as much as SWI in some instances.

It is therefore possible to measure the combined impact of multiple retrofits, even if the reductions in HTC achieved by individual retrofits were not always measurable. However, it is not possible to disaggregate the specific benefits of each retrofit without additional performance tests (heat flux measurements and air tightness testing).

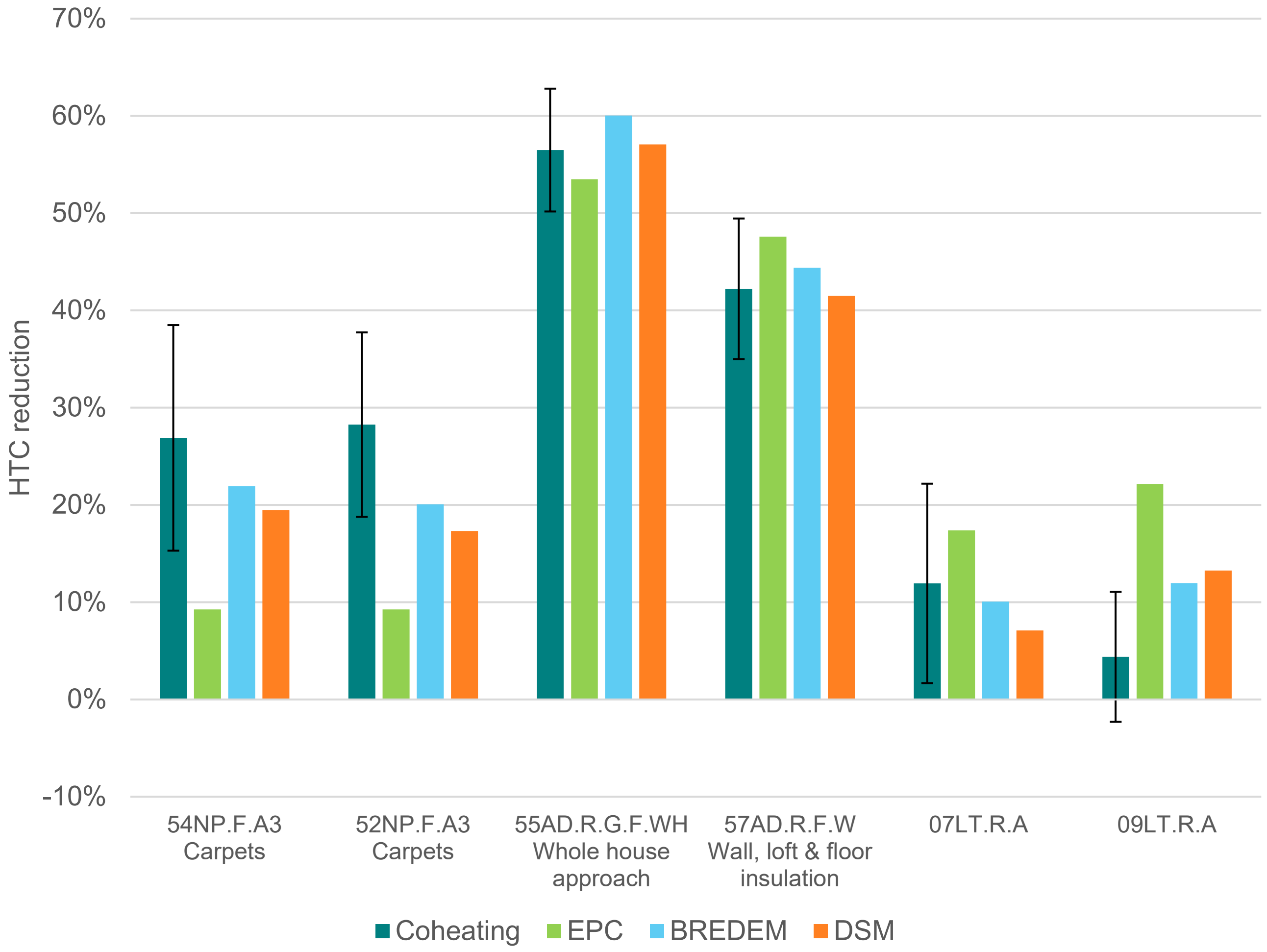


Figure 2-16 HTC reduction achieved by multiple measure retrofits

3 Modelling the impact of retrofits

This section presents the lessons learned from the case studies for building energy models. The three energy models used in DEEP to predict the energy performance are:

1) RdSAP, which is used to create EPCs for existing buildings, and in which the ability to change inputs is limited.

2) BREDEM, the mathematical engine behind RdSAP, which has flexibility to alter all inputs. This is described as ‘steady-state’ as it uses a daily heat balance calculation for a typical day of each month and extrapolates the results to provide an estimate of annual energy consumption.

3) DesignBuilder, a dynamic simulation model (DSM), which provides a dynamic alternative to BREDEM. This is described as ‘dynamic’ as it calculates the heat balance at hourly time steps to provide an estimate of annual energy consumption.

Each model was used to predict the HTC and annual energy consumption in the homes when their default input assumptions were systematically updated to include measured or calculated data. A detailed description of the modelling methods undertaken is presented in the DEEP Methods 2.01 report. Table 3-1 briefly describes the approach taken to understand how the predictions changed as the default inputs were overridden.

Table 3-1 Modelling Stages

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

The following sub-sections compare the predicted performances of the homes and the retrofits, for each of the three models and five calibration stages, as well as comparing how their predictions compare to measured values. The appropriateness of the default input assumptions of airtightness, U-values and thermal bridging that are used in EPC calculations is evaluated by comparing the defaults used in RdSAP to measured and calculated input values. Finally, general observations on the use of steady-state and dynamic energy models when predicting annual energy use in homes is discussed.

[2] Provided by Appendix S RdSAP 2012 version 9.94.
[3] Provided by Appendix K RdSAP 2012 version 9.94.
[4] Derived from blower door test.
[5] Derived from BRE calculator.
[6] Derived from HFP measurements.
[7] TRISCO bridging simulations (note that thermal bridges cannot be measured in situ and must be simulated).

3.1 Modelled versus measured HTC

Figure 3-1 plots all the HTC values measured in the case study homes, pre- and post-retrofit, against the respective predictions by RdSAP, BREDEM and DSM. RdSAP defaults represent the HTC predicted by the EPC using all default input assumptions. BREDEM and DSM show the HTC predictions after default input assumptions are replaced with measured infiltration rates, calculated U-values, measured U-values, and calculated thermal bridging heat losses. Generally, RdSAP and BREDEM predict higher HTCs than were measured, and EPCs using default inputs overpredict heat loss from homes the most (42 % on average across the homes). This suggests the *prebound effect* is occurring, i.e., the predicted retrofit savings are inflated. DSM is not as affected by this and can even slightly underpredict savings. Since RdSAP with default inputs predicts the largest HTCs, the prebound effect is greatest for EPCs.

Although replacing default model inputs with calculated or measured data tends to make predictions more in-line with measured values, the relationship it is not straightforward, and replacing defaults does not always make modelled and measured HTCs more closely aligned. For instance, a home may have higher infiltration heat losses than defaults, cancelled out by lower fabric heat losses than defaults. Updating just one of the defaults therefore could cause greater disagreement. This is exacerbated in homes with uninsulated solid walls, since heat loss from these walls can vary substantially depending on the wall's material properties, construction make up and the presence of dry lining or thin IWI.

Variation between modelled and measured performance is smaller in homes with lower HTC, in part because heat loss via insulated fabric has less uncertainty and so predictions of the performance may be more reliable, even when using default inputs. Thus, although uncertainty cannot be eliminated, replacing defaults with measured data is most useful in poorly performing homes, i.e., pre-retrofit.

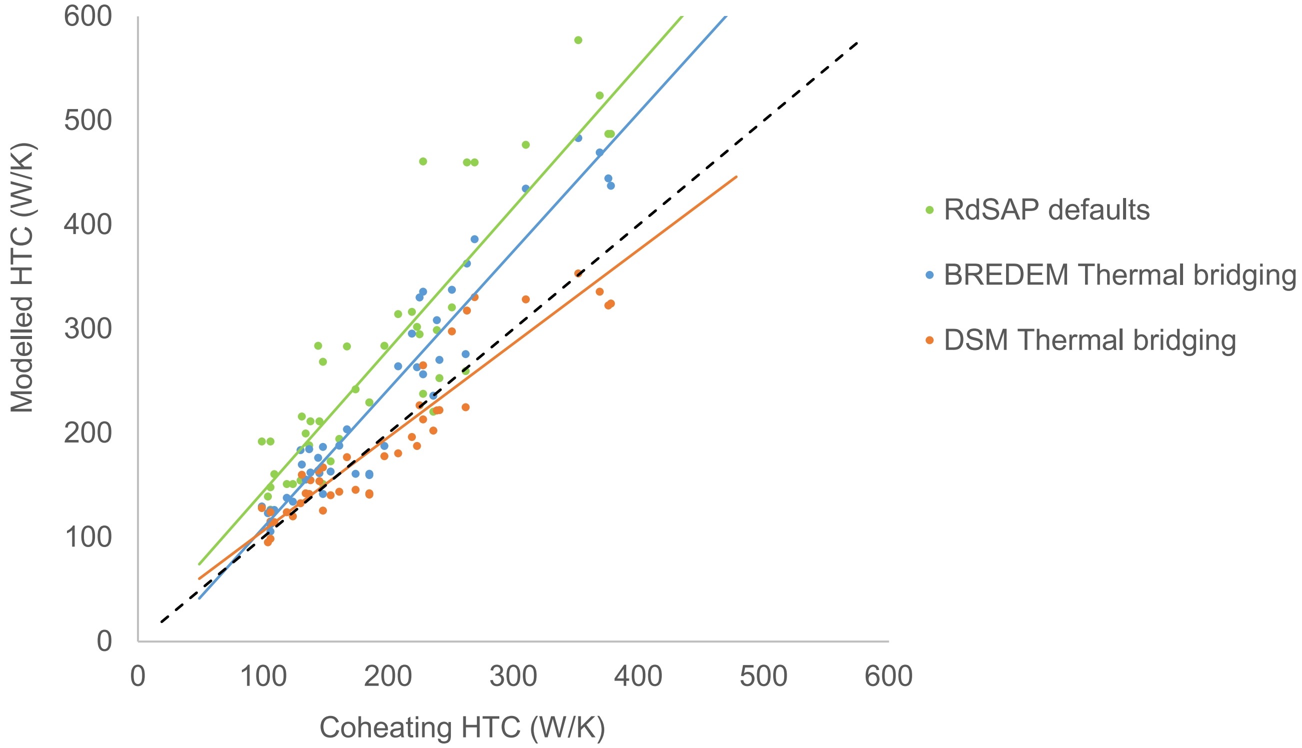


Figure 3-1 Measured vs. modelled HTC (black dashed line indicates 1:1 relationship)

3.2 Modelled and measured retrofit success

The success of a retrofit can be measured by the reduction in heat loss from homes. To allow comparisons of retrofit performance across dwellings of different sizes, the reduction in HTC can be divided by floor area to provide the heat loss parameter (HLP). Figure 3-2 compares the reduction in HLP predicted by RdSAP, BREDEM and DSM, which varies between 0 and 2.4 W/K/m², compared to the measured reduction in HLP, which varies between 0.3 and 1.9 W/K/m². Only results where a statistically significant reduction in HLP was measured by the coheating test are shown. There is a general trend that the models and the coheating tests agree on which retrofits achieve greater savings, however there is seldom good agreement for specific retrofits.

All three models can overpredict or underpredict the savings that a retrofit achieves, although the predicted reductions are greatest, and savings are highest when the default input assumptions are used. However, updating the defaults does not always improve the predictions. For instance, overpredictions in air leakage may be offset by underpredictions in measured U-values, so correcting just one default input can worsen the prediction.

Generally, RdSAP and BREDEM tend to predict greater savings than measured, since they overpredict the uninsulated baseline energy use (i.e., above the dashed line). This confirms EPCs are likely to have the strongest prebound effect, which has implications for retrofit policy evaluations, finance models and payback calculations which rely on savings predicted by energy models. Conversely, DSM usually (but not always) predicts savings more in line with those measured or lower (i.e., below the dashed line).

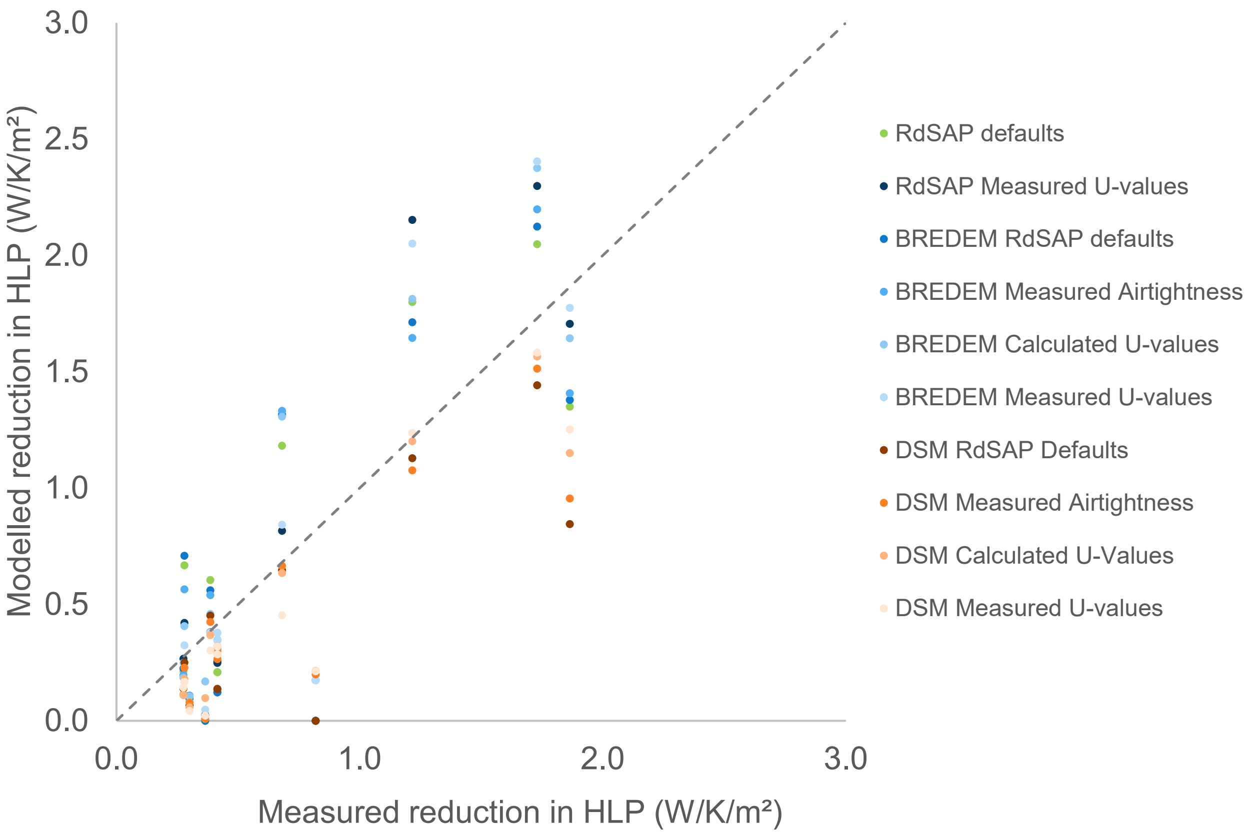


Figure 3-2 Reduction in measured vs. modelled HLP (black dashed line indicates 1:1 relationship)

3.3 Airtightness input assumptions

In Figure 3-3, the infiltration rates measured by the blower door test pre- and post-retrofit are compared to the default airtightness assumptions in RdSAP. The method and results of the airtightness tests can be found in the DEEP Report 2.01, Case Study Methods, and the individual case study reports (2.02 to 2.12). The results show that the air leakage in the solid walled homes was higher pre-retrofit than post-retrofit in both the default values and measured data. This is expected, since the retrofits often included specific airtightness measures, the installation of new windows and doors (which have better seals) and the installation of insulation which can obstruct air leakage pathways. However, the average improvement achieved according to the blower door tests (2.4 $m^3/(h \cdot m^2)$ @ 50Pa) is greater than that assumed in RdSAP (1.3 $m^3/(h \cdot m^2)$ @ 50pa), since RdSAP defaults only account for air leakage reductions achieved by draught stripping and suspended ground floor insulation.

In general, the RdSAP default assumptions for the homes pre- and post-retrofit were higher than those measured by the blower door test. This indicates that EPCs generally assume solid walled homes are leakier than they are in practice, which suggests an overestimation in infiltration heat losses. Additionally, there is larger range of measured infiltration rates than found in the RdSAP default assumptions, i.e., there are a minority of solid walled homes with extremely high air leakage rates, as well as some that are much more airtight than the defaults assume. This means updating defaults may either increase or reduce ventilation heat losses depending on the condition of the original home.

Most of the pre-retrofit solid walled homes had measured air permeability values within the same range as those assumed in RdSAP, between 11 and 18 $m^3/(h \cdot m^2)$ @ 50pa. However, post-retrofit, most solid walled homes had lower measured air permeability than the RdSAP defaults. This suggests incorporating measured ventilation rates into EPCs for pre-retrofit homes may not have a significant impact (unless extremely high or low air leakage is suspected). However, post-retrofit it is likely that including measured airtightness values may result in lower heat loss and improved EPCs. Consequently, by not factoring in changes in airtightness linked to retrofits, EPC predictions underestimate the reductions achieved by retrofits on air tightness. However, since predictions around retrofit savings made by EPCs tend to overestimate fabric heat loss benefits, the impact of underestimating airtightness improvements may be cancelled out.

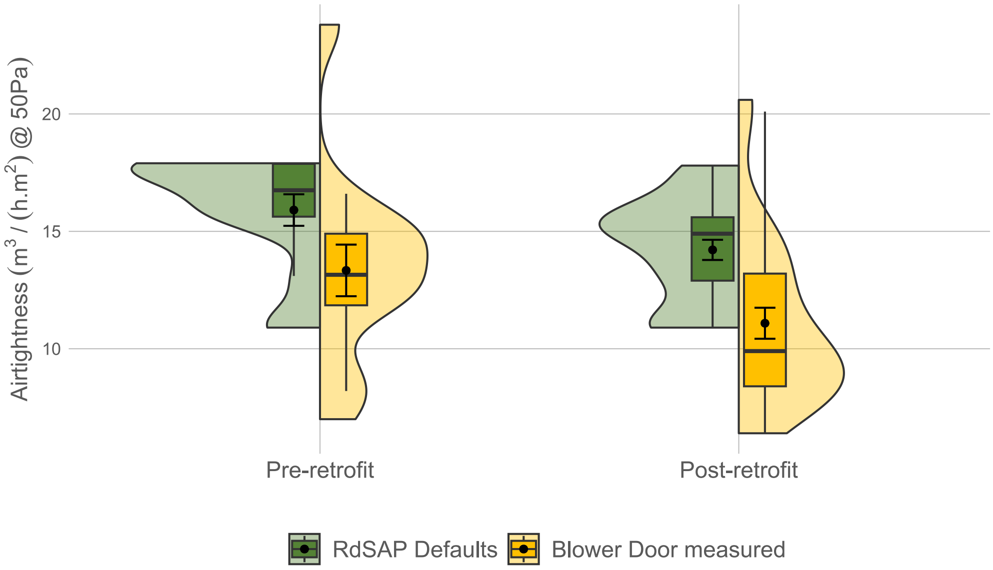


Figure 3-3 Violin plot of airtightness of homes pre- and post-retrofit comparing RdSAP default assumptions and blower door measurements

3.4 Incidental airtightness improvements following retrofit

Air leakage assumptions in RdSAP, used to produce EPCs for existing buildings, are based on default values linked to the home's age and characteristics. When suspended timber ground floor insulation or draught stripping is installed, the default infiltration rate reduces to account for the beneficial impact of these measures. Other fabric improvements such as wall insulation or loft insulation, are not considered by RdSAP to improve airtightness in homes. However, the results from the DEEP cases studies suggest that retrofits other than draught stripping and suspended timber ground floor insulation do affect air leakage from homes.

Figure 3-4 describes how the retrofits installed in the DEEP homes in some instances reduced, and in other cases increased, the air permeability of the homes. The impact ranged from a reduction of 6.0 $m^3/(h \cdot m^2)$ @ 50Pa to an increase (i.e., worse infiltration) of around 1.5 $m^3/(h \cdot m^2)$ @ 50Pa. Generally, the retrofits are shown to improve airtightness (displayed as a negative change), but the rate of improvement varied depending on the retrofit being undertaken and the original condition of the home.

Airtightness-specific retrofits (i.e., sealing around penetrations, fenestrations, floors, cracks, and gaps, and installing carpets) resulted in the largest reductions. In some homes, activities undertaken to ensure a whole house approach to retrofit also improved airtightness, as these often included fabric repairs and internal replastering which represent the primary air barrier in homes. Some savings were also measured following the installation of new double glazing and external doors, insulating rooms-in-roof, insulating lofts, as well as internal and external SWI.

Ground floor insulation sometimes reduced and sometimes increased airtightness, even where they had the same specifications. This may be because the air tightness membranes were inconsistently applied, but also because the extent of air leakage through the ground floor and replacement floor coverings was variable. Although air leakage in homes is complex and unpredictable, these findings provide evidence to suggest retrofits can reduce infiltration rates and this could be accounted for in RdSAP for more retrofits than just draughtproofing and suspended timber ground floor retrofits. More research is needed to understand what the appropriate values for various retrofits would be.

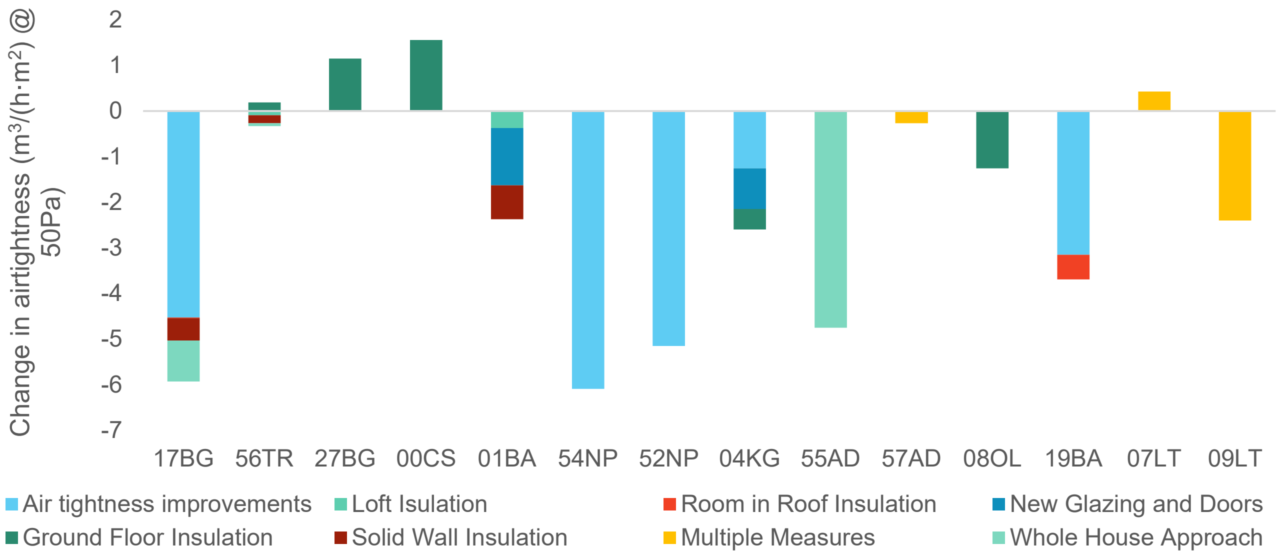


Figure 3-4 Cumulative change in airtightness achieved in each DEEP case study home by each retrofit (a negative value is an improvement in airtightness)

3.5 U-value input assumptions

Default U-values are applied in RdSAP when producing EPCs based on a home's construction and age band. However, these default ranges are too narrow to reflect the variety of fabric element U-values in solid walled UK homes, or those measured in the DEEP case studies. Figure 3-5 compares RdSAP default U-values, calculated U-values (based on site observations) and measured U-values derived from heat flux density measurements for the major fabric elements in the case study homes, pre- and post-retrofit. As can be seen, the pre-retrofit measured values are significantly different to the EPC default and calculated U-values for solid walls and sloping ceilings found in the rooms-in-roof. The average difference between the RdSAP U-values and measured U-values for all the elements in the case study homes is (0.49 ± 0.09) W/(m2·K) for uninsulated elements, but (-0.03 ± 0.05) W/(m2·K) for insulated elements. This is likely due to greater certainty around the thermal performance of insulation. Broadly, default U-values tend to overestimate heat loss in uninsulated fabric which contributes to the prebound effect, where predicted retrofit savings are overestimated.

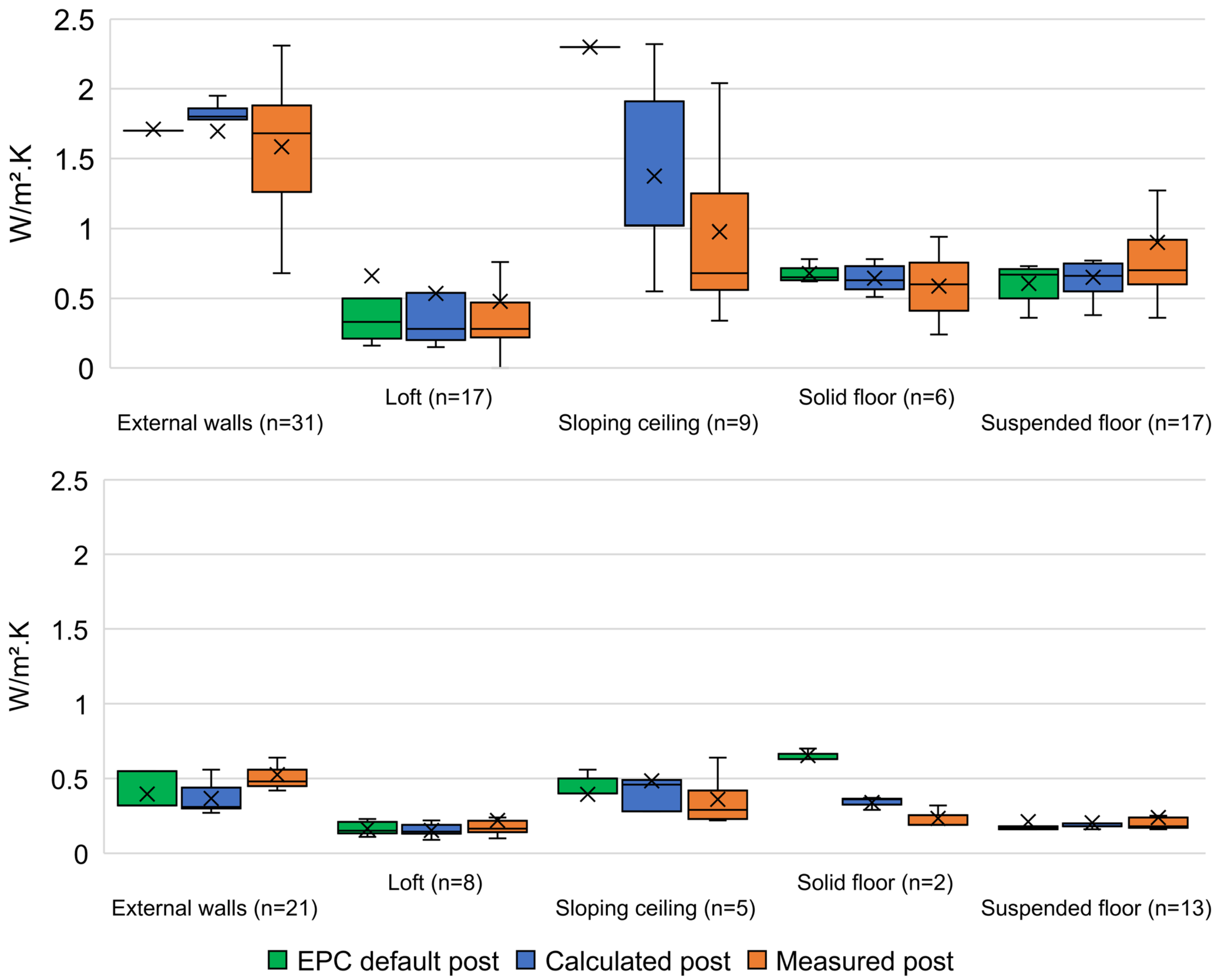


Figure 3-5 U-values in case study homes pre- (top) and post-retrofit (bottom), where n= number of elements (e.g., there was more than 1 external wall type per dwelling)

3.6 Y-values and thermal bridging heat loss inputs

Y-values describe the thermal bridging heat loss of a property, normalised by the building heat loss area. In EPCs the RdSAP default y-value of 0.15 W/(m^2·K) is assumed for all homes. However, insulating homes impacts the extent of thermal bridging taking place. To investigate the appropriateness of this default y-value, thermal modelling was undertaken of all the junctions in the DEEP case study homes in which SWI was installed: 17BG, 01BA, 56TR and 55AD. The detailed modelling approach is described in the case study reports.

Figure 3-6 shows that the RdSAP default y-values, are generally overestimated in EPCs. The calculated y-values range from 0.04 to 0.24 W/(m^2·K), equivalent to a variation of between 6 and 50 W/K. Y-values changed after each retrofit, though this is not accounted for in the defaults. In DSM, an alternative approach to calculating the bridging heat loss is taken; multiplying the Ψ-value listed in Appendix K of the SAP 2012 manual [6] by the lengths of junctions. The y-values using Appendix K values are also compared in Figure 3-6. The findings highlight that, the RdSAP default y-value of 0.15 (dashed black line) overestimates heat loss for many solid walled homes (it more closely resembles Appendix K bridging values for new build homes).

Generally, y-values increase as insulation is installed in homes via piecemeal approaches, since heat loss between adjacent elements becomes more varied. For example, the EWI retrofit in 01BA caused a discontinuity and thermal bridge at the eaves. However, thermal bridging heat loss can be reduced following retrofits which resolve design or installation problems. For instance, a discontinuity in loft insulation was responsible for over half the bridging in home 56TR, which the loft retrofit resolved. Furthermore, when retrofits follow a whole house approach, the y-value can be reduced, where thermal bridges or discontinuities in the insulation that occurred during the piecemeal retrofits are addressed. In the DEEP case studies, removing the discontinuity between the SWI and the loft insulation resulted in heat loss reductions between 2 and 11 W/K, though removing other discontinuities around window and wall junctions or wall and floor junctions in other case studies was less impactful. The results suggest that having multiple default y-values to represent solid walled homes, pre- and post-insulation of various fabric elements, could improve the accuracy of EPCs to some extent, though more investigation is needed to understand what updated y-values should be.

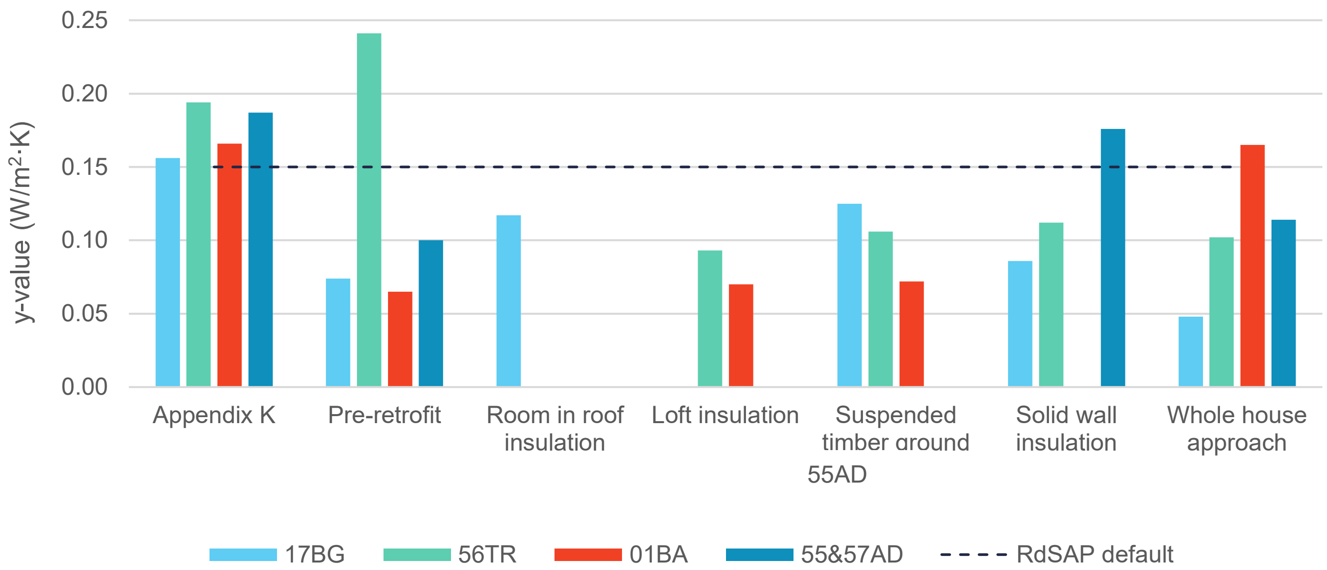


Figure 3-6 Modelled y-values of 4 case studies at various retrofit stages (Appendix K values calculated through DSM)

3.7 Temperature factors and surface condensation risk

To assess the risk of surface condensation and mould growth before and after retrofits took place, thermal modelling of junctions in the building fabric was undertaken in four homes that received SWI. Minimum internal surface temperatures were calculated and used to derive a temperature factor (f_{Rsi}) for each junction at each retrofit stage. An f_{Rsi} below the critical value for domestic buildings of 0.75 indicates that the junction may be at risk of surface condensation and mould growth. Though it is important to note that the temperature factor indicates only the potential for and not the presence of risks in homes, an evaluation of ventilation and moisture transfer through fabric is also required to gain an holistic appreciation of risk. Figure 3-7 shows the percentage of junction lengths that were found to have an f_{Rsi} below 0.75. The results suggest that uninsulated solid walled homes are at substantial risk of surface condensation, with between 66 % and 89 % of junction sections being at risk in the case study homes.

Generally, retrofitting the properties reduced the proportion of junctions that were at risk of surface condensation. SWI installed via a piecemeal approach was shown to be effective in removing risks from timber and uPVC window and door frame junctions, wall corners and ground and floor junctions. Furthermore, the whole house approach (applying additional SWI to remove discontinuities) was found to be the lowest risk approach, because it successfully removed discontinuity between EWI and loft insulation at the eaves. However, there were some exceptions. Surface condensation risk at the wall to ground floor junction was predicted to worsen following suspended ground floor retrofits, though installing SWI resolved this (though the f_{Rsi} remained very close to the 0.75 threshold). Interestingly, the door threshold posed a surface condensation risk in the uninsulated homes, and this worsened even after a whole house retrofit. Limited retrofit solutions exist for solid stone or concrete door thresholds, and thus this may be a widespread issue in retrofitted homes.

Surface condensation risk is only one risk type. To get a full appreciation of moisture risks, for instance those associated with suspended timber ground floor retrofits, hygrothermal simulations to explore moisture build up in various pre- and post-retrofit scenarios is needed. Additionally, the use of a single threshold of 0.75 f_{Rsi} produced by models may not be a robust approach to risk assessment. Models might not necessarily reflect uncertainty in material properties or construction make up, so approaches which incorporate more uncertainty are needed. Similarly, risk profiles are continuous rather than binary, and so more comparative approaches to assessing risk should be developed to improve evaluations of risk for retrofits.

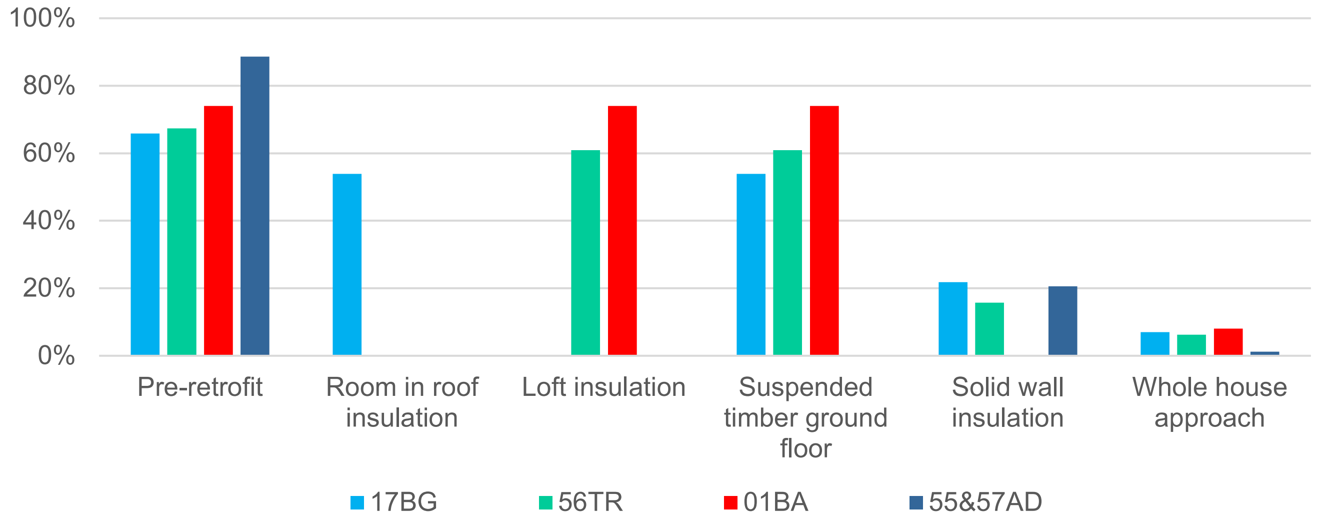


Figure 3-7 Percentage of junction lengths with a temperature factor below 0.75

3.8 Steady-state vs. dynamic annual energy predictions

Steady-state (RdSAP and BREDEM) and DSM models consistently predict different levels of space heating demand for the DEEP case study homes, even with total heat gains in the DSM models adjusted to match those in the steady-state models. The primary reason for this is the difference in the HTC values and the influence this has on annual space heating demand. BREDEM (and therefore SAP/RdSAP) uses a bottom-up method to calculate the HTC for the heat balance calculations, based on the thermal transmittance, area of construction, and background infiltration rate. The DSM models mimic the coheating test conditions and therefore use a top-down method the calculate the HTC. Using an unrestricted version of the BREDEM software, it is possible to overwrite the HTC with that calculated in the DSM model.

Figure 3-8 illustrates the impact of normalising the BREDEM baseline models using the HTCs calculated by the DSM models (BREDEM_htc). This has a significant impact on the estimated space heating demand, resulting in a relatively small difference between most DSM and BREDEM predictions following this adjustment. This indicates that top-down HTC calculations undertaken by steady state models may not be reflective of real-world heat loss in homes. Another difference between RdSAP and the DSM models is the way floor areas are considered. Steady-state models consider only the perimeter walls, ignoring internal party walls and features such as chimney breasts. Such features are, however, included in the 3D geometry of the DSM models. This way of treating geometry in DSM results in a smaller internal area and volume of the home, which in turn means heating demand is lower. The impact of normalising for conditioned volume (BREDEM_htc_m^3) is also shown in Figure 3-8.

Steady-state models used in the case studies limit glazing orientation to the cardinal and ordinal directions, whereas the DSM uses the true orientation, modelling more accurate solar gains which can influence space heating demand. Furthermore, the amount of solar irradiance hitting the homes alters the external surface temperature of the fabric. This affects the heat loss calculations, i.e., higher external surface temperatures result in lower heat loss and lower temperatures lead to higher heat loss. Ultimately, the results shown in Figure 3-8 confirm that it is the difference in HTC values, and potentially the calculation method, that accounts for most of the difference between space heating demand predicted by BREDEM (and therefore RdSAP/SAP) and DSM. Conditioned volume also has some impact, but these results suggest that other variables such as internal heat gain, have a negligible impact. In some instances, the normalisation of the BREDEM models results in a lower predicted space heating demand, so more work is required to understand how these predictions compare to demand in real homes.

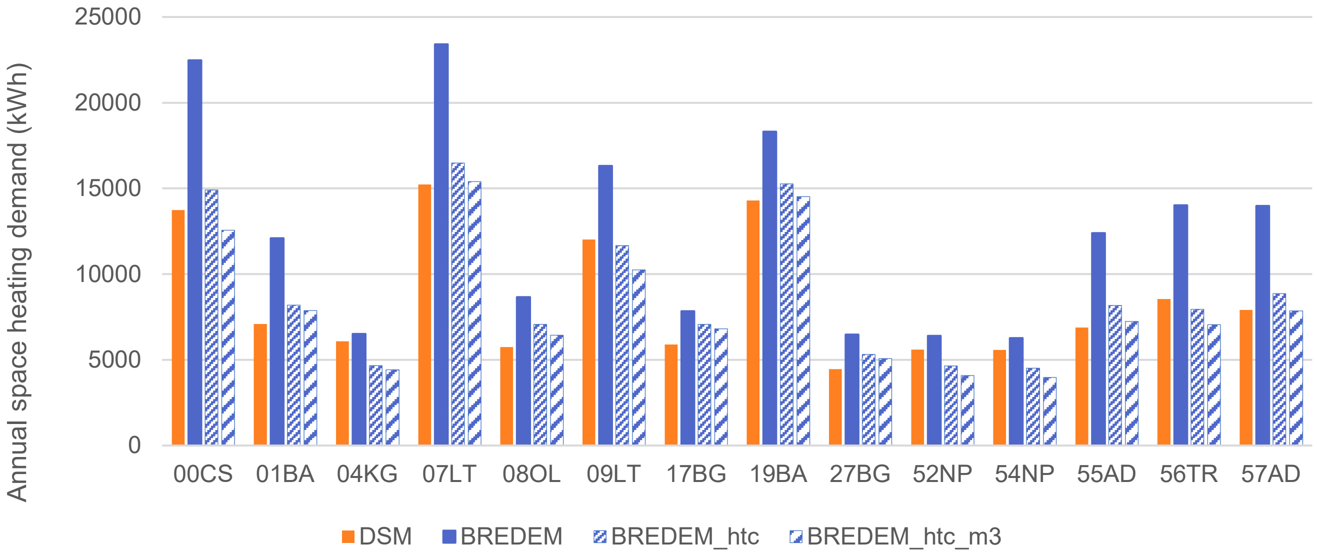


Figure 3-8 Normalised BREDEM space heating demand outputs

3.9 Overheating risk

The potential overheating in the DEEP case study dwellings was evaluated using CIBSE TM59, as recommended in PAS 2035. The methods and details of this can be found in each of the case study reports. Two overheating checks, or "criteria", are assessed; Criterion A assesses the percentage of occupied hours that living rooms, kitchens and bedrooms exceed a comfort threshold, and any room spending over 3 % of time above the threshold is deemed at risk of overheating. Criterion B says a home is at risk of overheating if the bedrooms spend more than 1 % of annual sleeping hours in excess of 26°C.

Most of the pre-retrofit dwellings failed these assessments; only four of the 14 passed Criterion A, and one passed Criterion B. Following the retrofits, five dwellings passed Criterion A and four passed Criterion B, suggesting that retrofitting can reduce overheating risk, but it depends on what is installed. Figure 3-9 summarises the impact of the retrofits on Criterion A. Positive values represent an increase in overheating risk, while negative values indicate a reduction.

Airtightness, loft, and floor retrofits generally led to increased risk due, respectively, to reduced air change, reduced heat exchange into the unconditioned loft space (which may be colder in the night-time) and decoupling the colder summer ground temperatures from the living spaces. Indeed, 08OL, which passed the assessment pre-retrofit, failed after its floor retrofit.

Room-in-roof and SWI retrofits were mostly likely to reduce overheating risk by limiting the transfer of heat into internal spaces through the opaque elements. Retrofit glazing reduced risk in all cases, and although the use of low g-value glazing was also observed to reduce risk, the improvements were mainly due to the increased opening areas compared to the original windows, which allowed for more natural ventilation.

The results for the Criterion B assessment were similar, but with more pronounced reductions in overheating risk achieved by wall, glazing and room-in-roof retrofits. Since internal doors were assumed to be closed in bedrooms overnight, the retrofits that limited heat gains through opaque elements of the bedrooms and increased their ventilation were most effective. The reductions in overheating risk became less significant when future weather files were considered, meaning most homes, even those with beneficial retrofits, would fail both criteria in 2050.

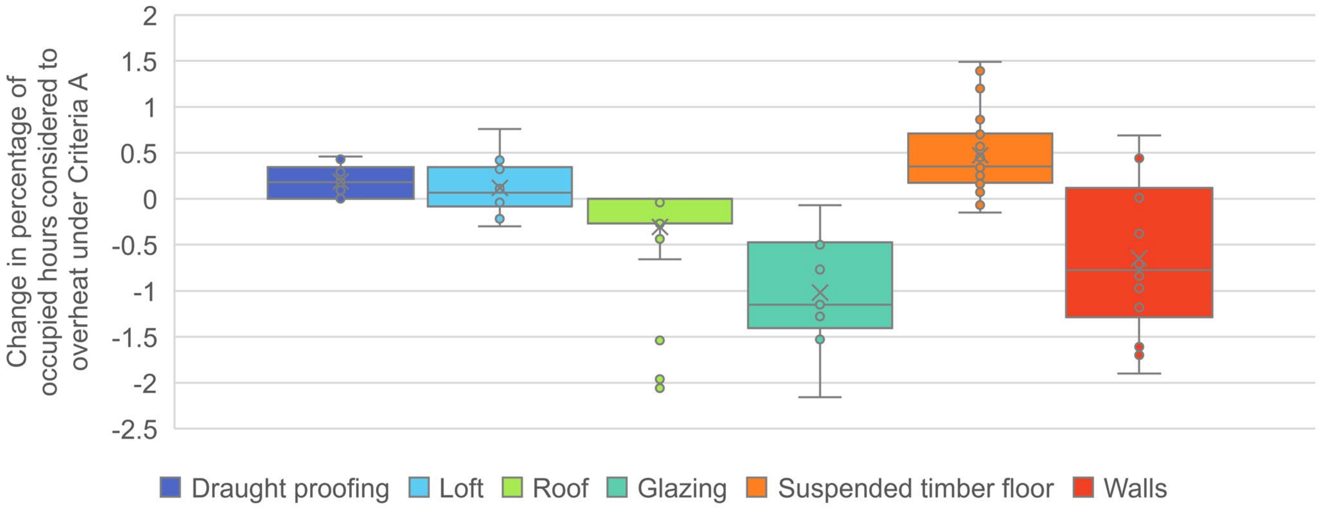


Figure 3-9 Change in percentage of occupied hours considered to overheat under Criterion A for each retrofit stage across all case study rooms

4 Retrofit costs and payback

DEEP took place at a time of unprecedented disruption in energy markets, yet the fuel bill savings and payback analysis presented in the DEEP case study reports use fuel costs that are embedded in RdSAP software, i.e., 3p per kWh for gas and 13p per kWh for electricity compared to the April 2023 Ofgem price cap of 13p per kWh for gas and 51p for electricity. In addition, the DEEP retrofits were undertaken during a global pandemic which affected supply chains and normal operating procedures of companies, which may have affected the retrofit installation costs. Moreover, the DEEP retrofits were generally one-offs, and not able to fully take advantage of economies of scale or procurement frameworks. For these reasons, the payback rates of the DEEP case study retrofits are not representative of commercially available projects taking place under current fuel prices but provide useful comparisons between the retrofits which are summarised in Figure 4-1.

As can be seen the payback rates vary considerably for each measure installed. The savings are influenced by the specific heat loss from the home pre-retrofit (e.g., existing levels of insulation), the specification of the retrofit, as well as the extent of enabling costs encountered in each home (e.g., general maintenance and repair costs). These factors combine, making it challenging to accurately predict payback times for retrofits. Generally, however, the payback times for the DEEP case study retrofits are of the order of many decades and commonly over 100 years.

Despite the DEEP case studies having pre-existing loft insulation, toping-up or replacing the loft insulation was still the most cost-effective retrofit available (though not according to EPCs which predicted existing loft insulation was performing perfectly). Ground floor and new glazing retrofits were among the least cost effective, while airtightness, room-in-roof, and SWI retrofits had better paybacks, though still generally over 100 years.

Changes in the price of energy and retrofit supply chains significantly alter these projections. To gain a more sophisticated understanding of paybacks, future price changes need to be factored in. These results illustrate that financial drivers for retrofits may not be particularly strong motivators, and that non-financial motivations for installing retrofits (improving comfort, addressing fuel poverty, and reducing peak heat) may be more compelling arguments for insulating the nation's homes.

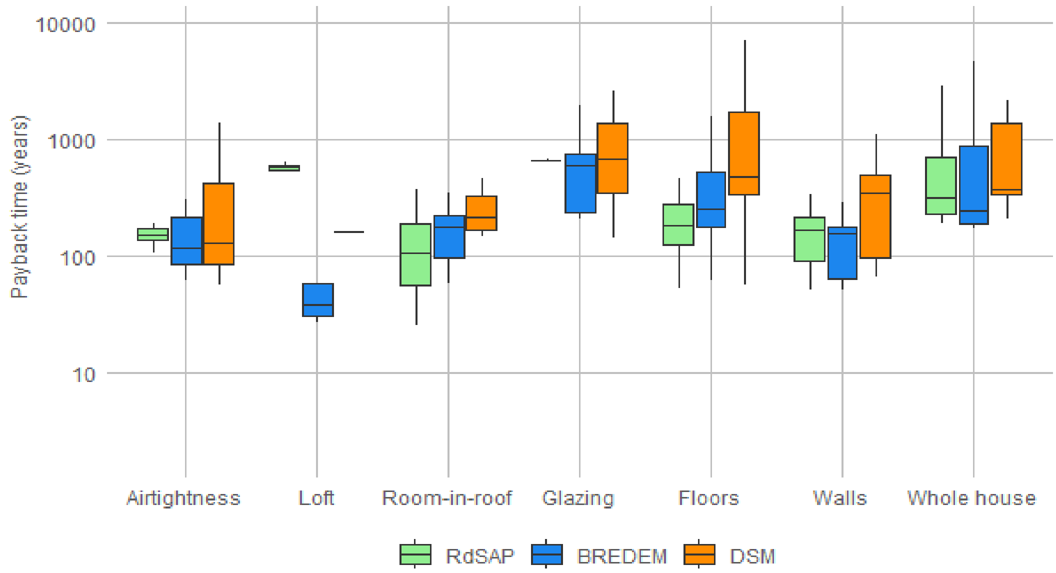


Figure 4-1 DEEP case study payback rates

4.1 Cost of additional work

Retrofit costs include materials, labour and additional costs resulting from onsite changes. The additional costs encountered in the DEEP retrofit case studies included fixing leaks from plumbing and rainwater penetrations, repairing brickwork, rebuilding a garden wall, increased plastering to make good, carpentry adaptations, extra scaffolding, replacing lintels and floorboards, removing storage items from lofts, and relocating services.

Additional costs are usually unknown in both severity and magnitude prior to the retrofit, which can be a barrier. Including these costs meant the DEEP retrofits were more expensive than cost estimates identified in literature, which perhaps exclude these. Figure 4-2 shows the total installation costs incurred for each DEEP retrofit, including the planned retrofit installation budget, plus additional costs. The average additional cost across the cohort of homes was 26 % of the total retrofit cost, though this ranged from 0 % to 38 %. These costs were incurred whether individual or multiple measures were installed and whether a piecemeal or whole house approach was adopted.

Some retrofits had particularly high additional costs, specifically the room-in-roof work at 07LT, 09LT and 19BA, and the external solid wall retrofit at 56TR, as leaking roofs and roof timbers needed repairing. 01BA also required a garden wall to be rebuilt at a cost of £6,000 and experienced other delays, resulting in further scaffolding costs. Suspended timber floor retrofits tended to add the highest proportion of costs as the original timber floorboards were damaged (often by the retrofit) and needed removing and replacing. Conversely, simpler retrofits such as applying a solid floor covering or installing loft insulation had relatively low or no additional costs. The same retrofit could result in different additional costs in different homes, depending on the construction. For instance, in 04KG damage was done to the walls when installing new windows, meaning the replastering was eight times more expensive than in 01BA (a similarly sized home). These findings suggest that more complex retrofits have higher additional costs, but *any* retrofit can have substantial and unknown additional costs, suggesting that a contingency fund is necessary. This has implications for retrofit budgeting for individual retrofit projects and national policy.

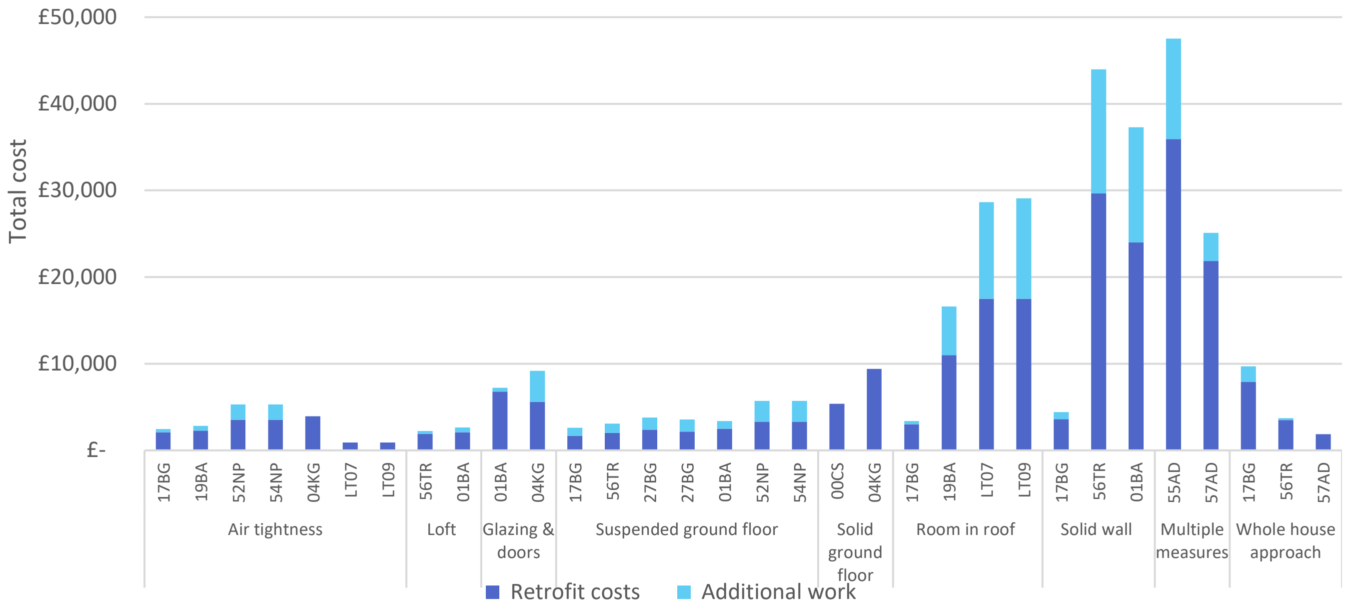


Figure 4-2 Cost of DEEP case study retrofits

4.2 Fuel bill savings of retrofits

The fuel bill savings resulting from the DEEP retrofit case studies were estimated according to various modelling software and assumptions, and details of these are provided in the case study reports. As a summary, this section presents the fuel bill savings predicted according to RdSAP, using all the default inputs (i.e., the EPC prediction), as well as from BREDEM and DSM when the default inputs are updated with measured airtightness and U-values and, where possible, thermal bridging calculations (i.e., “updated inputs”). Figure 4-3 illustrates the estimated annual fuel bill reductions across the DEEP case study retrofits. As discussed, EPC predictions are likely to estimate the greatest savings, while the DSM estimates, using updated inputs, predict the lowest savings.

There are generally predicted to be low or no estimated savings for airtightness improvements in EPCs, since these do not consider airtightness-specific retrofits beyond draught stripping. However, the models using updated input values suggest savings up to 8 % are possible. Only SWI (and multiple measures including SWI) are likely to achieve higher than 10 % fuel bill savings per year, and as much as 38 % where homes have a large area of external wall and the SWI achieves a low U-value. The lowest predicted saving for SWI is 7 %, where there was a limited amount of external wall area, pre-existing IWI on the base case home and a higher target U-value was specified to avoid interstitial condensation risk. EPCs predict that room-in-roof retrofits could also achieve over 10 % fuel bill savings, however, this is because they overestimate uninsulated room-in-roof fabric U-values, thus these savings are not expected to be achieved in practice. The findings highlight that fuel bill savings for retrofits other than SWI are likely to be negligible, which has implications for the focus of future retrofit policy, and that the savings predicted for the various retrofits can vary substantially depending on the surface area that is treated in each home and the presence of existing insulation.

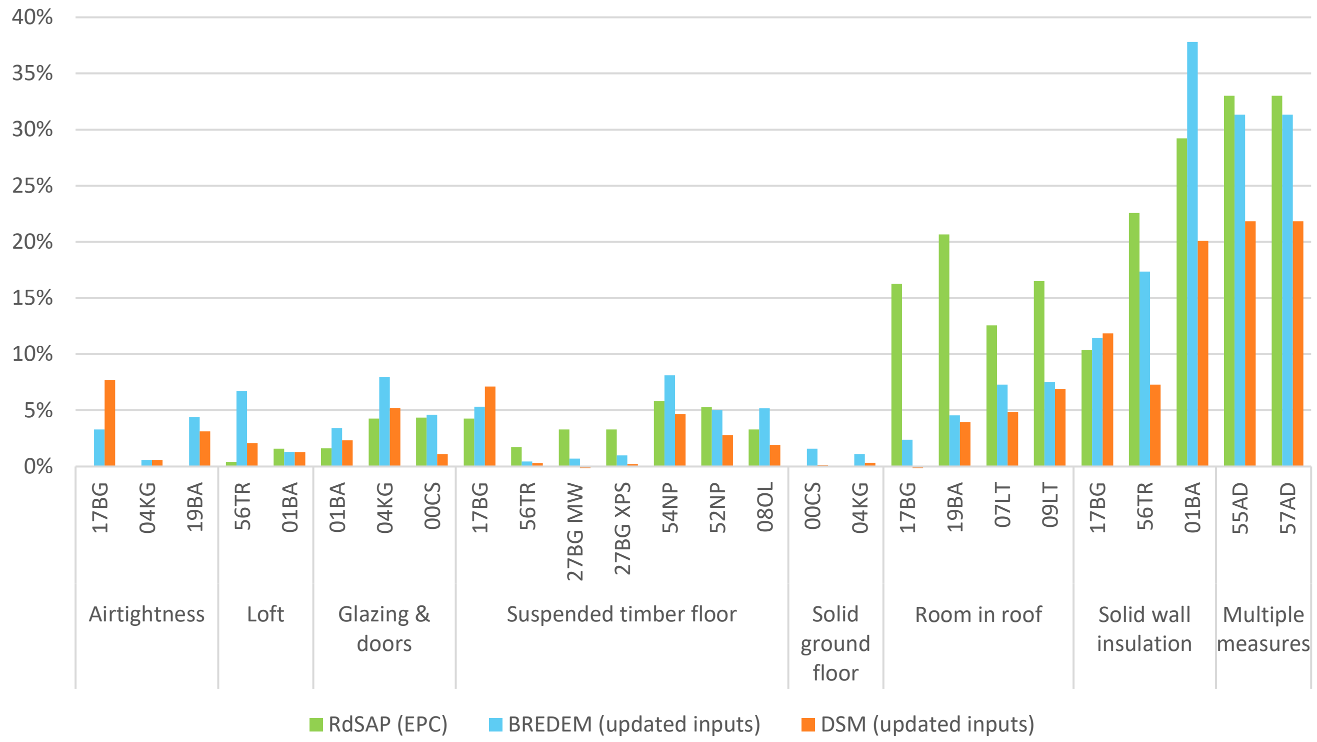


Figure 4-3 Annual fuel bill reductions resulting from retrofits

5 Piecemeal and whole house approaches to retrofits

One of the overarching themes of the DEEP project is comparing the differences between piecemeal and whole house retrofits. Throughout this report various issues are identified, which build support for the importance of adopting a whole house approach. These are discussed more thoroughly here.

The whole house approach does not mean that all elements in a house need to be retrofitted at the same time, but that retrofits must consider existing measures, as well as other whole house issues such as ventilation, interstitial condensation risk and overheating. SWI interacts with multiple other elements and these interactions must be given consideration in the whole house approach, or discontinuities in the insulation can occur. When this happens thermal bridges manifest, which can increase surface condensation risk and heat loss.

To investigate the scale of the thermal bridging caused by discontinuities in the DEEP case studies, technical risk and performance was assessed when SWI was initially installed in a piecemeal approach, i.e., without consideration of interactions to the loft, floor, window, and door junctions, and again following the whole house approach activities phase, i.e., after these junctions were given appropriate consideration and thermal bridges minimised. This allowed a quantification of not only the reduction in surface condensation risks, but the energy gains associated with the additional activity.

Activities undertaken as part of the whole house approach to retrofit to reduce the chances of surface condensation risk are identified in Figure 5-1. It should be noted that there are other risks associated with the details identified in Figure 5-1 that are not considered in DEEP, for instance the moisture accumulation in suspended ground floor timbers, which may also need considering to provide holistic risk assessment guidance for these details.

The findings from this project indicate that it may not be necessary to always minimise all risks, by as much as possible in a whole house approach retrofit, i.e., a risked-based balanced approach can be adopted. For instance, discontinuities at the eaves junction following EWI piecemeal retrofits were observed to cause excessive thermal bridging and condensation risks in 57AD, yet a discontinuity caused by not relocating windows into the EWI was not a risk in 55AD. This is important since moving windows into the EWI cost over £7,000 in 55AD.

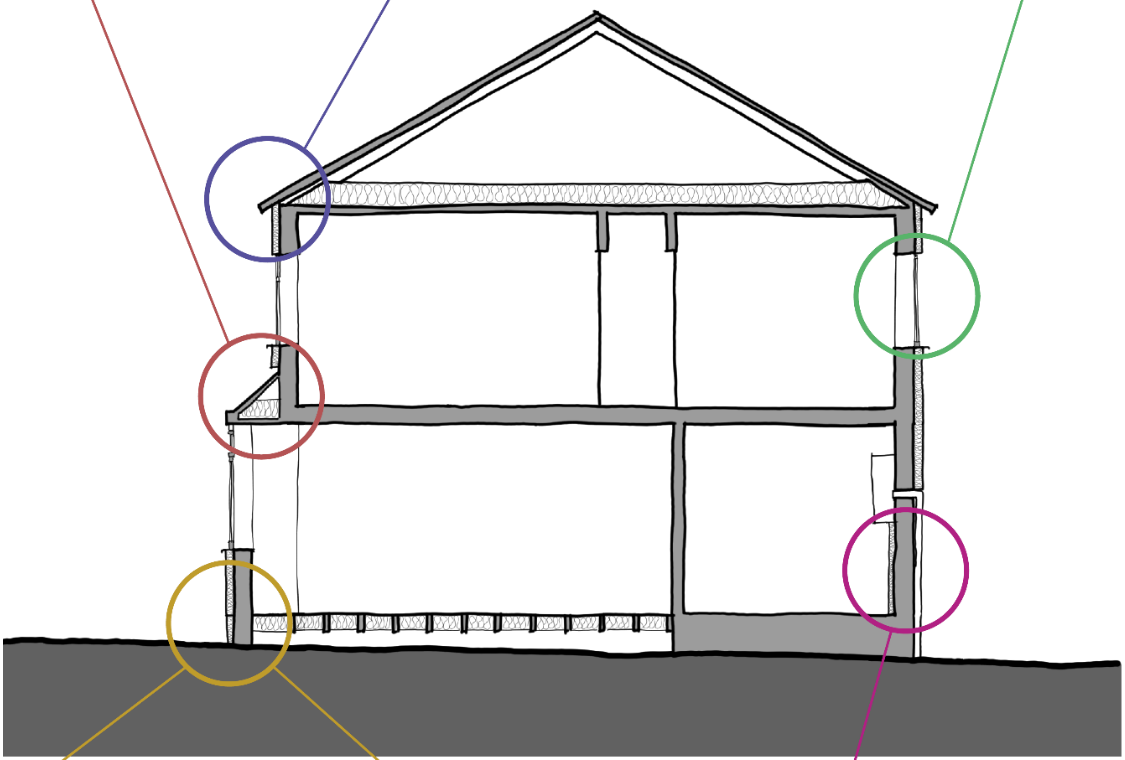
Outcomes may be different in different situations depending on the material properties, construction make up, and design details of the junctions. Guidance is therefore needed to illustrate activities that are essential in all retrofits to reduce risk, compared to those which, although they may help minimise thermal bridging may not be needed to remove a risk. Future research should aim to provide guidance for a range of common retrofit scenarios.

However, even in situations where a thermal bridge is not considered a risk i.e., it is above 0.75 f_{Rsi}, it is important that this is properly managed. This is because the models contain uncertainty, cannot accurately replicate specific situations, and use binary thresholds to apportion risk, which does not account for this uncertainty. The whole house approach, therefore, also requires there to be other risk management and mitigation processes in homes, including providing adequate ventilation even where models identify junctions as “safe”.

Bay
When the bay roof is left uninsulated after EWI in one DEEP case study home, this caused the thermal bridge to increase and the temperature factor to drop be below the critical temperature factor threshold. Additionally, this was responsible for between 1 and 2% of the homes heat losses post-retrofit.

Eaves
When EWI did not extend to the loft insulation in the DEEP homes the resulting thermal bridges were severe, these substantially increased surface condensation risks causing the temperature factor at this junction to fall below the critical threshold. Additionally, this was responsible for up to 10% of the homes heat losses post-retrofit.

Windows
After EWI retrofits in DEEP case study homes, surface temperatures at the window to wall junctions increased, and the temperature factor improved to be above the critical threshold, even when windows were left in their original position, though moving the windows in line with the EWI was the lowest risk approach.



DPC
When the EWI was not extended below the DPC this caused a surface condensation risk to fall below the critical temperature factor threshold at the wall to floor junction in the DEEP case study homes which had solid floors, though this surface condensation risk was not present for the case study homes with suspended floors when the DPC was not insulated.

Floor
EWI caused the temperature factor at wall to ground floor junction to improve above the critical threshold, i.e., EWI removed the risk of surface condensation without the need to install any suspended timber floor insulation.

Cut outs
At locations where cut outs of the EWI were undertaken to accommodate gas pipes, the temperature factor was seen to fall below the critical threshold in the case study homes, i.e., surface condensation risk was marginally increased, though this only posed a significant risk if the cut outs were located close to wall edges at corers or openings. Adding IWI at these locations removed any risks.

Figure 5-1 Impact of whole house approach activities on surface condensation risk

As mentioned, because the whole house approach reduced the severity of thermal bridges, it achieved additional heat loss reductions over the piecemeal approach. These were calculated for the DEEP retrofit homes by undertaking coheating tests after the piecemeal retrofits were complete, and again after the whole house approach activities were completed. The results are shown in Figure 5-2. The difference between the piecemeal and whole house approach retrofits for 17BG and 56TR relate to discontinuities in sloping ceilings in both homes, as well as insulating a single storey offshoot roof in 56TR. As can be seen, addressing these discontinuities did not achieve significant reduction in whole house HTC in the homes.

Also shown in Figure 5-2 is the difference between the HTC reductions achieved for 55AD and 57AD. These were a pair of identical semi-detached homes (HTC of 239 ± 9 and 225 ± 9 W/K, respectively) where a similar retrofit was installed in each. 55AD had a whole house approach to retrofit while 57AD had a piecemeal retrofit (discontinuities at the eaves, bay ceilings and windows) so the difference between these is used as a proxy for the impact of adopting the whole house approach. The comparison is complicated, since 55AD also had new glazing and external doors installed, expected to be responsible for around 7 % of the HTC reduction shown. Despite this, the results suggest there was a measurable improvement in HTC from adopting the whole house approach and removing the discontinuities in 55AD. Specifically, removing a large bridge at the eaves and insulating the bay roof were anticipated to be equivalent to around 7 % and 4 % reduction in HTC, respectively.

Figure 5-2 Whole house HTC reduction by calculation method

These results suggest there is potential for the whole house approach to achieve relatively small reductions in HTC, their size being dependent on the home and retrofit details, and specifically, whether significant bridges are reduced. The main justification for adopting the whole house approach to retrofit, therefore, is to ensure risks in the home are minimised.

The DEEP case studies show that the whole house approach minimises these risks and, importantly, that while piecemeal retrofits can reduce many surface condensations risks at some junctions, at others they can increase risks where discontinuities persist. The project also shows that a risk-based balanced approach is compatible with the whole house approach being taken, i.e., it is not necessary to insulate every fabric element, nor to minimise all risks in a home as part of a whole house approach to retrofit. Further guidance on which activities are essential and which are not for various retrofits in various types of homes is needed.

6 Assessing the accuracy of building performance evaluation tools

Building performance evaluation (BPE) investigations were undertaken before and after the 41 individual fabric retrofits across the 14 homes. A total of 43 coheating tests were undertaken (14 baseline and 29 post-retrofit). The baseline homes had HTCs ranging between 138 and 376 W/K. 118 blower door tests were conducted with an average baseline infiltration rate of 12.6 $m^3/(h \cdot m^2)$ @ 50Pa, and a range between 7 and 23 $m^3/(h \cdot m^2)$ @ 50Pa. 410 heat flux density measurements were taken, with an average of 30 HFPs being installed per home, giving measured U-values for the fabric elements.

The volume of testing undertaken in the DEEP project provides a unique opportunity to critique BPE methods themselves and improve the quality of data that can be collected from buildings. Over the course of the BPE tests, several observations were made which may have implications for BPE testing. This section describes these, specifically:

- An evaluation of the accuracy of the coheating test and the importance of uncertainty when considering before and after retrofit HTC measurements.
- A comparison between the coheating test and the quick U-building (QUB) test estimations of HTC.
- The potential for the blower door test to cause inter-dwelling air exchange, which may inflate inside-to-outside infiltration measurements.
- A comparison between the blower door test and low-pressure pulse airtightness test methods.

The findings can inform future use of BPE methods generally, and specifically in the context of evaluating retrofits.

6.1 Coheating test uncertainty

Coheating tests measured the HTC pre- and post-retrofits in the DEEP case study homes, and a detailed methodology for these is presented in the DEEP Methods 2.01 report. It is important when measuring HTCs to report “uncertainty”, i.e., the range in which the true HTC is likely to be. Historically, the uncertainty of the coheating test has been in the region of 10 %. In DEEP, lower uncertainties were often achieved, with 33 of the 43 coheating tests achieving an uncertainty lower than 10 %. Indeed, the average uncertainty across all the coheating tests undertaken was 6 %, and 22 of 43 coheating tests achieved an uncertainty below 6 %. For those tests with higher uncertainties, unfavourable environmental or test conditions (e.g., periods of extreme weather or complex party-wall heat exchange) were the principal reasons for the slightly higher uncertainty. For example, the largest recorded uncertainty was 18 %, and this was for a property with two large party walls.

When calculating changes in HTC, the uncertainty in pre- and post-retrofit HTCs becomes compounded. Even if uncertainties are low in the pre- and post-tests, the compound uncertainty can be large. Figure 6-1 illustrates this, displaying the percentage uncertainty in HTC differences. A percentage greater than 100 means the result is not statistically significant. The improvement measured by the coheating test was statistically significant for 13 of 29 pre and post comparisons. Most of the statistically significant results were for retrofits that achieved larger savings (EWI and multiple measures).

The coheating tests in the DEEP project had significantly lower uncertainty (average of 6 %) than alternative HTC measurement techniques. This has implications for attempts to measure the impact of retrofits that achieve small HTC reductions (e.g., loft and floor insulation, new glazing, or airtightness improvements) on a house-by-house basis without the coheating test. This challenge may be reduced perhaps by extending testing periods, undertaking multiple tests, or assessing improvements over larger samples sizes.

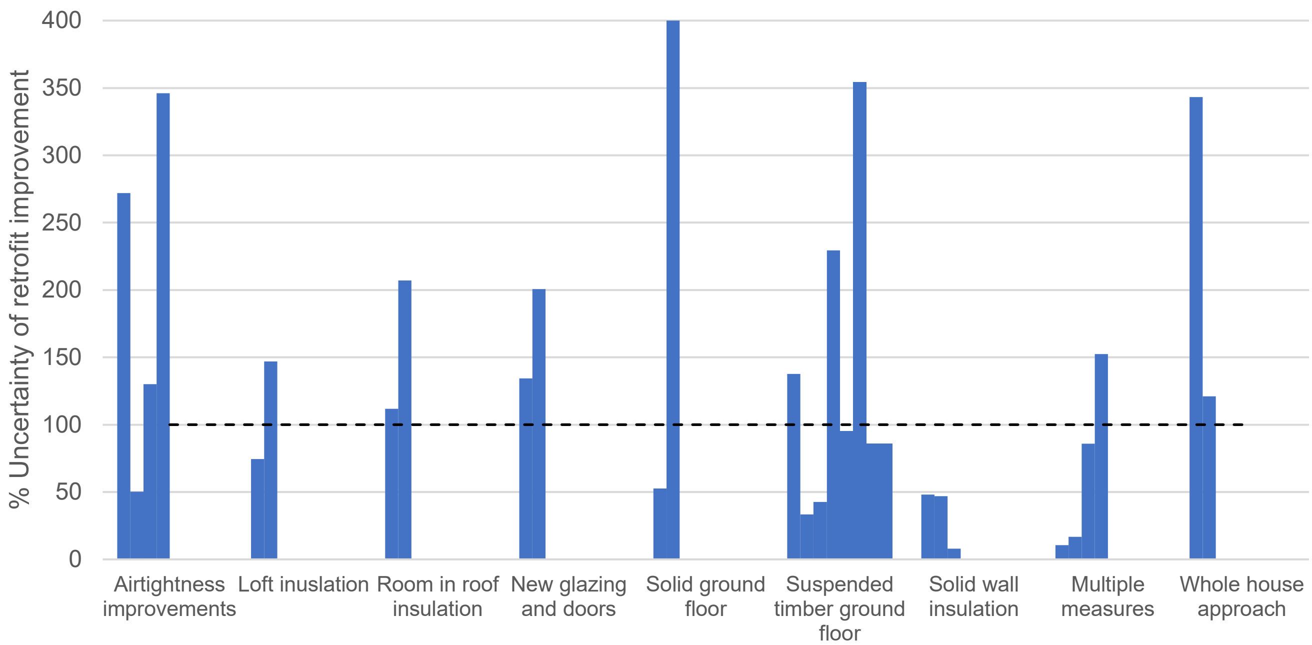


Figure 6-1 Uncertainty in measured HTC improvement. A value below 100 % indicates a statistically significant improvement i.e., a reduction in HTC (a solid ground floor value is truncated for clarity, the true value is 1235 %)

6.2 QUB tests and HTC

QUB is an alternative HTC measurement method to coheating and is described in the DEEP Methods 2.01 report. In brief, QUB employs two distinct phases of equal length, a constant heat injection phase followed by a free cooling phase. The input power and resulting temperature response are monitored to calculate the HTC. QUB can obtain an HTC result in a single night, making it a cheaper and less time-intensive measurement method than coheating, though it often has higher levels of uncertainty.

Comparative QUB and coheating tests were performed on 12 houses across 26 retrofit configurations to investigate the accuracy (closeness to the coheating HTC value) of the QUB test. By completing multiple QUB tests the precision (spread of repeated results) could also be considered. For each retrofit stage where QUB tests were undertaken, Figure 6-2 shows the average QUB measurement against the equivalent coheating measurement. There is generally a good average agreement between the methods, though any single test can be significantly different. The average difference between the QUB and coheating tests was 15 %, though this varied between 1 % and 47 %. Additionally, where multiple QUB measurements were made the average range of results, relative to the mean measurement, was 16 %, suggesting relatively good repeatability in the tests.

There was a large variation in the accuracy and precision between each house and retrofit stage. This is shown by the proximity to the dashed line in Figure 6-2 and varying size of error bars depicting the dispersion of measurements. Most QUB tests were observed to report slightly lower HTC than the coheating tests (i.e., they are below the dashed line).

Some case studies showed a notable improvement in accuracy, and, or precision as they progressed through the retrofit stages, with insulation and airtightness levels increasing. However, this was not consistent across all properties. The cause of this could be multiple, unquantified sources of measurement uncertainty present in the QUB tests. These might include indirect heat losses through party walls and solid floors as well as the impact of varying environmental conditions. Further understanding is needed of how the accuracy and precision of QUB tests in solid walled homes varies with building characteristics and environmental test conditions.

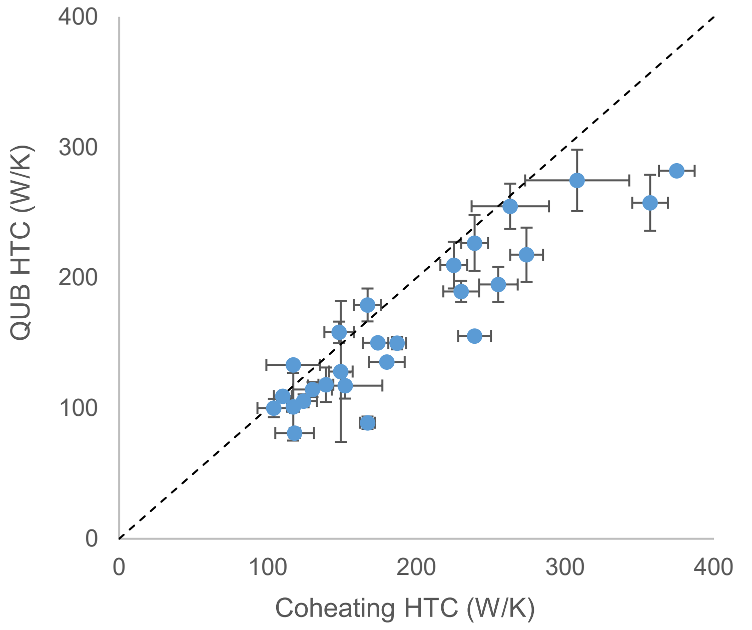


Figure 6-2 Comparison of QUB and coheating measurements by insulation status (dashed line = 1:1 relationship)

6.3 Inter-dwelling air exchange and co-pressurisation testing

The airtightness of the DEEP case study homes was measured using the blower door test. In total, 118 tests were undertaken in the 14 homes, and 15 of these were co-pressurisation tests. A co-pressurisation test involves taking an airtightness measurement while holding the test home and its neighbour at the same pressure (50Pa) to eliminate drivers of inter-dwelling air exchange. The methodology followed is detailed in the DEEP case study reports and the DEEP Methods 2.01 report. Figure 6-3 shows the results of the co-pressurisation tests.

As can be seen, in every instance the co-pressurisation tests resulted in a lower measurement of air permeability than their equivalent individual blower door test (above the black 1:1 line). This indicates that the standard blower door test results include inter-dwelling air exchange which may not necessarily take place under non-pressurised conditions. As such, blower door tests may be incorrectly reporting the inside-to-outside air leakage in attached dwellings needed for heat loss calculations and assessment of the need for mechanical ventilation.

Across the cohort, inter-dwelling air exchange made up an average of 17 % of the total blower door test value, though this ranged from just 2 % up to 28 %. The five post-retrofit homes reported slightly less inter-dwelling air leakage, suggesting the general trend that inter-dwelling air exchange caused by blower door tests is higher in less airtight homes. Of the 14 homes, five were mid-terraced properties where it was only possible to undertake the co-pressurisation test with one neighbour, thereby allowing inter-dwelling air exchange with the other neighbour. Thus, the reduction in reported air leakage may have been greater if both neighbours had been co-pressurised for the tests.

These findings have implications for all blower door tests undertaken in adjoined properties (over 75 % of the UK housing stock [7]) suggesting these may have overestimated inside-to-outside air leakage. Inter-dwelling air exchange does not necessarily constitute heat loss since neighbouring dwellings may both be heated to similar temperatures. Thus, heat loss estimates that rely on blower door tests may be overestimated. Inter-dwelling air exchange also does not constitute fresh air and has implications for the spread of fire, airborne disease and nuisance noise and smells. More data is needed to explore this issue.

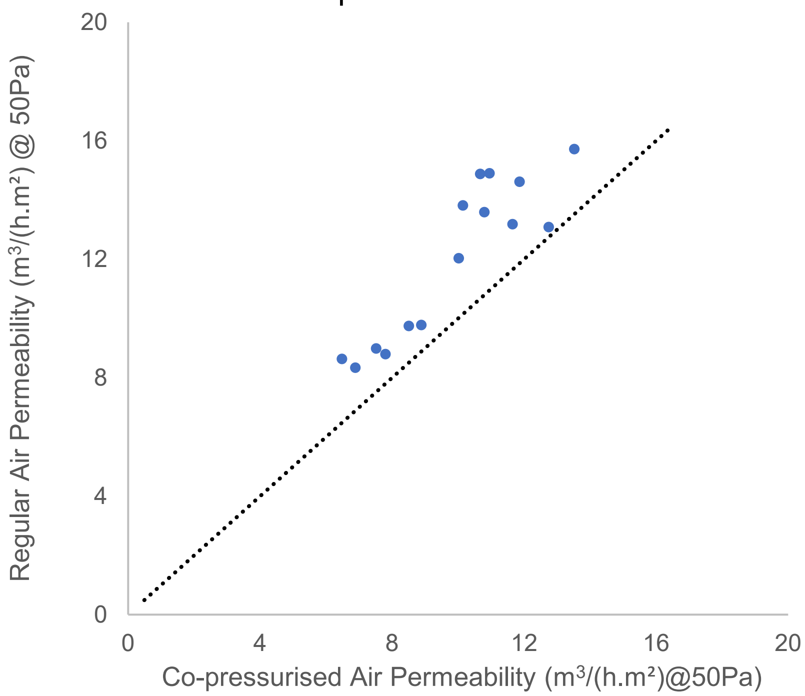


Figure 6-3 Regular vs. co-pressurised blower door tests (black dotted line = 1:1 relationship)

6.4 Blower door and low-pressure pulse airtightness testing

The low-pressure pulse test is an accepted alternative to blower door testing in new dwellings (CIBSE TM23:2022). It was developed to test the airtightness of homes at much lower pressure differences of ~4 Pa. This may, to some extent, overcome the uncertainties introduced into the blower door tests caused by inducing artificially high pressures.

Where possible, pulse tests were undertaken on the case study homes for comparison to the blower door test. The detailed methodology for these can be seen in the DEEP Methods 2.01 report. In total, 17 successful pulse tests were undertaken at various stages of retrofits. Ten were carried out prior to retrofit work being undertaken and the results of these are plotted in Figure 6-4 against results from the blower door tests undertaken at the same stage. The houses were vacant at the time of the tests and in various states of disrepair. The pulse tests, which are measured at a pressure of 4 Pa, are converted to an elevated pressure differential 50 Pa for comparison with the blower door tests. This conversion uses the $5.254*(AP_4^{0.9241})$ conversion factor stated in CIBSE TM23, where AP_4 is the pulse air permeability result at 4 Pa. As shown in Figure 6-4, for some homes the data points are close to the 1:1 line, indicating a good agreement between the tests, though this is not always the case. Moreover, the pulse test predicts higher levels of infiltration than the blower door (above the 1:1 line) in all but one of the case study homes in vacant, pre-retrofit condition. This finding is in contrast to the findings from in DEEP report 3.00, DEEP energy efficiency surveys where the pulse test tended to predict lower air permeability than the blower door.

The two test methods, while measuring similar metrics, are fundamentally different techniques and comparing results between them is challenging. The limited number of data points from the DEEP case study homes make it difficult to draw any significant conclusions.

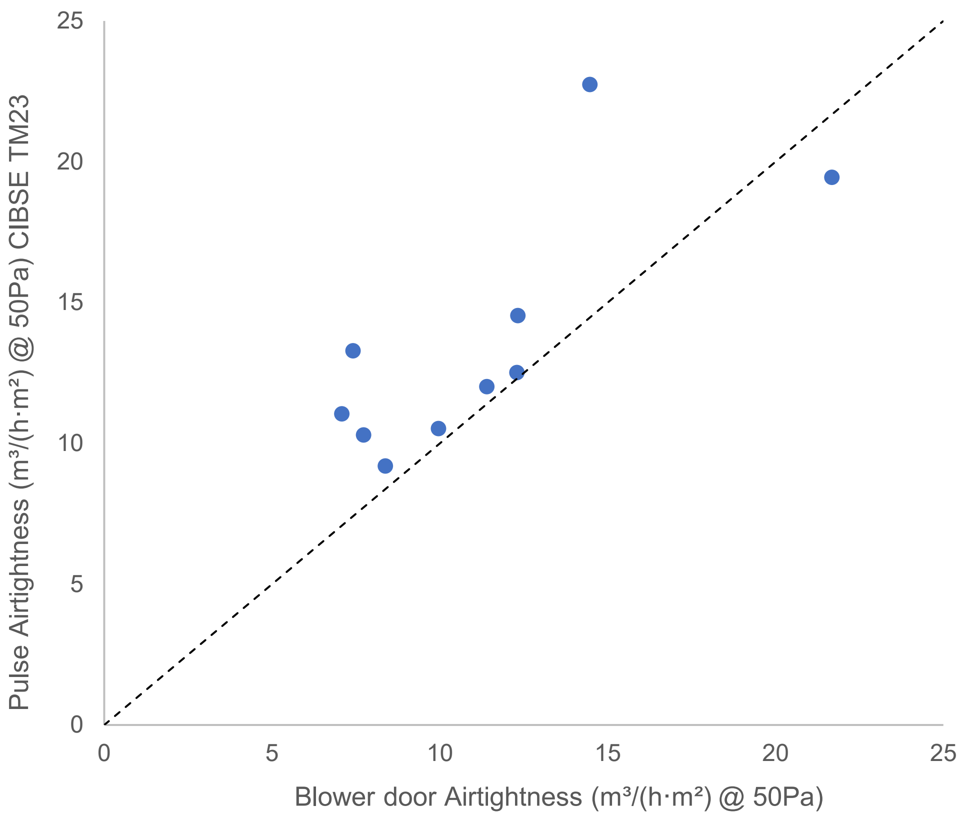


Figure 6-4 Blower door and low-pressure pulse test results (black dashed line = 1:1)

7 Conclusions

The DEEP research project makes a significant contribution to understanding retrofitting solid walled homes safely and effectively, the importance of the whole house approach to retrofit, how modelling predictions can be improved, and how accurately building performance can be measured.

Whole house approach and piecemeal retrofits
The DEEP case studies provide evidence to confirm that the whole house approach can result in lower surface condensation risks than piecemeal alternatives, even if they may not always achieve additional heat losses. Additionally, they identify specific thermal bridges which can cause risks (e.g., eaves junctions following EWI), as well as instances where it is not always necessary to remove all thermal bridging completely (e.g., relocating windows into the EWI layer). This provides important evidence and guidance to retrofit practitioners and decision makers and supports the uptake and effectiveness of the whole house retrofit approach.

Technical performance of retrofits
SWI significantly reduced heat loss in the case study homes, although its impact depended on the amount of external wall that was insulated and the degree of pre-existing SWI (usually IWI) already in the homes. SWI reduced fuel bills between 7 and 38 %, and reduced HTC between (19 ± 9) % and (55 ± 5) %. It was also one of the most effective retrofits at achieving reductions in overheating risk, resolved most pre-existing surface condensation risks in homes, improved surface temperatures, achieved the SHDF target space heating requirement, and ensured the home achieved an EPC band C.

Other retrofits, including airtightness improvements, loft insulation, solid and suspended ground floor insulation, room-in-roof insulation, and installing new glazing and external doors, were still successful. Each was found to have the potential to reduce fuel bills between <1 and 8 % and to reduce HTC between 0 and 20 %, depending on the retrofit specification and the modelling assumptions used. The implications are that the benefits of retrofitting homes are highly context specific and that, with the exception of SWI, individual retrofits may need combining to achieve a significant reduction in heat loss.

All other retrofits were also assessed for their potential to reduce overheating. Pre-retrofit, the DEEP case study homes were considered at risk of overheating. Installing room-in-roof insulation (to reduce the amount of solar radiation entering the home), and new glazing retrofits (to increase the amount of natural ventilation) were successful in reducing overheating risk. Suspended timber floor, loft insulation and air tightness retrofits, however, only marginally increased risk since they reduced the effect of beneficial summertime heat loss mechanisms.

Accuracy of model predictions
The DEEP project has confirmed that EPCs are generally not good at predicting heat loss from homes and that they overpredicted heat loss by an average of 42 % across all the homes, though this varied between 7 % lower, and over 100 % higher. This means the prebound effect is a significant concern and is especially problematic for homes with high heat losses. In some instances, updating the model default inputs with measured values for air tightness, U-values and thermal bridging heat loss improved the accuracy, however, this was not straightforward to do, and sometimes did not improve the predictions. Comparisons were made with dynamic models (DSM), which appeared to predict HTC more in line with coheating tests and which were useful in performing overheating assessments. It may be beneficial to consider how EPCs could incorporate the benefits of DSM. Specific recommendations are proposed to improve EPC conventions, which include removing room-in-roof simplifications as well as updating EPC default inputs (e.g., having a larger range of default y-values and U-values).

Retrofit costs
While the DEEP project took place during a time of significant upheaval in the energy and construction markets, and although DEEP was not attempting to identify the precise costs of retrofits, the case studies provide useful data on the cost effectiveness of retrofits in solid walled homes. Overall, the retrofits had very long payback times often in excess of 100 years. However, payback times are greatly affected by fuel and supply chain costs and so may change in future years. One of the main reasons for the long payback times associated with the DEEP case study homes was the significant additional costs associated (e.g., repairing roofs, extra scaffolding, etc). These costs varied significantly depending on the issues of the specific home being retrofitted but were, on average, around a quarter of the total costs and, significantly, usually only came to light once the retrofit had begun.

Use of building performance evaluation tools for retrofit assessment
The coheating tests undertaken in the DEEP project achieved an average uncertainty of 6 %, which represents a much lower level of error than previously recorded. Despite this, the tests were only able to measure statistically significant savings in around half of cases, because the before and after test uncertainties compound. SWI achieves such large savings that a significant saving was successfully measured in every case. Where multiple retrofits were installed, the combined benefits could often be measured with statistical certainty. However, for other individual retrofits, which were predicted to achieve lower HTC savings in the models, it was not usually possible to measure the reductions in HTC on a house-by-house, measure-by-measure basis, even when using the coheating test. Alternative approaches, such as analysing cohorts of homes or undertaking multiple measurements in single homes, may therefore be needed to ensure robust analysis of heat losses following retrofits in homes. This is an important consideration if real data is to be used to enhance and support evaluations via EPCs.

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