Department for Energy Security & Net Zero

DEEP Report 1: Synthesis

Demonstration of Energy Efficiency Potential

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Contents

Executive Summary

Retrofitting solid walled homes is one of the greatest challenges for the UK in achieving its net zero ambitions. Solid walled homes have unique features, that require special consideration. They are among the least efficient in the UK, and their occupants are more likely to be in fuel poverty. They are also at elevated risk of surface condensation, excessive cold in winter and overheating in summer. Retrofitting these homes is a cornerstone of UK policy to tackle fuel poverty and to facilitate the delivery of decarbonised electrified heat into homes. However, installing solid wall insulation is costly and poses more risks of unintended consequences than any other retrofit. Previous projects investigating solid wall insulation have identified major failures when retrofits are installed in a 'piecemeal' way i.e., they did not consider how the retrofit measure affects risks of damp, inadequate ventilation, and overheating in homes. This led to the adoption of the whole house approach in new technical standards for retrofit installers (PAS 2035[1]) to ensure that all risks of retrofit measures were always considered, even if only one measure was being installed at a time. Industry is beginning to adapt to these standards, but more research is needed to explore the benefits of adopting the whole house approach, and more guidance is needed to support retrofits in solid walled homes. Insights from this project explain how solid walled homes can be retrofitted more safely and effectively.

The Demonstration of Energy Efficiency Potential (DEEP) project was one of the UK's largest research projects into retrofitting solid walled homes and has expertise from three universities:

- Leeds Beckett University (LBU) led the project and used case study field trial investigations to measure technical performance and risks, before and after retrofitting 14 solid walled homes. LBU then compared the measured findings to the modelled predictions.
- The University of Salford replicated one of the LBU case study retrofits in the Salford Energy House to explore the issues under more controlled conditions, and to identify the impact these retrofits have on heating system efficiencies.
- Loughborough University modelled risks associated with retrofits and undertook scenario analysis to investigate situations that could not be observed in the field studies.

Over the course of the project answers to important questions emerged, around which the findings are presented in this report:

1) What are the most effective retrofits for solid walled homes?

The findings from 41 fabric retrofits in 14 case study homes showed that installing a combination of draught-proofing, loft or room-in-roof insulation, new windows and doors, ground floor insulation, and solid wall insulation (SWI) could reduce whole house heat losses by up to 60%. SWI alone could achieve between 19% and 55% reductions, equivalent to between a 7% and 38% fall in fuel bills, while other single retrofits achieved fuel bill savings between <1 and 8%. SWI was also able to bring homes up to an Energy Performance Certificate (EPC) band C, and dramatically reduce the chance of surface condensation in these homes, but was also the most expensive retrofit, costing between £4,000 and £44,000. All retrofits had paybacks over many decades, and costs could be up to a third higher than expected due to the need to make repairs or prepare homes for retrofits. Lab investigations found similar results which suggests that one of the most significant findings from the research is therefore to confirm that solid wall insulation is by far the most impactful measure.

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[1] https://www.bsigroup.com/en-GB/standards/pas-2035-2030/

2) How can technical risks be reduced when retrofitting solid walled homes?

In DEEP, the uninsulated homes were found to be at risk of surface condensation. The piecemeal retrofits generally reduced this risk, with SWI being the most beneficial. However, some risks remained around discontinuities in insulation and in limited instances, risks were worsened. Removing discontinuities in the insulation layer, as required by the whole house approach, reduced risk to acceptable levels. SWI was also successful in reducing overheating risks in homes, although providing additional natural ventilation and solar shading was needed to ensure homes do not overheat, especially in a future warmer climate. Interstitial condensation risk was introduced to homes when internal wall insulation (IWI) was installed, though by targeting U-values around 0.8 W/(m^2·K), rather than the Building Regulations limiting U-value of 0.3 W/(m^2·K), the risk was reduced while still receiving two-thirds of the energy savings.

The findings from this element of the work show that risks in homes can be significantly reduced where the whole house approach to retrofit is followed. However, it also revealed that existing risk assessments used to inform retrofits may not be capable of adequately assessing risks. In this context, other features of the whole house approach to retrofit are essential, such as ensuring adequate ventilation in homes to improve the management of moisture risks.

3) How can building energy models and risk assessments be improved?

EPCs are currently used to predict the energy efficiency of homes, and the impact of retrofits, in national policy. EPCs overestimated the heat loss measured in the DEEP case studies by, on average, 42%. The EPC overprediction was greater pre-retrofit than post retrofit. This aligns with other research suggesting EPC bands A and B had no significant difference between EPC and measured energy use while the over prediction for Band C homes was ~8% on average [1]. They also overpredicted the retrofit savings achieved by an average of 46% across the case study homes; this is known as the *prebound effect*. However, the amount of overprediction varied.

Replacing default inputs used in EPCs with measured values for airtightness, U-values, and thermal bridging heat losses was somewhat effective at limiting the overprediction in modelled savings, to between 17% and 27% on average. The existing default input values used in EPCs are therefore a source of inaccuracy and could be improved. However, despite using measured values for these inputs, the prebound effect was still observed, and in a few instances, replacing defaults with measured values made predictions worse. This suggests there may be systematic causes of overprediction in the EPC that should be further investigated. The EPC is a steady-state model; alternative dynamic simulation modelling (DSM) resulted in less over-prediction of heat losses in the case studies on average, between <1 and 13% depending on which inputs were used. There could therefore be value in exploring how DSM could support the delivery of more accurate and useful EPCs.

Uncertainty in risk modelling highlighted that pass-fail risk assessments, i.e., considering a home to be “safe” when it was marginally above a critical threshold, were found to be too simplistic and by themselves may not provide adequate information to make risk-based decisions when retrofitting homes. Risk is a continuous scale, i.e. risks judged to be marginally above critical thresholds are similar to those marginally below it. This is because the models cannot fully account for uncertainty associated with the weather, variations in construction materials, or differences in internal conditions in homes (humidity, air temperature, and ventilation provision) which are affected by how occupants use their homes. More sophisticated approaches are therefore proposed in DEEP. More guidance is needed generally to support decision-making around risks. For instance, to understand when a thermal bridge results in an unacceptable risk and how risks in homes can be managed.

4) What are the procedural implications for achieving the whole house approach to retrofit?

Achieving a whole house approach to retrofit is not straightforward. One of the biggest challenges is to remove uncontrolled air leakage from homes. The findings of DEEP suggest airtightness testing and leakage detection in homes before works are undertaken would be useful, even essential, for all retrofits. Of 146 homes surveyed, 10% had excessive air permeability (>15 $m^3/(h \cdot m^2)$ @ 50Pa), and it could not be predicted prior to testing which homes these would be. Excessive air leakage can also undermine retrofit performance, and air movement in the fabric reduces the potential to achieve energy savings and can exacerbate moisture risks. Airtightness strategies should be a fundamental component of all fabric retrofits since draught-proofing alone is not effective or long-lasting.

Many issues facing the delivery of the whole house approach could be avoided if more effective surveys were undertaken in homes. For instance, identifying where insulation has previously been installed in the homes, as this may alter the new retrofit design. In the DEEP case studies, this commonly included polystyrene-backed plasterboard on walls, which presented a risk of interstitial condensation. Surveys would allow the risks of previous retrofits to be evaluated and rectified where necessary.

More thorough surveys will also identify potential additional costs associated with retrofits, for instance repairing the building. In DEEP these costs added an average of 26% to the cost of the retrofits. Surveys should also capture information about the services in the home even if fabric-only retrofits are planned. For instance, the boiler or heat pump settings may need adapting to maintain efficient operation once the fabric heat loss in the home has been reduced by the retrofit. Investigations showed that when this was not done boiler efficiency was reduced by 5% which resulted in 3% lower retrofit space heating energy savings. To support surveys, information about home alterations should be captured. In most instances in DEEP, landlords did not have a good understanding of the fabric and system performance of their homes. This meant more extensive surveys were needed, and that original decisions about the retrofit were made with imperfect knowledge, resulting in on-site adaptations being needed.

5) Are measurements of retrofit performance and risk robust?

DEEP undertook a large amount of building performance evaluation (BPE) testing; over 40 coheating tests, 400 heat flux density measurements and 200 air tests. These investigations highlighted several issues with measurement techniques that are commonly used.

For instance, that blower door tests were overpredicting internal to external air exchanges by 17%, on average, in the case study homes which had attached neighbours. This was because inter-dwelling air movement was taking place under the induced high pressures used by the test. Since many thousands of blower door tests are undertaken in homes each year, this may be significant.

Moreover, alternative BPE tests (the low-pressure pulse test for measuring airtightness and QUB test for heat loss from homes) had good agreement, on average, with the blower door and coheating test respectively. However, the results for individual homes varied significantly. The value of these tests in supporting decision-making and evaluating specific retrofits requires more investigation. One of the major benefits of using BPE tools is to help inform retrofit designs and evaluate their performance. However, BPE tools require careful implementation to ensure they provide accurate and relevant information. The uncertainties of BPE methods need to be understood, especially if the outputs are being used to evaluate retrofits or inform retrofit decisions.

Introduction

The Demonstration of Energy Efficiency Potential (DEEP) project combines multiple research activities to provide an appraisal of piecemeal and whole house approaches to retrofits in solid walled homes. It also explores how to improve measurements and models of technical performance and risks associated with retrofits. This report presents the research findings around the importance of and practical implications for adopting the whole house approach to retrofits in solid walled homes.

The Department for Energy Security and Net Zero (DESNZ)[2] commissioned the DEEP project, which ran between 2019 and 2024. DEEP was undertaken by a consortium led by Leeds Beckett University (LBU) and supported by the University of Salford (UoS), and Loughborough University (LU). Lucideon Ltd also undertook laboratory testing of brick samples and Thermal Image UK performed airtightness and retrofit surveys as part of the project. An overview of the research approach is below in Figure 0-1.

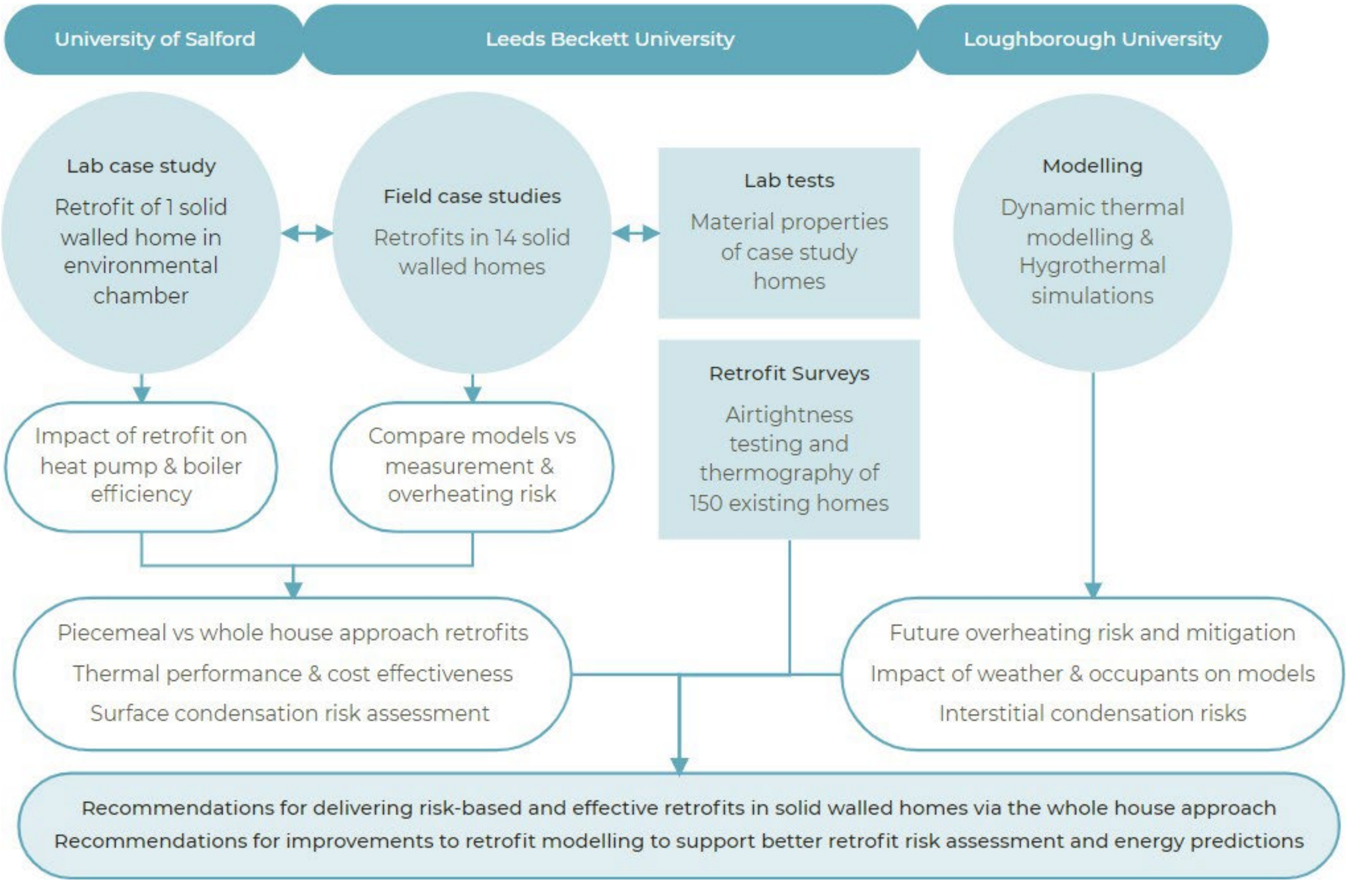


Figure 0-1 DEEP research overview

Collectively DEEP constitutes a significant body of work, and this report draws out the important themes in each of the 21 subsidiary reports outlined in Figure 0-2.

[2] Known at the time as the Department for Business, Energy and Industrial Strategy (BEIS)

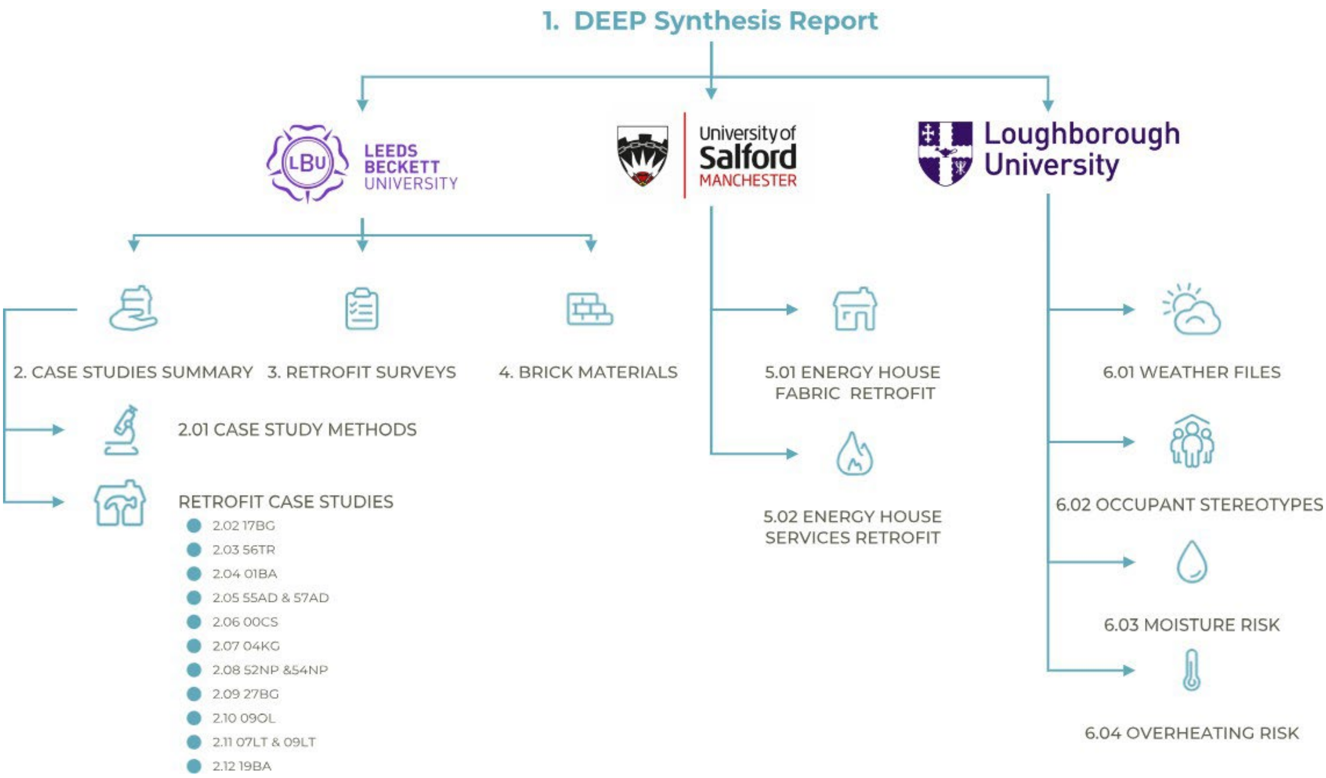


Figure 0-2 DEEP reporting structure

Table 0-1 describes the focus of each of the DEEP reports:

Table 0-1 DEEP reports overview

DEEP Report	Content of report
1. Synthesis	Collective implications, interpretations, and recommendations.
2. Case Studies Summary	Commonalities and insights from all case studies.
2.01 Case Study Methods	Common methodologies undertaken in the case studies.
2.02 - 2.12 Individual case studies	Detailed description of 14 individual case studies and findings.
3. Retrofit Surveys	Results from 150 airtightness and retrofit surveys in UK homes.
4. Brick Materials	Compares measured properties of brick types to book values.
5.01 Energy House Fabric Retrofit	Describes the impact of the piecemeal Vs whole house retrofit.
5.02 Energy House Services Retrofit	Retrofit impact on gas boiler and heat pump performance.
6.01 Weather Files	Produces improved method for using weather data in models.
6.02 Occupant Stereotypes	Understand how occupant behaviour impacts retrofit savings.
6.03 Moisture Risk	Determines the moisture risks of installing internal wall insulation.
6.04 Overheating Risk	Explores retrofitting solutions to avoid overheating risks in homes.

The six research questions in the DEEP invitation to tender[3] were: what are the benefits of (1), and risks of not (2), taking a whole house approach to retrofit? What is the potential for less common retrofits (3) and technical potential for improving solid walled homes (4)? Is risk mitigation guidance appropriate (5) and is retrofit degradation and failure a concern (6)?

In synthesising the findings from across the DEEP reports the following themes have emerged which provide a narrative to address these questions, around which this report is structured:

1. What are the most effective retrofits for solid walled homes?
2. How can technical risks be reduced when retrofitting solid walled homes?
3. How can building energy model inputs and moisture risk assessments be improved?
4. What are the procedural implications for achieving a whole house approach to retrofit?
5. Are measurements of retrofit technical performance robust?

Before exploring the findings, it is useful to outline what the difference is between piecemeal and whole house approaches to retrofit. The "whole house approach" is a way of thinking about retrofit in a holistic and risk-based manner; it does not necessarily mean retrofitting all fabric elements in the home. Rather it means ensuring that when retrofits take place, the impact this has on the performance and risk profile (energy or otherwise) of adjoining elements and the dwelling as a whole is considered.

Considerations include implications for ventilation, moisture, overheating, occupant comfort, and structural integrity. This concept is visualised in Figure 0-3, where the outcomes of the different retrofit approaches are outlined. The key difference is the level of risk that is associated with each approach, not how many measures are installed.

	Single measures	Multiple measures
Piecemeal	Higher risks Lower energy savings	Higher risks Higher energy savings
Whole house approach	Lower risks Lower energy savings	Lower risks Higher energy savings

Figure 0-3 Schematic of the piecemeal and whole house approach to retrofitting homes

3 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/837866/Invitation-to-Tender-for-Demonstration-of-Energy-Efficiency-Potential-DEEP.pdf

Over recent decades, retrofits have tended to install single measures; notably loft insulation, double glazing, and new gas boilers, installed at different times and often with many years between each retrofit. The design of these measures has not usually considered the interactions between them to any great extent, or how they affect other risks in homes, and so most retrofits taking place in UK homes have been piecemeal retrofits.

Installing retrofits via a whole house approach means consideration of how measures interact with those already installed, or those likely to be installed in the future. It should also consider how risks throughout the entire house may be affected by the retrofit. For instance, including, but not limited to:

- ensuring thermal bridges will not cause surface condensation in homes,
- providing adequate fresh air ventilation in the home to remove excess relative humidity and stale air in homes,
- reducing air moving through the fabric which may result in interstitial condensation or thermal bypassing by ensuring a continuous air barrier in homes,
- limiting overheating by reducing solar and excessive internal gains and facilitating purge ventilation.

Research methods

DEEP deployed building performance evaluations (BPE) to determine the physical performance and risks associated with energy efficiency retrofits for 14 case study homes, shown in Figure 0-4. The BPE tests provided the aggregate whole house heat loss, via coheating tests, as well as disaggregated heat losses from background (uncontrolled) ventilation, elemental U-values, and thermal bridging. In addition, laboratory testing was performed to determine the material properties of bricks. Energy, thermal, and hygrothermal modelling was used to explore technical performance and risk, which were also supported by surface temperature measurements in the homes.

Assessments were undertaken on the impact of the retrofits on predicted EPC score, fuel bills, energy use, and carbon emissions when different modelling tools and inputs are used. The modelling also allowed a range of additional scenarios and model input assumptions to be explored, for instance considering different insulation system designs, as well as performing sensitivity analyses, such as the impact of varying weather or occupant inputs.

Additionally, the Salford Energy House (a replica house inside an environmental chamber) was retrofitted under controlled conditions, to confirm trends observed with more precision than is possible in the field. This also afforded the potential to explore the impact of retrofits on the efficiency of heating systems (heat pumps and gas boilers).

Longitudinal monitoring of the homes before and after the retrofits were installed was not in the scope of the project. Thus, the research could not assess the success of the whole house approach from the point of view of receiving feedback from occupants on their comfort and experiences. Additionally, DEEP could not assess retrofit impact from in-use measurements, for example assessing the impact on internal temperature or fuel bills. Modelling was instead used to assess these.

These methodologies are commonly used to investigate specific issues relating to building performance and risk. By bringing all these methodologies together in a single project, DEEP presented a unique opportunity for detailed investigations of retrofits in case study homes. General building performance evaluation tests used are described in the methodology report (2.01) and specific methodological details are described in the case study reports.

Figure 0-4 DEEP case study homes, left to right:

Top 17BG, 56TR, 01BA, 19BA,
Middle 57AD (left) & 55AD (right), 00CS, 27BG, 07LT (left) & 09LT (right),
Bottom 04KG, 52NP, 54N, 08OL

The case studies homes included 11 brick-built, one concrete *no-fines*[4] (04KG), one stone (00CS) and one *non-traditional*[5] (08OL) constructed of a mixture of brick, block, and concrete. The age ranges of the case study homes were from pre-1890s through to the 1960s.

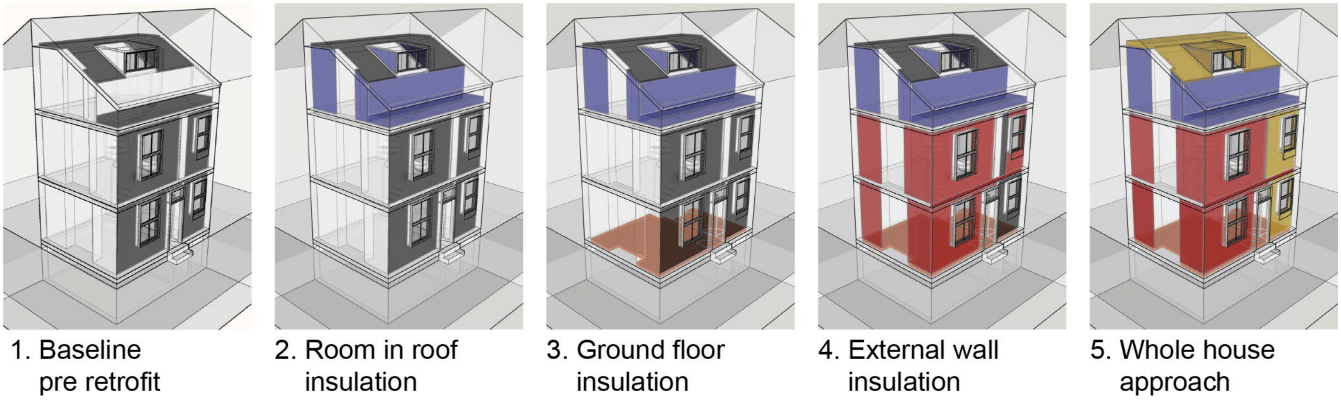
The homes were in varying conditions of energy efficiency with some homes already having some solid wall insulation, relatively new double glazing, or good levels of loft insulation. Others only had minimal energy efficiency improvements.

All the homes were provided by landlords around the North of England, except two located in the Midlands (55AD & 57AD). One home was detached, three were semi-detached, three were end terraces and five were mid-terraced. There were also three pairs of neighbouring homes in the sample.

[4] Type of construction using concrete with no fine aggregates poured in-situ
[5] Type of construction that does not use brick and block walls, often including pre-fabricated concrete panels

Methodology to investigate the whole house approach
Adopting the whole house approach and complying with technical standards (PAS2035) [2], requires additional activities to take place that installers and designers may not have previously considered, to ensure the retrofits will be delivered safely and effectively, and that consumers are protected. However, there is uncertainty around which actions are essential in different situations, leading to variation in practice and the technical performance and risks in homes.

To explore these issues in DEEP, the case study homes were first installed with piecemeal measures one-by-one, and finally converted to whole house approach retrofits, i.e. the additional activities to remove discontinuities in the insulation layer. This is illustrated by Figure 0-5, where only in the final whole house approach stage were interactions between insulation measures considered.



Grey **Existing insulation of unknown performance**
Purple **New room in roof insulation**
Orange **New suspended timber ground floor insulation**
Red **New External Wall Insulation (EWI)**
Yellow **New insulation to remove discontinuities and replace poorly performing insulation**

Figure 0-5 Representation of typical retrofit stages in the DEEP case study homes

The number of retrofit stages, and the extent of additional activities undertaken to ensure discontinuities were removed in the final retrofit stage, differed from house-to-house, and are described in detail in each case study report.

This methodology allowed the differences in fabric design of piecemeal versus whole house approaches to retrofit, on technical performance and risk, to be evaluated to understand the extent and effect of discontinuities in the insulation layer on:

- plane element heat loss
- background ventilation heat loss
- thermal bridging heat loss
- surface condensation risks
- interstitial condensation risk
- overheating risks

Without longitudinal in-use monitoring, the impact of improving ventilation in the home on internal conditions (relative humidity (RH), internal temperature, air movement etc.) could not be investigated. Data on the extent to which these internal conditions are improved are needed to provide a holistic understanding of the benefits of the whole house approach to retrofit.

In total, 41 fabric retrofits were installed in the 14 DEEP case study homes, 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 0-6. For instance, code *17BG.IWI.WF* refers to the test house 17BG, and the internal wall insulation (IWI) retrofit stage which used Wood Fibre insulation (WF). For simplicity this can be referred to as 17BG.W (wall retrofit), though the full code is described in the below summary for added clarity.

Figure 0-6 Overview of case study homes and retrofits

The DEEP project provides evidence to support the importance of the whole house approach and identify which unintended consequences can occur in piecemeal retrofits. The evidence identifies energy, carbon, and risk reduction, as well as broader benefits, of the whole house approach. It also considers financial costs, so that a risk-based, cost-optimal approach can be adopted. Thus, data provided can support better retrofit decision-making at all levels. More research will be needed to explore a broader range of homes, constructions, and retrofit scenarios to determine how representative these findings are for the UK housing stock. Complementary evidence on the in-situ performance of homes following whole house retrofits may provide useful additional insights to support and build upon findings from DEEP.

1. What are the most effective retrofits for solid walled homes?

Solid wall insulation (SWI) is among the most expensive and complex retrofit measures to be undertaken in homes. It is therefore useful to understand if solid walled homes can be brought up to acceptable energy efficiency levels without requiring SWI. This section explores the energy efficiency potential for retrofits in solid walled homes.

DEEP investigated the effectiveness of multiple retrofit measures; some in isolation, others in combination. After each retrofit was installed, building performance testing was undertaken so that the technical performance of each retrofit stage could be assessed, independently and collectively. The reduction in whole house heat loss, or *heat transfer coefficient* (HTC), was measured by the coheating test (details are provided in DEEP Report 2.01 Case Study Methods), which calculates the steady-state heat loss through the thermal envelope of a building. HTC reductions achieved by individual retrofit measures in the case study homes are presented in Figure 1-1. The reduction and the test uncertainty range of each individual retrofit is shown. Any range which overlaps zero is not considered statistically significant.

The results show how variable the reduction in heat loss can be for different homes and retrofits depending on their idiosyncrasies. The material properties of fabric, the presence or otherwise of existing insulation in the homes, the size of the home and its insulated (or replaced, in the case of windows and doors) areas, and the extent of existing air leakage and thermal bridges, all had an impact on how effective the retrofits were. Savings also depended on the specification of the retrofit, e.g., the thickness in which insulation was applied or its thermal conductivity. These differences mean predicting the success of retrofits in homes is extremely challenging. Some trends, however, can be observed. For instance, SWI is the only retrofit that always achieved savings with statistical certainty, confirming findings from previous studies. Other retrofits sometimes achieved significant savings, but usually the impact of the retrofit was within the uncertainty of the test, (i.e., the uncertainty bounds extended below 0%).

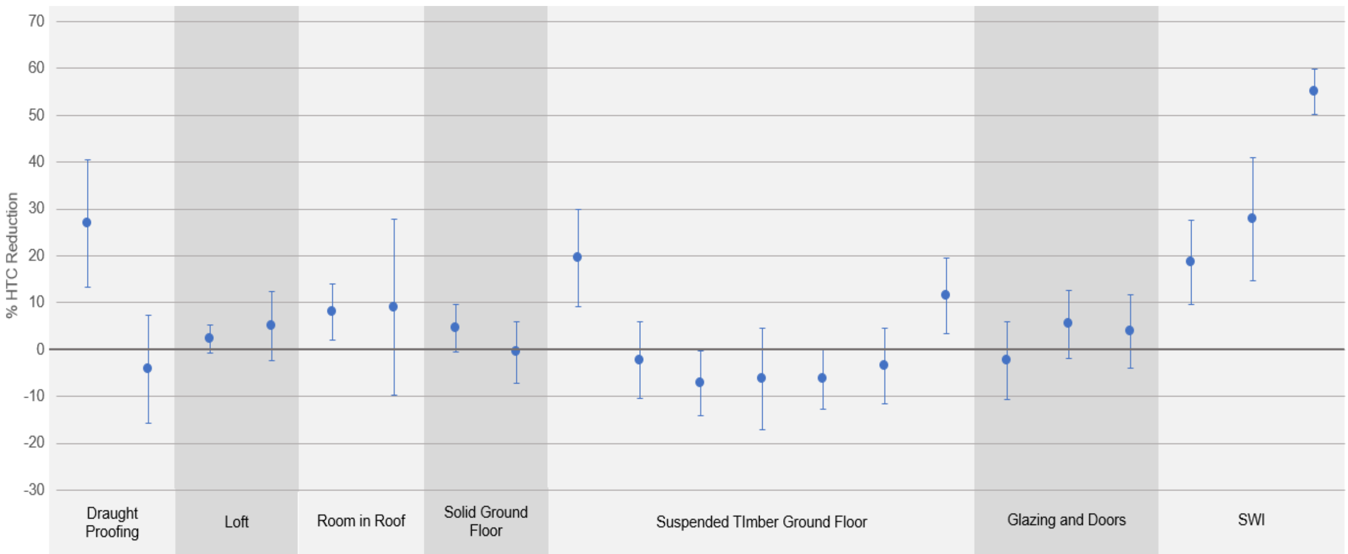


Figure 1-1 Heat transfer coefficient (HTC) reductions achieved by piecemeal retrofits. Blue bars show the range (including uncertainty) of the reduction for each individual retrofit. Any range which overlaps zero is considered not statistically significant.

Combining measures in the case study homes was more likely to achieve statistically significant reductions in HTC than individual interventions. This is shown in Figure 1-2, where in most instances, a significant reduction was achieved by the multiple measures installed. The scale of saving was highly variable and, again, determined by the specific home and retrofits being installed. Combining SWI with other measures was by far the most effective approach and led to reductions of up to 60% in HTC.

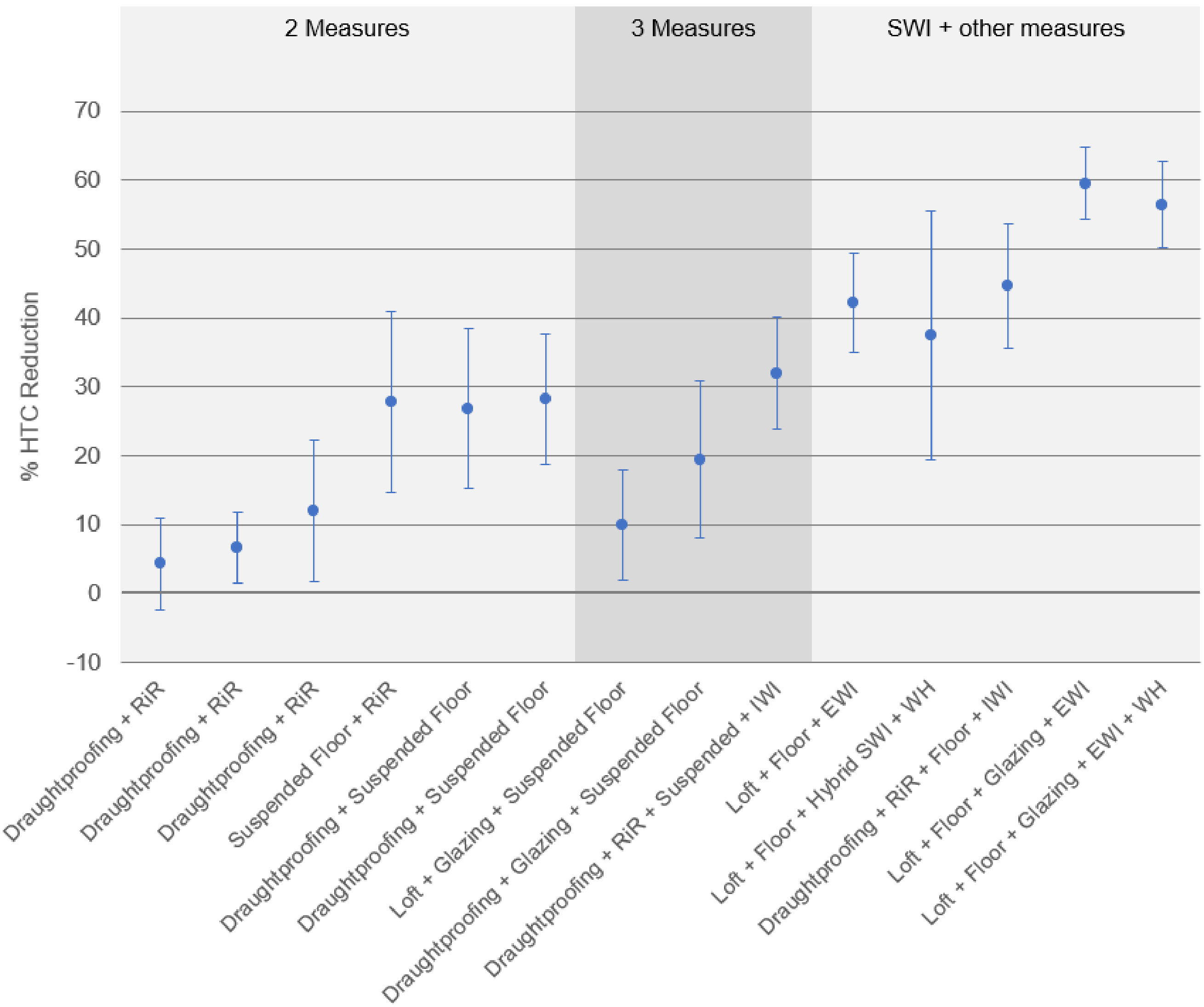


Figure 1-2 HTC reductions achieved by combining measures (RiR = Room in roof retrofit, WH = additional measures to remove discontinuities). Blue bars show the range (including uncertainty) of the reduction for each retrofit.

These savings are specific to the case study homes being investigated. The measured reductions in HTC may be indicative of those realised in similar dwellings but may not be representative of expected savings in other property types. The DEEP Literature Review[6] also identified variations in the success of retrofits, as outlined in Table 1-1. The reductions are similar to previous findings, though there is considerable measurement uncertainty.

[6] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/972027/deep-literature-review.pdf

Table 1-1 Range of HTC reductions achieved by retrofits in DEEP compared to literature

Retrofit (no. of DEEP homes)	DEEP literature review	DEEP case studies	DEEP case studies (inc. uncertainty)
Draught-proofing (n=3)	n/a	0 - 27%	0 - 41%
Loft insulation (n=2)	4% - 17%	5% - 8%	0 - 14%
Room in roof (n=2)	n/a	5% - 9%	0 - 28%
Windows & doors (n=3)	6% - 15%	0 - 5%	0 - 13%
Suspended timber ground floor (n=6)	9% - 25%	0 - 11%	0 - 20%
Solid ground floor (n=2)	n/a	4% - 20%	0 - 40%
Solid wall insulation (n=3)	13% - 68%	19% - 55%	10% - 60%
Multiple measures excluding SWI (n=9)	12% - 20%	4% - 32%	0 - 41%
Multiple measures including SWI (n=5)	35% - 56%	38% - 60%	19% - 65%

For the DEEP case studies, the impacts of the heat loss reductions on fuel bill savings have been estimated by various pieces of modelling software. Details of these are provided in the case study reports. Savings predicted by three different models are shown:

i. The Reduced data Standard Assessment Procedure (RdSAP), using all the default inputs used in EPCs [3].
ii. The Building Research Establishment Domestic Energy Model (BREDEM) [4], which is the underlying calculation tool of RdSAP. The BREDEM models represent what the EPC would be if using measured airtightness and in-situ U-values, and where possible, thermal bridging calculations (i.e., “updated inputs”), to better represent the case study buildings.
iii. Dynamic Simulation Modelling (DSM) predictions using DesignBuilder [5], which also have default inputs replaced with updated inputs.

The most common and simplistic assessment of retrofit effectiveness is to compare how the SAP points and resulting EPC Bands change as the retrofits are installed. This is illustrated in Figure 1-3 for each of the case study homes and their retrofit measures, according to RdSAP.

Most of the homes in the base case were Band D, with three being in Band C (since these had EWI installed previously) and two in Band E (one stone cottage and the other an end terrace Victorian back-to-back home). Every SWI retrofit was successful in bringing the homes up to a Band C. However, even though most other measures did increase the number of SAP points achieved, they were not effective enough to bring the homes up to a Band C, with the exception of the room-in-roof retrofits in 07LT and 09LT.

SAP points and EPC bands are not, however, a good indication of the actual energy efficiency of the homes or effectiveness of the retrofits, since they rely on default input assumptions for airtightness, U-values and thermal bridging heat loss, among others. Indeed, the measured savings for room-in-roof retrofits were much lower than the predictions.

Figure 1-3, therefore, shows what the EPC might be if these defaults were updated with measured and calculated values. As can be seen, the SAP points are similar, sometimes higher and sometimes lower than the default predictions. However, some important differences can be observed. For instance, when the defaults are replaced, 17BG becomes an EPC band D instead of E, even in the base case. This is due to 17BG having some IWI installed prior to the DEEP retrofits, which was not considered by the EPC because it was <50mm. Similarly, the benefit of the <50mm solid floor insulation in 00CS and 04KG was only shown when the defaults were updated.

None of the airtightness retrofits show any benefit in the default EPCs, since airtightness values cannot be input into the EPC software. However, when the defaults are replaced, the benefits of being more airtight are shown. Conversely the benefit of room-in-roof retrofits generally *reduces* when the defaults are updated, since there is often pre-existing insulation in these locations that are not captured by the defaults. In some instances, updating the default information can even pushes the homes into a different EPC band (e.g. 27BG), depending on how close the home is to a band threshold.

Regardless of which inputs were used, none of the measures (individually or collectively) were able to bring any of the homes to an EPC Band B. However, the retrofits undertaken in these case study homes were undertaken specifically to explore a range of different fabric improvements, and it was not the aim of the retrofits to achieve a particular EPC band. Therefore, the retrofits did not change any other features of the homes which also contribute to the EPC scores such as lighting, heating, hot water systems, or renewables.

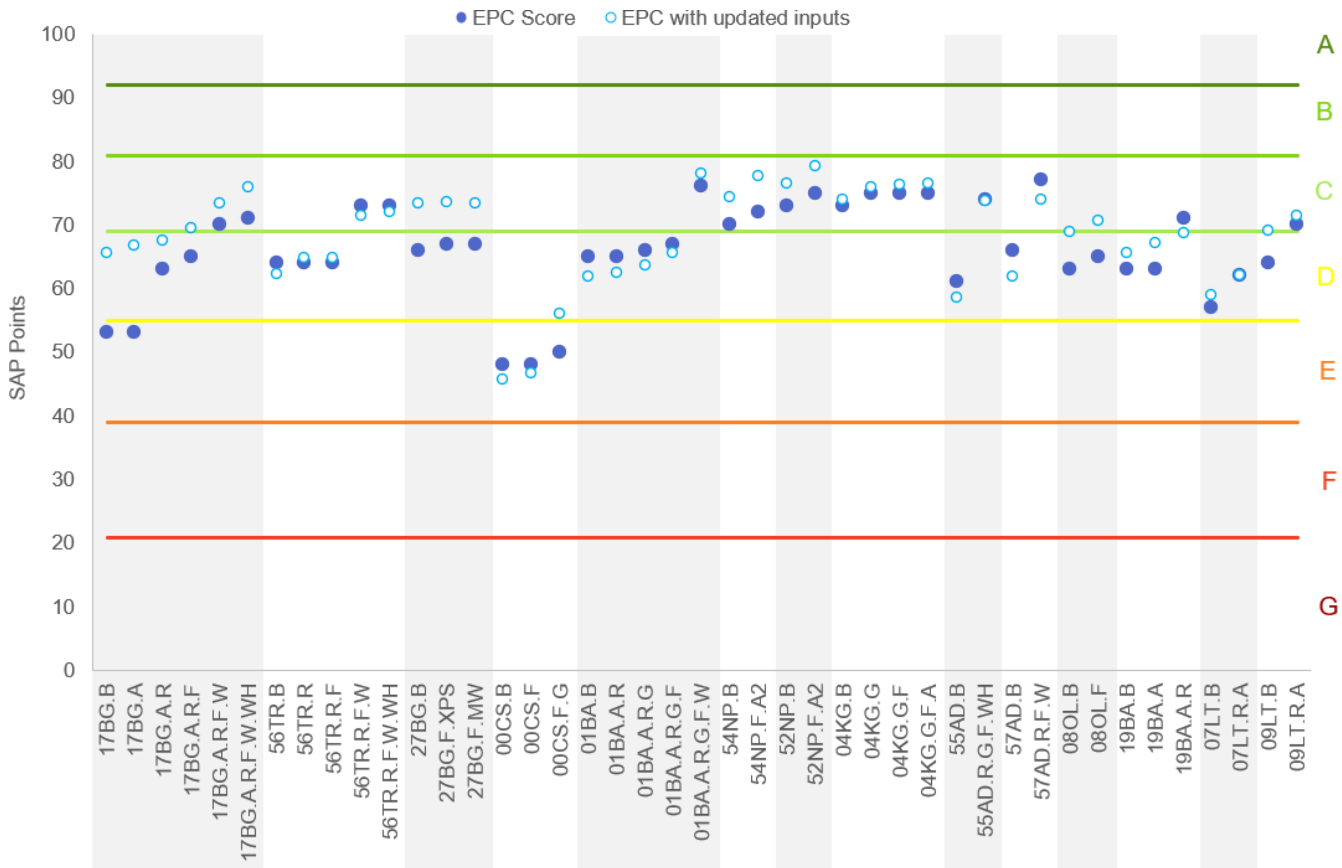


Figure 1-3 SAP points and EPC bands of case studies before and after each retrofit

Figure 1-4 illustrates the estimated annual fuel bill reductions across the DEEP case study retrofits according to each of the different models employed. The default EPC predictions show the greatest savings, while the DSM estimates using updated inputs predict the lowest savings. Sometimes no savings are predicted at all for EPCs where the measure cannot be input to the software. The reasons for these issues are discussed in Section 3.

Only SWI (and multiple measures including SWI) are predicted to achieve higher than 10% fuel bill savings per year, and as much as 38% (with BREDEM models) where homes have a large area of external wall and the SWI achieves a low U-value. EPCs predict that room-in-roof retrofits could also achieve over 10% fuel bill savings. However, this is because they assume much larger uninsulated room-in-roof fabric U-values, which will again be discussed in Section 3 of this report. Thus, these savings are not expected to be achieved in practice.

The findings highlight that SWI is by far the most significant retrofit, which has implications for the focus of future retrofit policy, and that the savings predicted for the different retrofits can vary substantially depending on the surface area that is treated in each home and the presence of existing insulation.

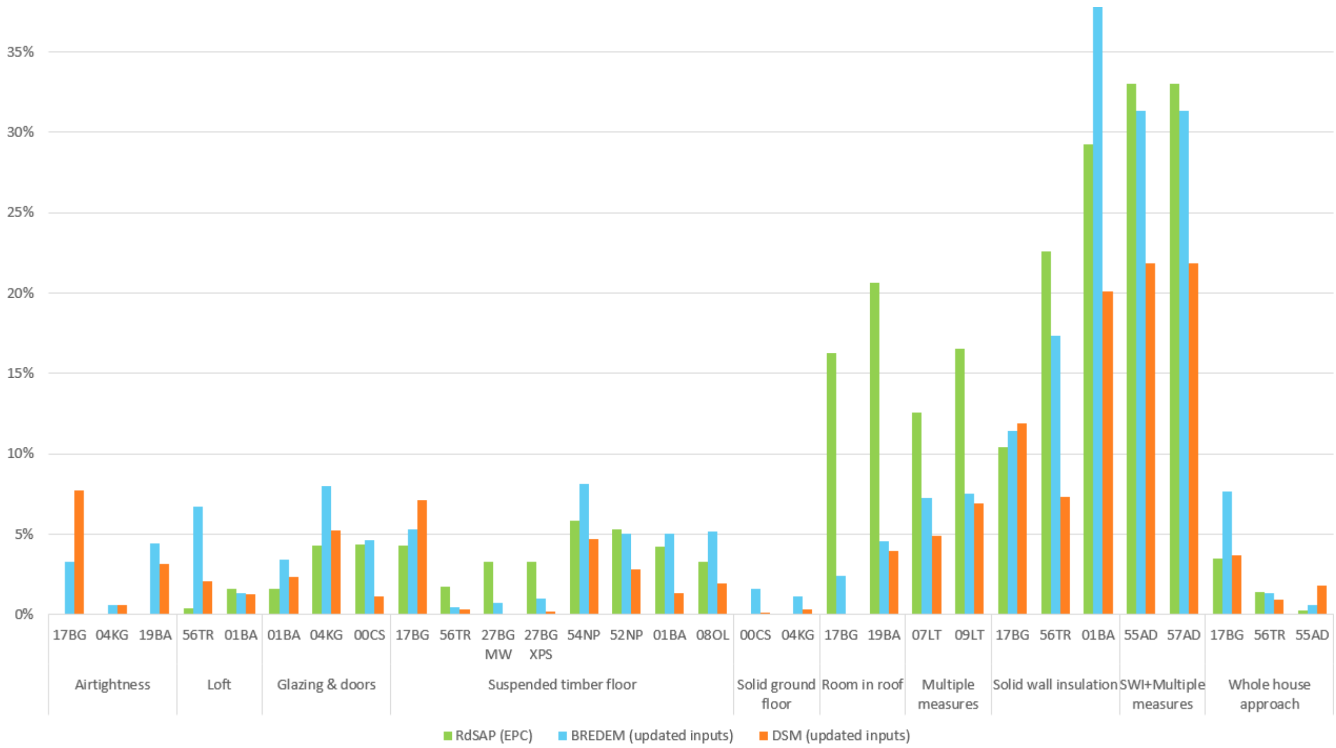


Figure 1-4 Modelled fuel bill savings for case study retrofits

Insulating homes improved U-values substantially. Often the improvements were lower than expected, though on occasion the improvement exceeded expectation. Figure 1-5 plots the U-value ranges used by the EPC defaults, those calculated according to estimates of the construction make-up, and those measured using heat flux plates.

The U-values are much more variable pre-retrofit, reflective of the variability in the original fabric performance. The low thermal conductivity of retrofitted insulation then becomes the dominant influence post-retrofit, reducing this variability. The measured pre-retrofit U-values for lofts and floors were similar to the EPC defaults. However, measured U-values of walls and sloping ceilings were often lower than the EPC defaults. This could be a contributing factor to the EPC predicting higher energy use than was measured in uninsulated homes and merits further exploration in future RdSAP updates.

Where the insulation used in the homes was below 50mm thickness the RdSAP post-retrofit U-values were identical to the pre-retrofit value, as RdSAP does not allow insulation less than 50mm thick. The calculated U-values were not always well aligned with either the default or the measured U-values, due to unknowns in the construction of the fabric, meaning outputs from these models may not be robust.

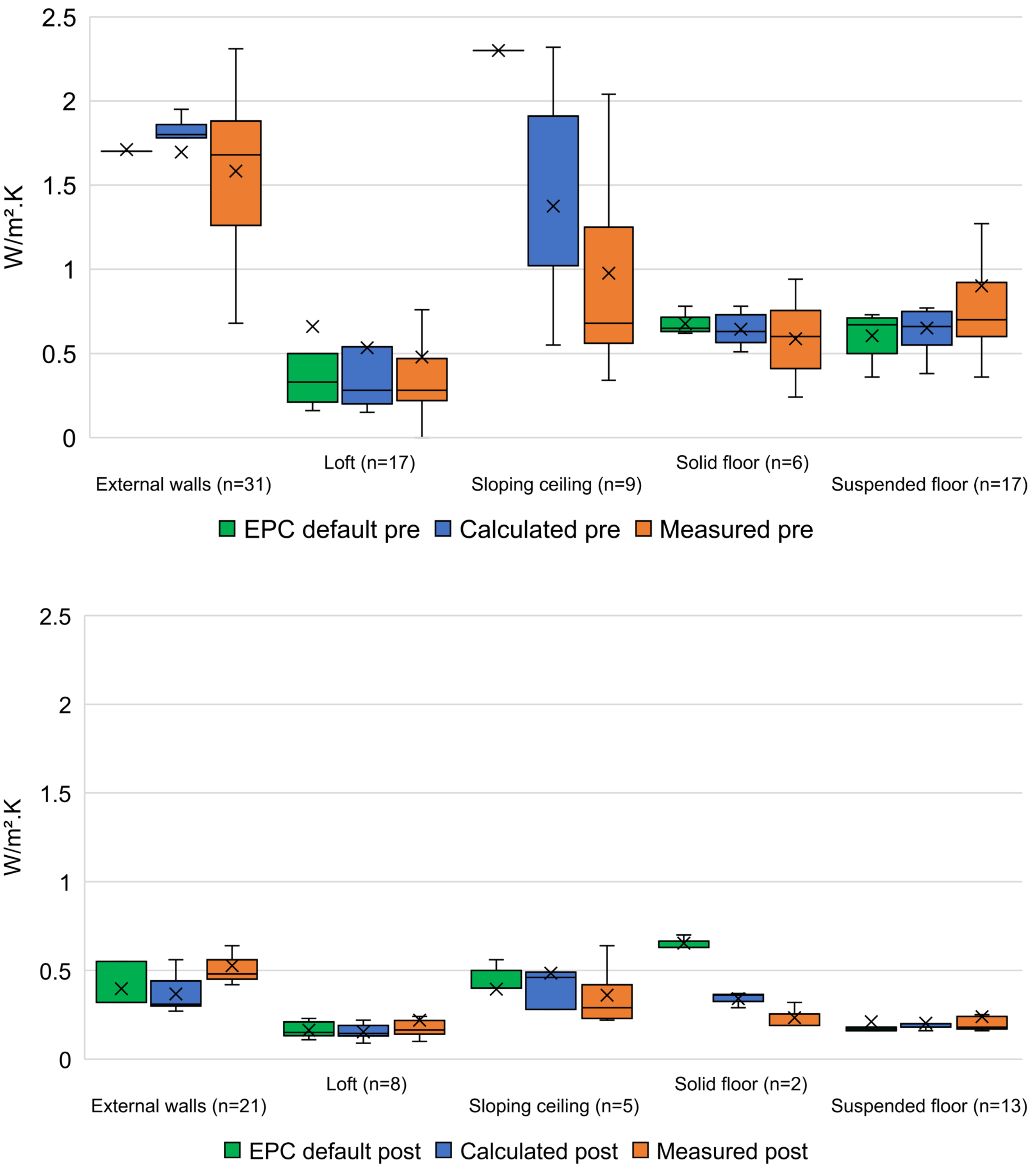


Figure 1-5 U-values in case study homes pre- (top) and post-retrofit (bottom), where n= number of elements, e.g., there was more than 1 external wall type per dwelling

The following sections outline some of the issues discovered when undertaking retrofits in the homes.

Draught-proofing

The airtightness improvements undertaken in the DEEP case study homes were, in the most part, draught-proofing measures. These relied on mastic sealing of gaps and cracks around penetrations and floor perimeters, as well as some instances of replacing boxed-in services and vents.

Approaches to improving the airtightness in existing homes have become more sophisticated since the start of the DEEP project as new techniques, developed from Passivhaus approaches, are being applied to historic buildings and low energy housing exemplar retrofits. For instance, sealing to existing (e.g., wet plaster) or new (e.g., floor membranes) primary air barriers with tape on a room-by-room basis. These approaches were not adopted in the DEEP retrofits, which used more standard practice for draught-proofing specialists i.e., the use of mastics and general-purpose tapes. However, the findings from the case studies revealed significant challenges which apply to both draught-proofing and more advanced airtightness improvements.

The success of the DEEP draught-proofing or airtightness interventions is illustrated in Figure 1-6. Reductions were often minor, with notable exceptions, indicating how variable the savings can be. Where improvements were achieved, whole house heat loss was reduced by 0 - 27% and modelling of the case study homes suggests these improvements resulted in between <1% and 8% reductions in household fuel bills.

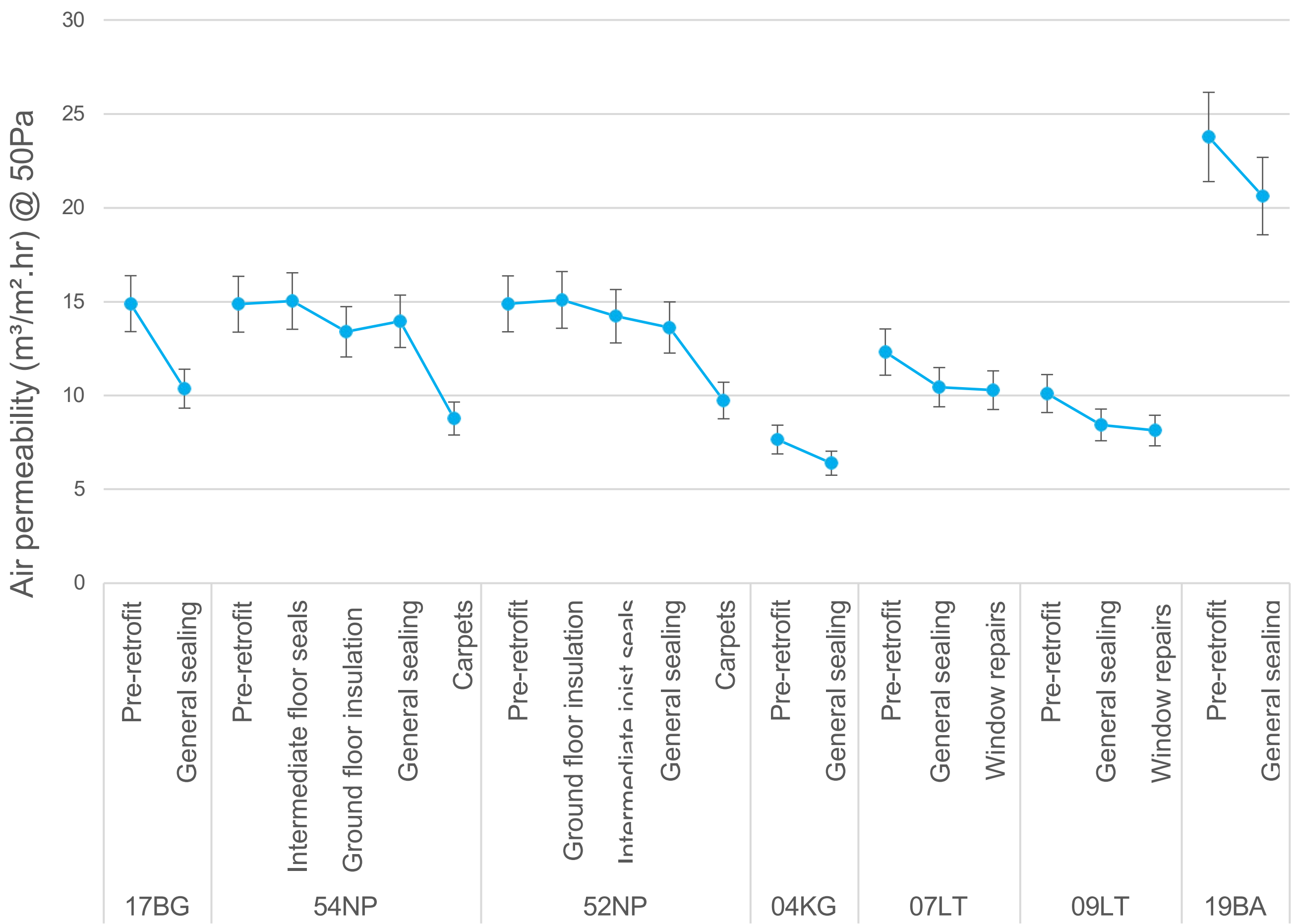


Figure 1-6 Reduction in air permeability from draught-proofing

Savings are unpredictable since they depend on the air leakage pathways of the original home, which are not always accessible. For a minority of homes excessive air leakage is a significant problem that should be addressed as part of the whole house approach to retrofit.

For instance, one home (19BA) had more than three times the maximum air leakage permitted for new build homes [6], and across the case study homes air leakage was found to contribute as much as a third of whole house heat loss.

Where air leakage pathways are short, simple, and direct to outside, they are relatively easy to address using draught-stripping and sealing of visible gaps. However, access to where the air enters or leaves the habitable space is often not straightforward. Effective sealing of these air leakage pathways may require the removal and reinstatement of fixtures and fittings such as boxed-in pipework, baths and sinks, plinths, and kitchen fittings, which is very disruptive.

Complex indirect air leakage pathways occur where the infiltrating or exfiltrating air travels through a number of inter-linked internal voids (e.g., via intermediate floor voids, boxed-in service voids, partition wall voids, voids behind dry lining or via micro cavities in solid walls). These indirect air leakage paths can be long, convoluted, and problematic to resolve. Figure 1-7 shows examples of direct vs. indirect air leakage pathways found in the DEEP homes.

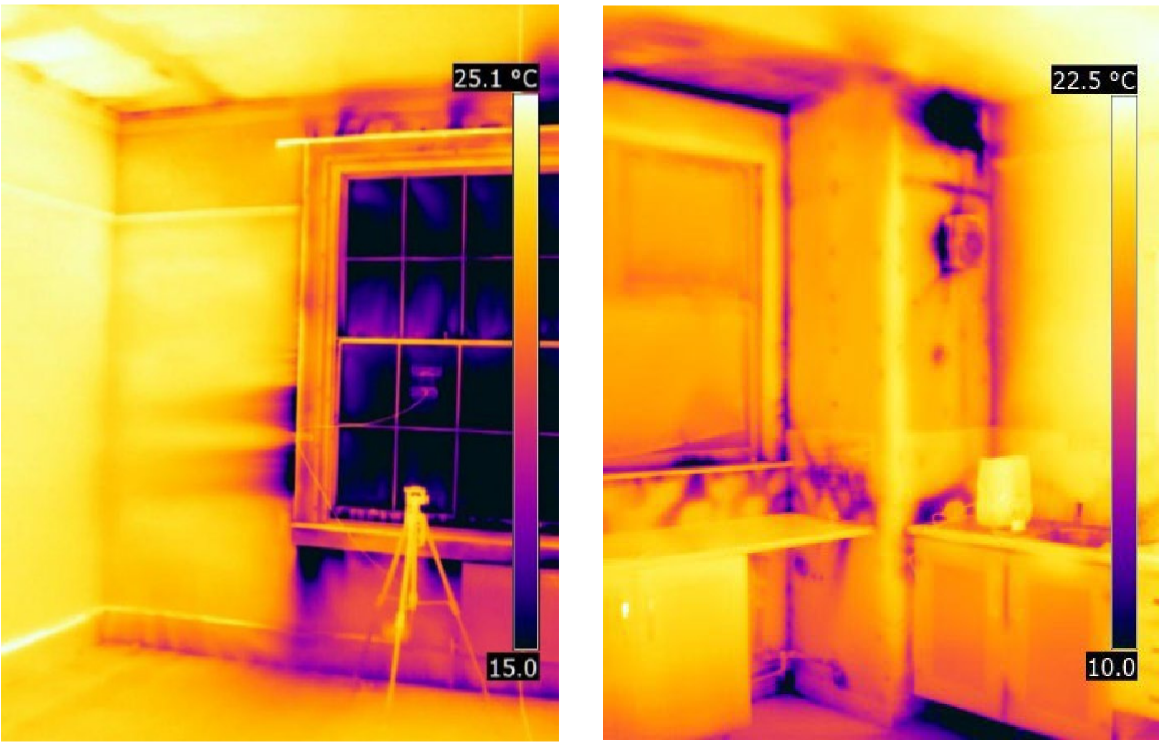


Figure 1-7 Left: direct air leakage around window frames, Right: multiple indirect air leakage pathways via boxed-in services, via electrical sockets, within bay roof ceiling and under kitchen units and suspended timber floor

The presence of complex and hidden air leakage pathways means that the costs of achieving reductions can be high, results are uncertain, and attempts to improve airtightness via draught-proofing may simply redirect rather than eliminate these air leakage pathways. There may, however, be a comfort benefit of removing draughts from occupied spaces. More advanced airtightness retrofit measures that adopt specialist tapes and membranes to seal between fabric elements may have more potential to achieve savings.

One of the simplest and most effective measures to improve airtightness in the case study homes was fitting floor coverings on all timber floors. Timber floors represent a significant proportion of potential air leakage areas in homes, i.e., direct air leakage through suspended ground floors and indirect air leakage through intermediate floors.

While most homes already have carpets, this does have implications for social housing, where floor coverings are often removed between tenancies for hygiene reasons. Installing alternative permanent floor coverings, sealed at perimeters, could maintain airtightness and allow coverings to be replaced to maintain hygiene.

The findings suggest that air leakage can be responsible for a large amount of heat loss from homes but also that the extent and location of air leakage cannot be predicted or simply observed in advance of undertaking retrofits. This means that in most instances it may not be possible to effectively adopt a whole house approach unless air leakage tests have taken place pre-retrofit. Where conductive heat loss through the building fabric is reduced by installing insulation, the proportion of heat loss due to air leakage, if unaddressed, becomes increasingly important. However, the installation of insulation can also cause incidental changes in airtightness. These are shown in Figure 1-8.

The scale of the changes was often small, with a few exceptions where draught-proofing was installed, or additional works were undertaken to ensure continuity of the insulation layer, as required by whole house retrofit approach. In some instances, the floor insulation and room in roof retrofit resulted in a marginal increase in air leakage (shown as negative air permeability), though this was often within the error of the blower door test.

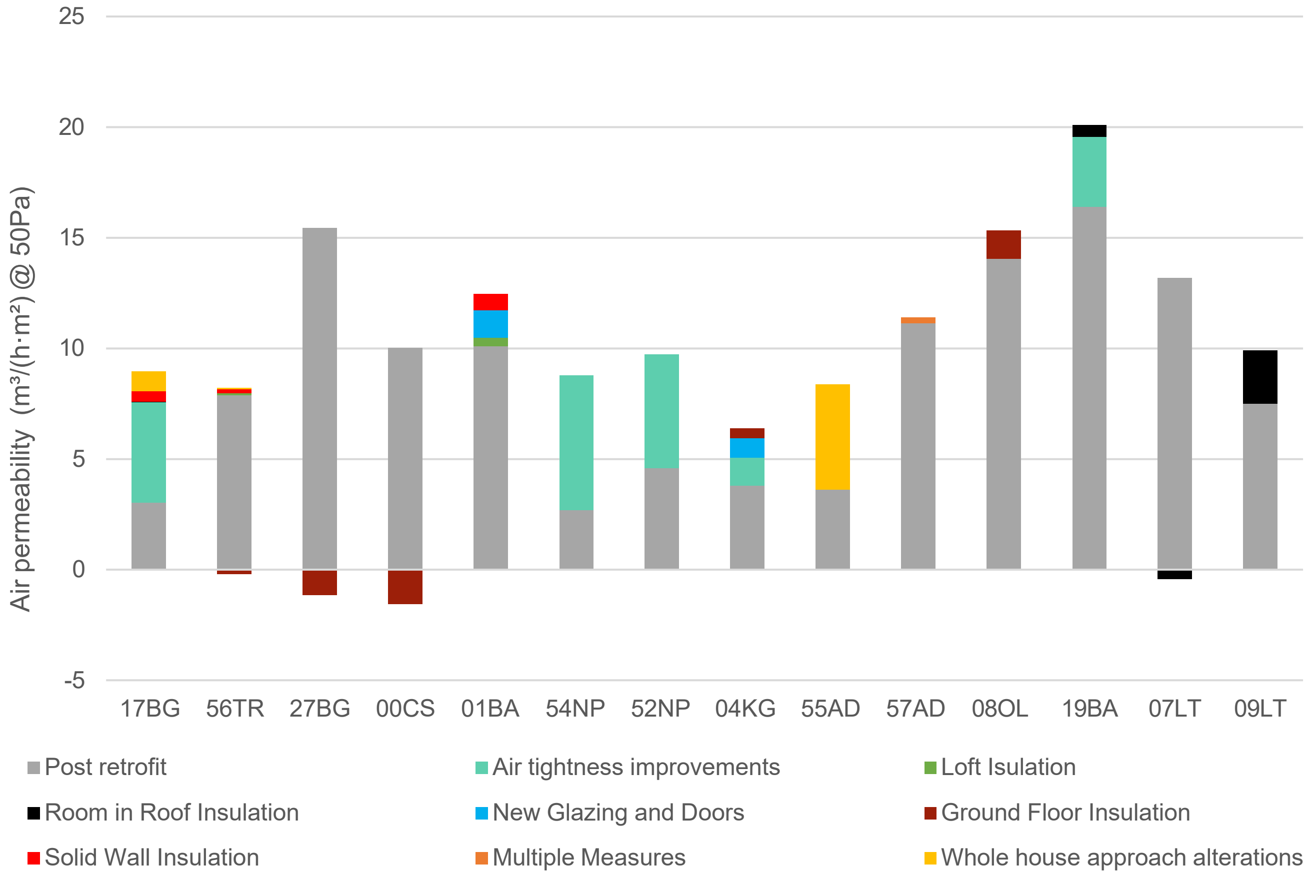


Figure 1-8 Reduction in air leakage after fabric retrofits in case study homes (grey = final air permeability of homes post-retrofits)

Airtightness tests in a separate sample of 146 homes were undertaken as part of the DEEP energy efficiency surveys described in DEEP Report 3.00. Although not a statistically nationally representative sample, this nonetheless provides useful context on the airtightness of homes in the UK housing stock and broadly agreed with findings from similar studies [7].

As shown in Figure 1-9, this sample identified that there are some homes with excessive air leakage; 10% had air permeability over 15 m³/(h·m²) @ 50Pa, and 78% of homes had measured air permeability above the Building Regulations limiting value of 8 m³/(h·m²) @ 50Pa for new build homes.

It was not possible to identify characteristics (age, floor type etc.,) that would provide good predictors of which homes or house types would have particularly poor airtightness levels prior to testing. These findings confirm those from the case studies, and again imply that pre-retrofit airtightness tests of homes will be needed, in most instances, to achieve a whole house approach to retrofit.

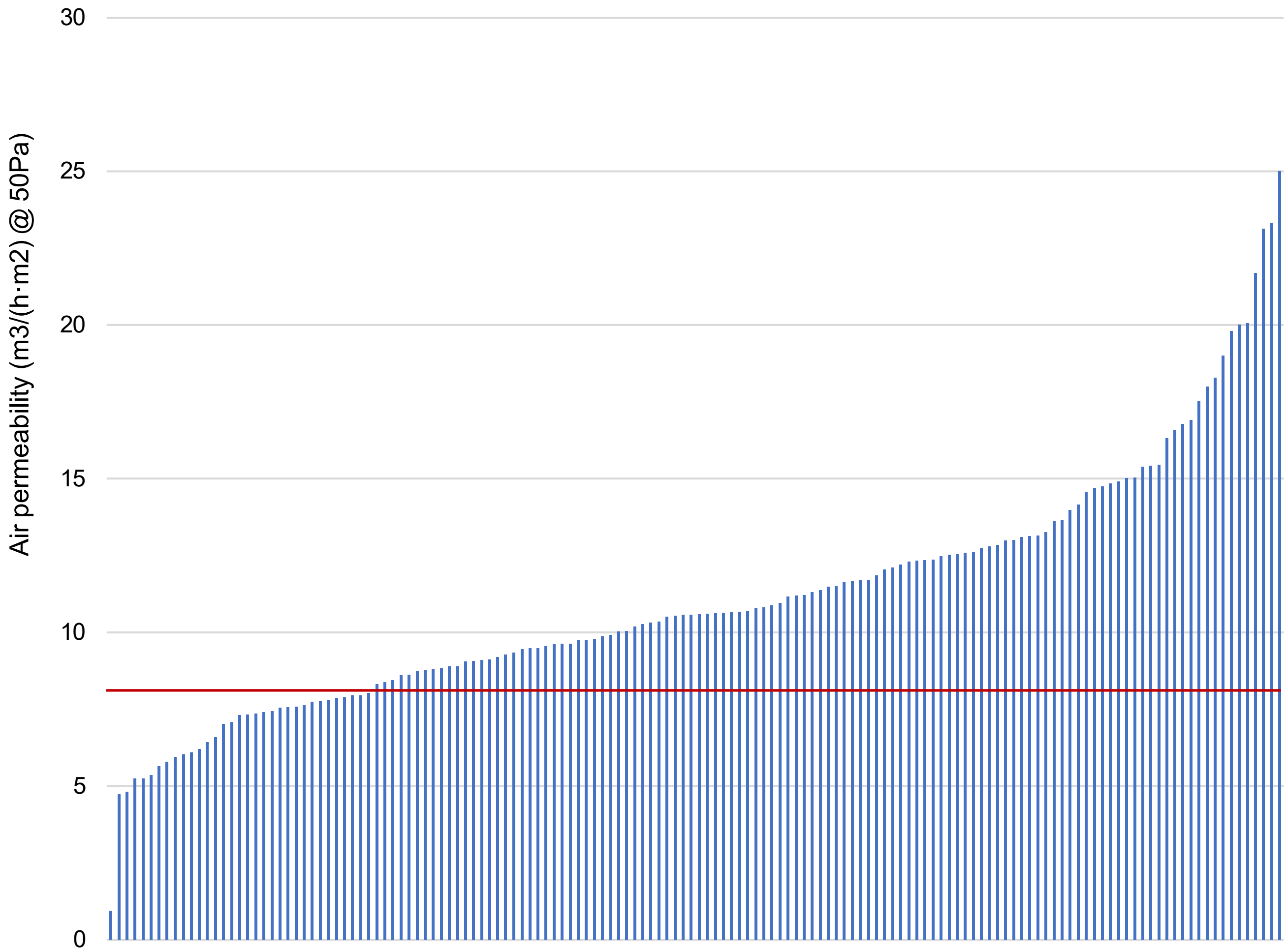


Figure 1-9 Airtightness in 146 homes tested as part of the DEEP project (red line = Building Regulations new build air permeability limiting value of 8 m³/(h·m²) @ 50Pa)

Loft insulation

Although most homes already have *some* loft insulation, it is not always in good condition and the insulation is often thin. Loft inspections in 114 homes under the DEEP energy efficiency surveys, described in DEEP Report 3.00, suggest that three quarters of homes have less than 250mm, and many were disturbed, so not performing to their original potential. Thus, topping up or replacing loft insulation is a viable retrofit measure.

When loft insulation was installed in two DEEP case study homes it was effective and resulted in fuel bill reductions between 1 and 7%. The EPC model however only predicted savings up to 2%, since it assumes pre-existing loft insulation performs perfectly. One benefit of topping up loft insulation as a retrofit measure, beyond the direct U-value improvements, is that issues such as discontinuities in loft installation, damp, damaged or compressed insulation and blocked ventilation pathways, can be resolved.

Many thermal bridges were observed in the case study homes, where loft insulation was missing e.g., behind hard-to-reach purlins, due to displacement during alterations to services (e.g., installing ceiling lights for rooms below the loft, removing water tanks or rewiring), or disturbances caused by occupants storing items. This is shown in Figure 1-10.

Figure 1-10 Disturbed loft insulation in case study home causing thermal bridging (left: insulation moved to install wiring, right: Purlin obstructing access to insulate)

Some disturbances of loft insulation were calculated to reduce the surface temperature of ceilings, which could increase the risk for surface condensation. In some instances, rectifying these thermal bridges reduced heat loss by as much as undertaking a full loft top-up. This highlights the importance of attention to detail in loft retrofits. Furthermore, removing existing loft insulation where it was in poor condition was expensive when performed as an individual task, whereas in cases where existing insulation was in good condition, loft top-ups were cost-effective.

Although loft insulation is one of the most common retrofits in UK homes, the findings from the case studies suggest that they have not been installed via a whole house approach, meaning they have embedded risks in homes. For instance, previous loft retrofits in some case study homes were observed to have inadequate ventilation, which may result in moisture being trapped in the cold loft space. Additionally, loft hatches were usually unsealed, i.e., warm moist air from the home could enter the cold unventilated lofts further increasing the chance of condensation. Uninsulated hatches were also common, posing a condensation risk until they were insulated during the DEEP retrofits. An example of these common issues is shown in Figure 1-11.

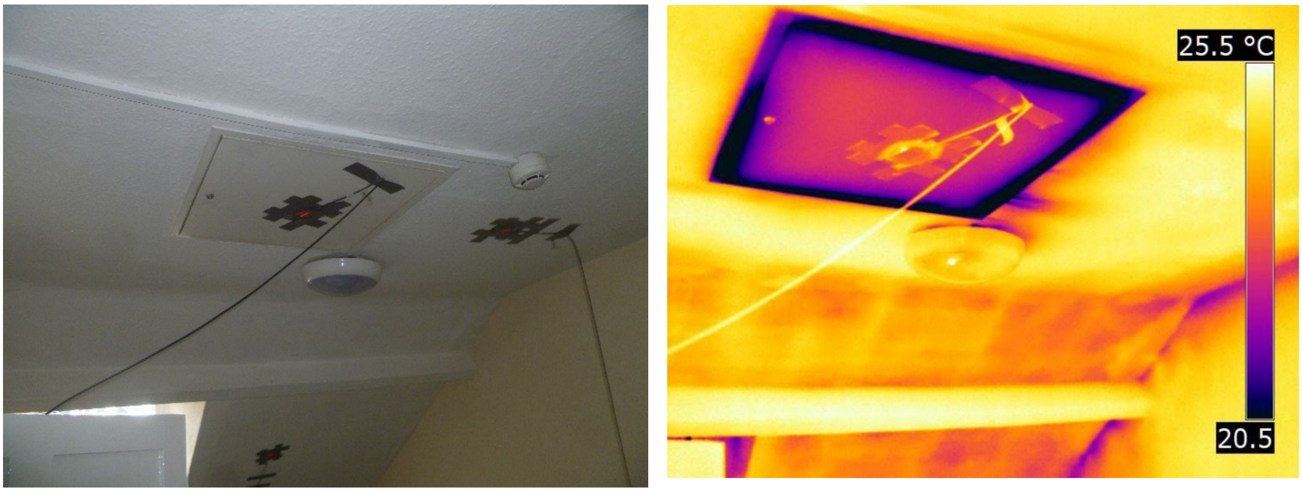


Figure 1-11 Example of unsealed and uninsulated loft hatch

Room-in-roof insulation

Many solid walled homes in the UK are built with rooms-in-roof or have had cold roof spaces converted to habitable rooms. These rooms tend to have complex geometry, multiple junctions between elements, and inconsistent levels of insulation. This makes them particularly prone to thermal bridges as well as excessive air leakage, heat loss, and summertime overheating.

These traits were all found in the DEEP homes with rooms-in-roof. In total four room-in-roof retrofits were undertaken in the case study homes. This involved stripping the fabric back to the structure for each heat loss element (typically knee walls, sloped ceilings, and dormer elements) and adding new insulation.

This was a disruptive and messy retrofit, which required not only enabling work (such as moving plumbing), but substantial additional work, like fixing roof leaks and repairing or replacing roof timbers, windows, and dormers before insulation could be added. Further, debris in lofts needed clearing and plaster removing in preparation for insulation. This was extremely disruptive, releasing decades worth of soot into homes which required cleaning post retrofit, (all of which added considerable cost to the retrofit), as shown Figure 1-12.

However, the room-in-roof retrofits in DEEP were predicted to reduce overheating risk and improve the temperature factors of room-in-roof junctions to above the critical threshold, meaning surface condensation is less likely. They also achieved predicted energy bill reductions between 1 and 8%, though the EPC predicted savings were between 13 and 21%, due to unrealistic default inputs in the EPC (discussed further in Section 3).

Energy savings depended on the size of the room-in-roof and the amount of external wall that was insulated (e.g., gable walls). Additionally, sloping roofs and knee walls often already had some insulation fitted, e.g., thin polyisocyanurate (PIR) or expanded polystyrene (EPS) laminate boards.

Figure 1-12 Disruption and excessive soot caused during room-in-roof retrofit

Access hatches needed to be insulated and sealed (or created) in ceilings and knee walls, which can require bespoke joinery. Furthermore, plumbing and electrical services often needed relocating (requiring specialist trades) and roofs and walls needed repairing (requiring scaffolding), all adding costs. Thus, achieving cost savings from retrofitting rooms-in-roof is challenging. However, the retrofit afforded the opportunity to identify existing maintenance and repair issues (e.g., leaking roofs, inadequate ventilation and repairs to brickwork) before they manifest as more serious issues.

New windows and external doors
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 full benefits of upgrading double glazing and external doors are not fully understood. Relying on simple comparisons of component or centre-pane U-values discounts the potential for airtightness, thermal bridging and aesthetic improvements. Although triple glazed windows are commonly installed in high performance homes, they are rarely retrofitted into standard existing homes and so were out of scope of this project.

Upgrading double glazed windows (or adding secondary glazing to single glazing), coupled with replacing external doors, only reduced heat loss and air leakage marginally in the case study homes. Post-retrofit testing was often undertaken prior to final decoration and caulking, since the landlord had a series of planned internal fit out and maintenance works outside the scope of the DEEP retrofits, so it is possible that this would have had an impact on results.

Models predicted homes would save between 1 and 8% on the case study homes' annual fuel bills. The addition of secondary glazing in one case study home; 00CS, a pre-1900 stone cottage, was as effective at improving thermal performance and airtightness as installing double glazing units in the other case study homes. This indicates that secondary glazing is an effective retrofit option where it is important to maintain the original external appearance of homes.

Replacing half single-glazed, older timber external doors achieved the greatest improvement in air leakage and heat losses (Figure 1-13), though the impact on whole house heat loss was again marginal. This is unsurprising as the doors represent a small proportion (in some instances <2%) of a home's heat loss area. However, an additional benefit of note was the new doors were *secure by design*, a commonly applied industry standard to improve security of homes, a significant co-benefit.

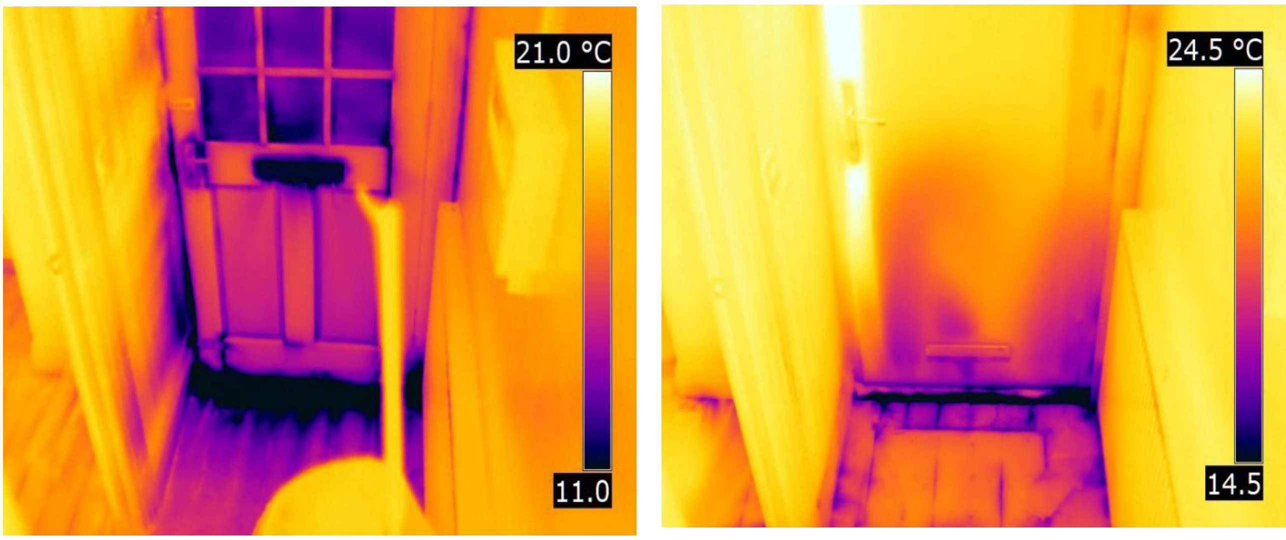


Figure 1-13 Left: Original timber external door Right: New composite insulated external door

Refurbishment of timber sash windows was undertaken in two case study homes, successfully restoring the opening and fixing mechanisms. However, the installation of draught-proofing brush strips at stiles and rails was not effective at eliminating air leakage at the elevated pressures of an airtightness test (Figure 1-14).

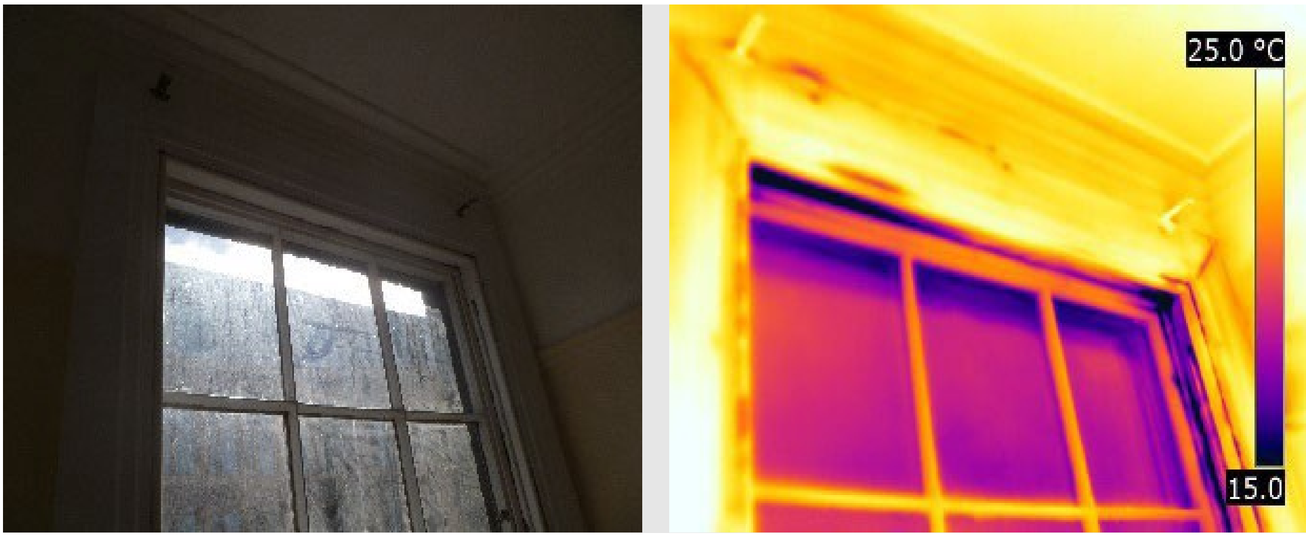


Figure 1-14 Air leakage present around upper sash window after repair and draught stripping

Another benefit of the window retrofits in some of the homes was that they now fit the structural openings when they had not done so before and were therefore a weakness in building fabric. New window design also allowed more openable area which was significant in reducing the risk of overheating in the homes, as well as ensuring that trickle ventilation was now present.

However, in the DEEP case study homes, removing existing window and door frames sometimes caused substantial damage to openings and required significant replastering, adding additional cost to the retrofit, as shown in Figure 1-15.

Figure 1-15 Damage caused during window installation

Suspended ground floor insulation

Millions of UK homes were built with suspended timber floors, which are often susceptible to air leakage. The impact of insulating suspended timber floors on reducing draughts and whole house heat losses is not well understood. Seven suspended timber floor retrofits were undertaken in the case study homes, using the traditional approach to suspended ground floor insulation of either mineral wool or extruded polystyrene (XPS) foam fixed between floor joists, as shown in Figure 1-16.

Figure 1-16 XPS (left) and mineral wool (right) suspended timber ground floor insulation

According to the EPC, the addition of insulation between timber joists would reduce fuel bills in the case study homes by between 1 and 8%, depending on the size and heat loss of the floor relative to the rest of the house, and the level of airtightness improvements achieved. Whether mineral wool or rigid foam insulation boards were used did not affect the savings, since they were designed to achieve similar U-values. Neither approach significantly increased the airtightness of the case study homes, despite being fitted with air membranes alongside the insulation retrofits. Repeat retrofits of the Energy House ground floor demonstrated that air membranes can increase airtightness when installed correctly, though their impact is dependent on workmanship. Thus, membranes can be effective in reducing air leakage through suspended timber floors, but they are susceptible to failures (Figure 1-17), and it is important that installers are aware of the significance of achieving continuous seals.

Figure 1-17 Left: Air movement through uninsulated suspended timber ground floor, Right: Air movement remains at room perimeters post mineral wool and air barrier installation

Addressing air leakage pathways through suspended timber floors using traditional insulation methods therefore requires careful detailing and is not always assured. Alternative approaches may be needed.

A novel approach to insulating suspended timber floors was also undertaken in one of the case study homes, which involved replacing the entire floor with a composite panel system. This was more successful in reducing airtightness (9% reduction) and was the most successful in reducing HTC, by 11 ± 8%, even though only half of home’s floor was suspended timber.

All the approaches to retrofitting the floors were very disruptive, requiring rooms to be clear. The removal of carpet grippers and lifting floorboards tended to damage the floor, often leading to entire sections of flooring needed replacing. In one case study the crawl space was adequately deep to allow access under the floor via the external wall, avoiding these additional costs and disruptions.

Another increasingly used alternative approach to insulating suspended floors is to apply spray foam insulation, by using a robot to access the floor void and install the insulation. This approach would avoid the additional disruption and costs of replacing the floor, which was observed in the conventional approach adopted in the DEEP case studies. The spray foam approach is also likely to address air leakage since it can provide an effective seal without requiring a membrane to be installed, though assessing the risks and benefits of this approach were out of scope of this project [8].

A benefit of all the floor insulation products installed was that ground floor surface temperatures were measured to increase, though not always. In some instances, increases of up to 1.4°C were measured, which can have comfort benefits as well as reducing the chances of surface condensation forming.

Finally, it was observed that in summer the sub-floor void was providing beneficial cooling, and so insulating suspended timber floors could marginally increase overheating risk by limiting this cooling effect. However, the provision of additional natural ventilation and shading of windows offset this risk.

Solid ground floor insulation

Retrofitting insulation into solid ground floors is a less common measure as it traditionally requires excavation of the existing solid floor before insulating and then laying a new floor, which is highly disruptive.

A less disruptive alternative is to install a layer of insulation on top of the existing concrete slab. This approach was undertaken in two case study homes. Insulation installed in one home was a 10mm aerogel blanket. The other used a 20mm aerogel blanket encapsulated by foil with 3mm ply covering, as shown in Figure 1-18.

Aerogel fibres have the potential to cause irritation to eyes, skin, and the respiratory system, so it is important to limit these fibres becoming airborne. Thus, the 10mm aerogel blanket was covered by a dust-protecting membrane, while the 20mm boards already provided dust protection. Although installing insulation on top of solid floors avoids the costs and disruption of removing the existing ground floor slab, the high cost of aerogel means install costs can still be higher than traditional approaches to insulating suspended timber floors.

Figure 1-18 Left: 10mm aerogel blanket, Right: 20mm aerogel panel

Models predicted that the retrofits could reduce fuel bills by up to 2% and reduce the home’s HTC by between 2 and 4%. However, the coheating tests measured a much larger 20 ± 10% reduction in HTC for the 20mm panel retrofit. This is possibly due to a reduction in a thermal bridge around the ground floor to solid wall junction, since this home previously had external wall insulation (EWI) installed without insulation below the damp-proof course (DPC). Therefore, homes without EWI may not achieve such a significant improvement.

This thermal bridging heat loss is not accounted for in EPCs, which only consider the benefit from improved U-values from retrofits. Furthermore, EPCs do not consider insulation thicknesses less than 50mm and so could not report any savings for either of the solid ground floor retrofits undertaken which implies that the current approach to EPCs means they cannot evaluate the carbon savings of retrofits where insulation thinner than 50mm is used.

Additionally, as with the case study homes with suspended timber ground floors, the retrofit was measured to increase the ground floor surface temperatures. This may improve comfort and reduce surface condensation risk on the floor and floor perimeter junctions with the walls.

Solid Wall Insulation
Insulating solid walls is seen as one of the most effective ways to reduce heat losses in solid walled homes, but it is not common since it is complex and costly to install. In the DEEP case studies, five homes were given new SWI retrofits. Three of these used external wall insulation (EWI), one used internal wall insulation (IWI), and one home had a hybrid of EWI and IWI.

All the retrofits achieved a significant improvement in U-values, although most did not fully achieve their intended performance. The installation of SWI was also the single most effective retrofit measure in reducing HTC. Post SWI, the majority of surface condensation risks in homes were removed and it was the most successful measure in reducing overheating risk. SWI was also the only retrofit that always resulted in homes achieving at least an EPC band C and the Social Housing Decarbonisation Fund (SHDF) space heating target of 90 kWh.m²/yr. HTC reductions were measured to be between 19 and 55%, depending on the home and type of insulation installed, and models predicted the savings would reduce energy bills by between 7 and 38% depending on how much external wall was insulated (e.g., mid-terrace homes with high glazing areas will have lower savings).

Savings also depended on whether homes already had some level of wall insulation installed. Measured pre-retrofit wall U-values from the case study homes often indicated existing IWI at the baseline stage, specifically polystyrene-backed plasterboard. This was found in several of the DEEP case studies (Figure 1-19), which reduced the potential to achieve savings from new SWI. However, it was noted that the insulated plasterboard used had often been installed with an unventilated cavity, which may increase risks of interstitial condensation. Thus, although the potential energy reductions from the new SWI retrofit were smaller in these homes, it was an opportunity to remove this risk.

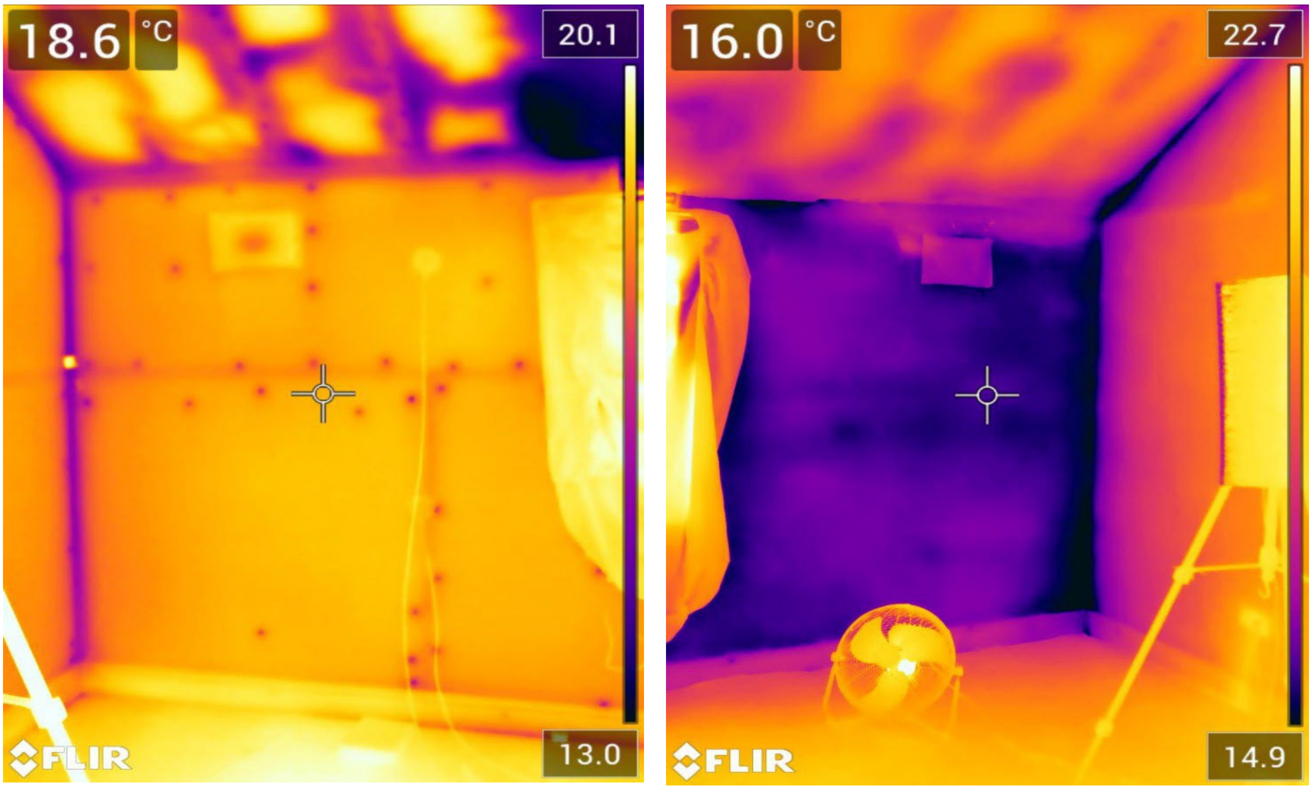


Figure 1-19 Polystyrene backed IWI was often installed on some walls (left), reducing the energy saving from future SWI retrofits and sometimes posing interstitial condensation risk. However, other walls in the same house (right) were uninsulated.

EWI installations achieved greater HTC savings than IWI, since the manufacturers of the wood fibre IWI solution designed their systems to have a higher (more heat loss) U-value (0.56 W/(m^2·K)) than the Building Regulations target of 0.3 W/(m^2·K). This was done to minimise the risk of interstitial condensation and moisture accumulation, i.e., they traded off energy savings for a lower risk design.

Issues observed with the application of EWI included a lack of space outside homes to store materials during construction, which could pose a significant barrier for installers. Additionally, removing wall-mounted or adjoining obstacles posed significant delays and costs (services, gate posts, garden walls etc.). It was also observed in three case studies that installing EWI around the bay windows was problematic (owing to complex geometry), and if the bay roof was not insulated at the same time as installing EWI, the risk of surface condensation on the bay ceiling will increase.

In one DEEP case study home, to preserve the heritage value of the streetscape, a hybrid retrofit of both IWI at the front elevation, and EWI on the walls to the side and rear, was adopted. Modelling and measurements indicated a reduction in the temperature factor around the area of transition between EWI and IWI, which increases the risk of surface condensation. However, the risk was borderline, i.e., the temperature factor was close to the critical threshold at which risk is judged to occur. This is further discussed in Section 2. Further, models indicated that installing an overlap of 400 mm of IWI at this junction reduced this risk.

Some of the DEEP case studies already had EWI installed prior to this project, and there were some issues noted with these which may affect performance and risk. Future retrofits, or general building maintenance and repairs, may have to rectify these. Figure 1-20 is one such example of the installers not following the system design in a previous retrofit. An expansion joint for the EWI between neighbouring dwellings had been omitted. This is now causing weathering of the junctions as well as water ingress.

Figure 1-20 EWI expansion joint installed between left hand side neighbour (left), but omitted between right hand side neighbour (Right) and resulting damage

Additionally, discontinuities around the boiler flue and DPC in the EWI for another case study home were observed, causing excessive thermal bridges (Figure 1-21).

Figure 1-21 Thermal bridge around boiler flue and below DPC caused by EWI discontinuities

A common issue with EWI was also identified in one of the case study homes, where a large thermal bridge at the eaves is caused by EWI not extending through to meet the loft insulation, causing a discontinuity in the insulation layer at the eaves (Figure 1-22). This is an example of EWI being installed in a piecemeal approach, not considering how the EWI interacts with the loft insulation and leading to an unintended consequence. The whole house approach would look to create a solution to avoid this from occurring, and this detail and risk are discussed in further detail in Section 2 of this report.

Figure 1-22 Thermal bridge where EWI does not extend to the eaves

Risks associated with retrofitting solid walled homes are further investigated in the DEEP case study homes and discussed in Section 2.

Cost effectiveness of retrofits

Finance-only assessments do not capture the full benefits of retrofits, such as warmer homes with improved air quality, lower risks of condensation and overheating, etc. However, it is still useful to evaluate the relative cost effectiveness of retrofits. In these case studies the costs of installing the retrofits are not necessarily representative and are based on a small sample, so it is not helpful to try to define any cost-per-energy saving values. However, the case studies did provide opportunity to understand the type and scale of additional costs of retrofits that may be expected, and some general trends and observations can be drawn. For instance, installing SWI was the most expensive retrofit to undertake, but it was also among the most cost effective, since it delivered significantly more savings.

In most cases, however, the measures installed in the DEEP homes had payback periods over many decades. This is because savings were relatively low (individual measures excluding SWI tended to save between <1 and 8% of fuel bills) and the cost was high, often because additional costs were incurred. 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, plus removing debris from loft spaces and relocating services.

The scale of additional costs cannot be fully predicted before a retrofit takes place, though an extensive pre retrofit survey can increase understanding of the likely costs. DEEP case study retrofits were more expensive than cost estimates identified in literature. Figure 1-23 shows the total installation costs incurred for each DEEP retrofit. The average additional cost across the cohort of homes was 26% of the total retrofit cost, though this ranged from 0 to 38%.

Some retrofits had particularly high additional costs, specifically, for the room-in-roof work and EWI where the roofs needed repair. Rebuilding a garden wall at one case study home, to allow access for EWI installation, cost £6,000. Suspended timber floor retrofits tended to have the highest proportion of additional costs as the original floorboards were damaged (often unavoidably by the retrofit, where the tongue and grove boards could not be separated or nails could not be lifted cleanly), and so needed removing and replacing. Conversely, simpler retrofits such as applying insulation on a solid floor slab, or installing loft top-up insulation, had relatively low or no additional costs. Furthermore, installing the same type of retrofit could have different additional costs in different homes. For instance, in 04KG more damage was done to the walls when installing new windows, meaning the replastering work was eight times more expensive than in 01BA (a similarly sized home but with a different solid wall construction).

The findings suggest that more complex retrofits have higher additional costs, but that *any* retrofit can have substantial and unknown additional costs, suggesting that a contingency fund and detailed pre retrofit surveys are necessary. This has implications for retrofit budgeting for individual projects, retrofit finance models, and national policy.

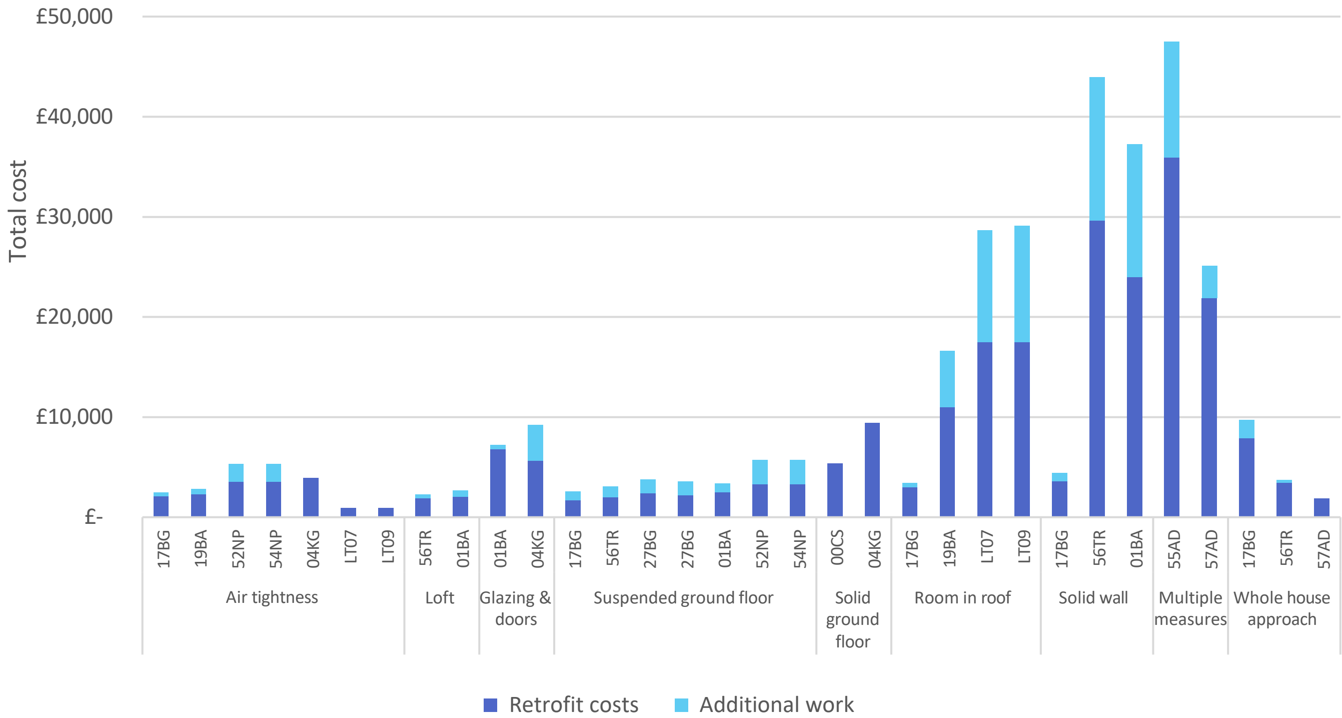


Figure 1-23 Cost of DEEP case study retrofits

2. How can technical risks be reduced when retrofitting solid walled homes?

A range of technical risks were investigated in the case study retrofits, including surface condensation risks at areas prone to thermal bridging, overheating risks in homes, and interstitial condensation risks associated with IWI. These risks were evaluated before and after a piecemeal retrofit was undertaken. The risks were assessed again after undertaking the whole house approach (i.e., avoiding discontinuities in the insulation layer) to the retrofits.

Modelling assessments were used to quantify the severity of surface condensation risk and overheating risk, as outlined in the DEEP Report 2.01 – Case Study Methods. Interstitial condensation risk for IWI was explored using methods presented in DEEP Report 6.03 – Moisture risk. These conventional risk assessments use pass-fail thresholds. However, this approach to risk assessment is imprecise since there is considerable uncertainty in models, and because models do not consider how the internal conditions are managed (air movement, relative humidity, location of furniture etc). These can have significant impacts on whether underlying risks manifest. This is especially important in cases where the assessment results are borderline, i.e., either just above or below a critical threshold. Thus, pass-fail categorisation of risks should always be considered in the context of this limitation.

Impact of retrofit on thermal bridging and surface condensation risk
Thermal bridging software was used to calculate the surface temperatures at junctions between fabric elements (often the coldest surfaces in homes) in four case study homes with SWI. For each junction a temperature factor (f_{Rsi}) was calculated. Warm, moist air condenses when it meets cold surfaces, with the potential for surface condensation where calculated temperature factors are below the critical threshold of f_{Rsi} >0.75 (i.e., the surface is too cold). Where condensation occurs in homes over prolonged periods, damp and mould growth is a risk, especially in homes with high levels of relative humidity (RH), which are under-heated and under-ventilated.

As shown in Figure 2-1, many junctions (66 – 89%) in the case study homes had temperature factors below this critical threshold pre-retrofit, i.e., there was significant potential for surface condensation in the uninsulated case study homes. However, as mentioned, other factors also contribute to the risk that condensation will occur while in use, such as the extent of ventilation, air movement, temperature, RH in the rooms etc. This means it cannot be determined from the temperature factor alone if surface condensation will occur. Nonetheless, it is a useful way to compare to a reference value to identify the extent of underlying relative risk.

The temperature factors in the homes were calculated again when insulation was installed via a piecemeal approach, i.e., without considering how it affected other adjacent elements. This resulted in there being several discontinuities (gaps) in the homes' insulation layer. Despite these discontinuities the temperature factors in the homes generally improved for most junctions. Following SWI installation, only 16 to 22% of junctions were below the critical threshold. Significant discontinuities often remained in some locations: at the eaves junction where the wall insulation did not tie in with the loft insulation, where there were unusual features that were not included in the retrofit (e.g., bay window roofs), or where multiple minor thermal bridges converged (e.g., EWI cut-outs, wall corners, and window openings).

Thermal bridges were assessed again when additional insulation was installed to address discontinuities to ensure a continuous insulation layer was achieved in the homes, as required in a whole house approach. In this final stage the critical temperature factors of junctions were, in almost all cases, further increased to be above the critical temperature factor; only between 1 and 8% of junctions were still below the threshold. Surface temperature measurements were also taken in the case study homes at specific junctions and the measured results generally confirm the trends observed in the models.

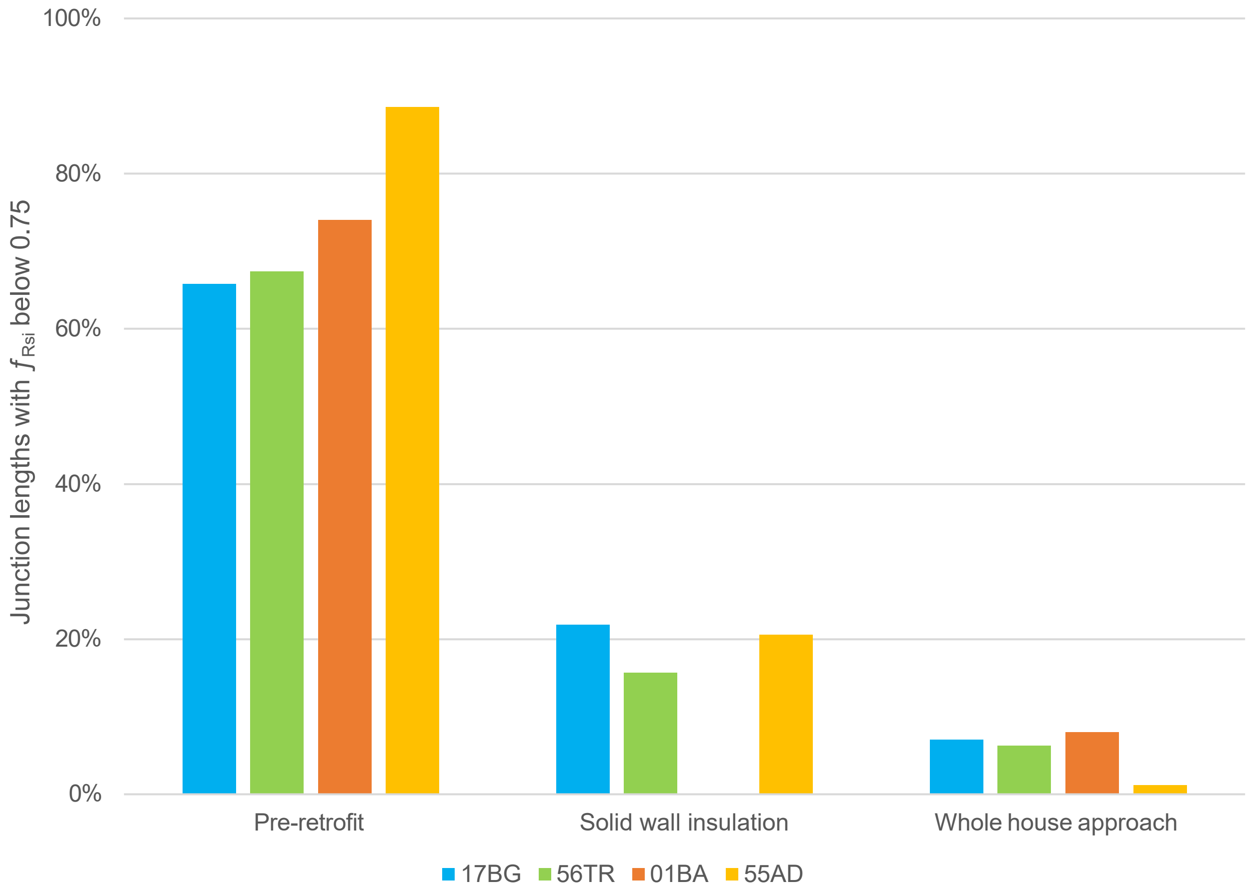


Figure 2-1 Impact of SWI retrofits installed via piecemeal vs. whole house approach on surface condensation risk in four case study homes (case study 01BA did not have a separate piecemeal SWI retrofit)

When discontinuities in the insulation layer are addressed, as part of the whole house approach to retrofit, there is a significant reduction in the proportion of junction lengths with temperature factors below the critical threshold compared to the uninsulated home. However, even after addressing thermal bridges in the DEEP case studies, some risk still existed. It is likely challenging, therefore, to improve temperature factors for *all* junctions when retrofitting solid walled homes.

However, it is simplistic to infer that all junctions in the case study homes for which f_{Rsi} >0.75 are “safe”, while all those below are “unsafe”. Risk is not a binary criterion; it is a continuous scale. Significant improvements in temperature factor were achieved at junctions in the case study homes, even where they did not manage to exceed the critical threshold. This is significant in the context that model input values, used for calculating temperature factors, also have uncertainties. There are also many factors affecting risks that are not included in models, for instance variable weather and internal conditions in homes.

Managing internal conditions to minimise risks is an important component of the whole house approach, i.e., ensuring the provision of adequate ventilation, management of RH, ensuring air circulation around junctions, delivering appropriate internal temperatures etc. The concept of a managed risk ensures that risks of surface condensation occurring at junctions with borderline temperature factors (around the critical threshold) are minimised and is a more robust approach than relying on simple temperature factor analysis in isolation. Adopting a managed risk approach also has implications for the retrofit industry and decision-making.

One example of this was observed in the case study home 01BA where architectural detailing (corbelling) at the eaves, represented a detail outside the EWI system. As such, a bespoke design was installed to retain the corbelling. Despite this the modelled eaves temperature factor remained below f_{Rsi} >0.75 after the retrofit, although this was borderline (f_{Rsi} = 0.71). Given the uncertainty around models, borderline results like this result cannot be stated as definitive risks. In this instance the insulation was applied to ensure a continuous layer, the ventilation in the home was adapted to comply with PAS2035, and surface temperature monitoring during quasi steady-state conditions of the coheating test suggested the temperature factor was above the critical threshold at f_{Rsi} of 0.94 ± 0.01. The whole house approach means a holistic approach to managing risk rather than relying on achieving simplistic modelled thresholds.

Attempts to increase the eaves' calculated temperature factor in 01BA further to f_{Rsi} >0.75 may have resulted in loss to the building's heritage value (i.e., removing the corbeling), or involve alterations to the roof construction, or the addition of IWI etc, adding significant costs to the retrofit. However, it is not certain that the calculated risk in the context of the uncertainty in the models would warrant this additional investment since the calculated temperature factor of the eaves junction was close to the critical threshold.

Guidance is needed to support practitioners and designers on appropriate decisions and interpretations of temperature factors for such instances, so that appropriate managed risk-based solutions can be adopted.

It is probable that pass-fail decisions for borderline temperature factors are not leading to appropriate risk-based decisions. To illustrate this, Figure 2-2 plots all the calculated temperature factors following the final retrofit stages for the four case study homes in which SWI was installed.

The results show that while only 9% of junctions are below the critical threshold of f_{Rsi} >0.75, there are 21% below 0.8, and only 3% below 0.7. Given uncertainty in the models around material properties of the fabric and the construction details, it is probable that the 0.75 cut off is not providing a robust assessment of risk in homes.

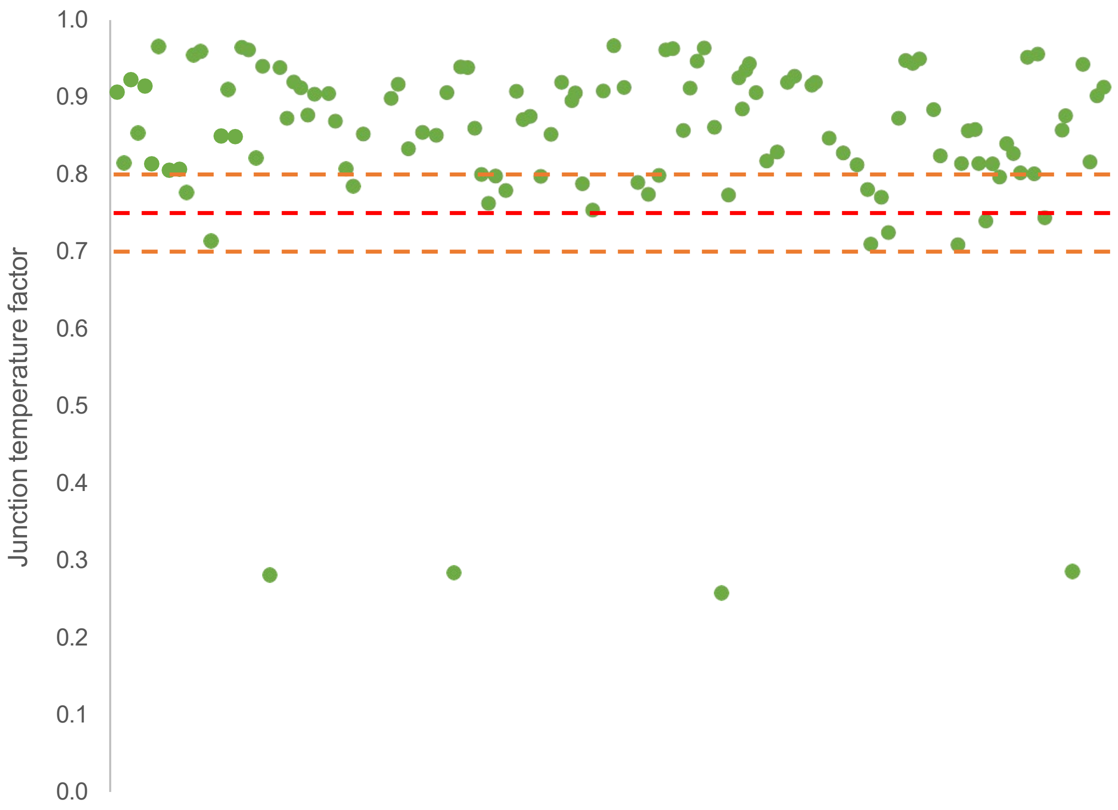


Figure 2-2 Calculated temperature factors of junctions in case study homes 17BG, 56TR, 01BA, and 55AD, post whole house retrofit stage showing a 0.05 range (orange lines) around the 0.75 critical threshold (red line)

Another risk that persisted even after the other discontinuities were addressed was the door threshold in all four homes, which had temperature factors below 0.3 (the four door threshold junctions can clearly be seen in Figure 2-2).

The thermal bridge here was the only junction in the homes that always increased (worsened) after SWI was installed. This may be a concern in some instances if they are adjacent to structural timbers in the suspended timber ground floor due to potential rot of timbers in the floor construction. Door threshold junctions are often missed from SWI retrofits, but these findings suggest they need more innovative solutions and consideration to reduce risk when they are included in the retrofit.

Specific discontinuities investigated in the case studies are set out in Figure 2-3. The scope of the assessments presented is limited to the retrofits' impact on temperature factors and so cannot comment of the risk that condensation will manifest, since this relies on multiple factors linked to the internal and external conditions (ventilation rates, RH, air temperature, air movement etc). It also cannot comment on those risks that were not investigated, e.g., changes to moisture accumulation or interstitial condensation. However, calculating the temperature facture is useful as a way of exploring changes in underlying surface condensation risk profiles when elements are insulated, and how unintended consequences can be mitigated by addressing discontinuities, as required by the whole house approach.

Bay

The uninsulated case study homes had temperature factors below the critical threshold at this junction.

Installing EWI without insulating the bay roof further reduced the critical temperature factor.

Insulating the bay roof improved the temperature factor above 0.75.

Eaves

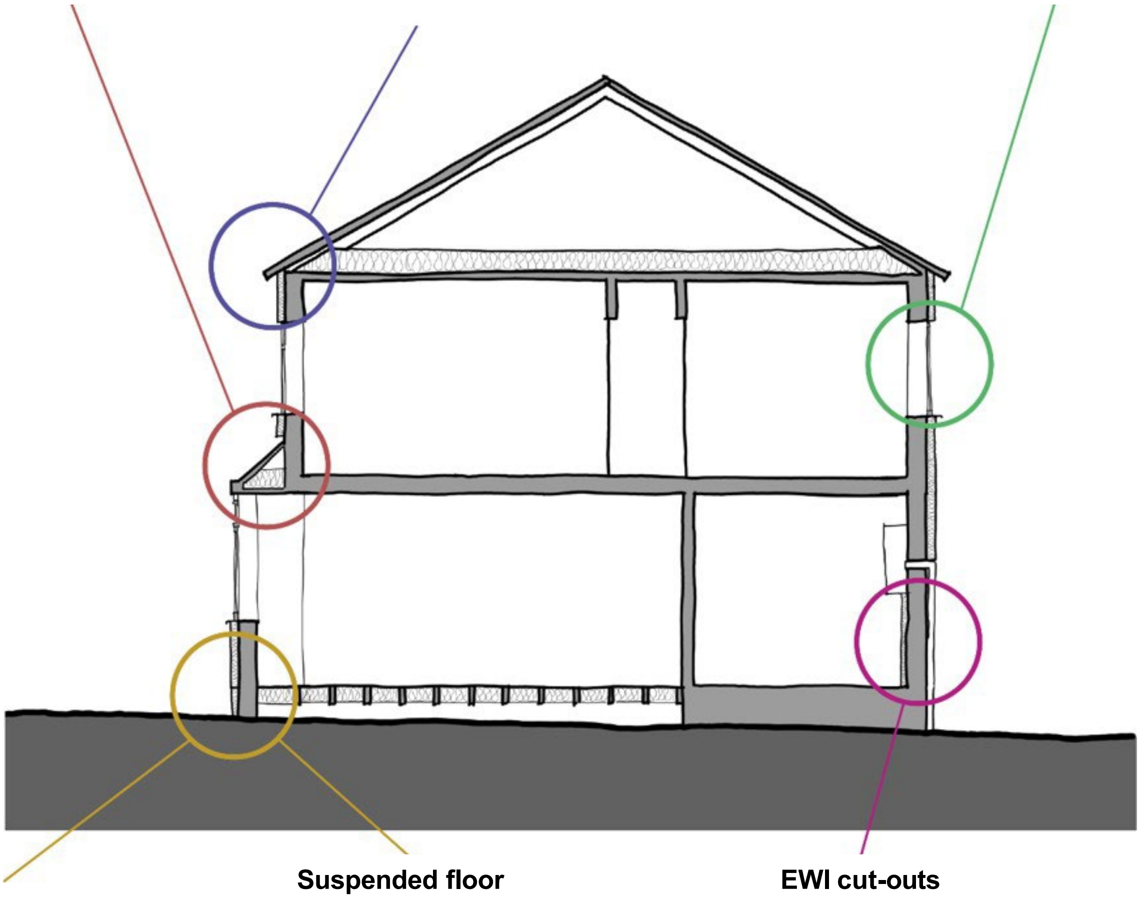
The uninsulated case study homes had temperature factors below the critical threshold at the eaves' junctions. When EWI was installed with a discontinuity between the EWI and loft insulation, this further reduced the temperature factor.

Removing this discontinuity by extending EWI behind soffits and facia, or extending the eaves, usually increases the temperature factors above the critical threshold. This would, however, be challenging where architectural details need to be retained for heritage value.

Windows

The uninsulated case study homes had temperature factors below the critical threshold at the junctions between the windows and external walls. Installing IWI, including window reveals, increased the temperature factor above the critical threshold.

Installing EWI also increased the temperature factor above the critical threshold, and it was not necessary to move the windows in line with the insulation layer (which can be very costly), although this did improve the temperature factor further.



DPC

Uninsulated case study homes had temperature factors below the critical threshold at this junction.

Installing EWI in homes without extending below the DPC increased the temperature factor above the critical threshold in homes with suspended timber ground floors, but not in homes with solid ground floors. For solid ground floor constructions, it was necessary to insulate below the DPC.

Installing IWI increased the temperature factor above the critical threshold in homes, regardless of ground floor construction.

Suspended floor

Uninsulated homes had temperature factors below the critical threshold at this junction.

Installing insulation below suspended timber ground floors had little impact on the critical threshold at this junction. Although the floor surface was warmer, this was cancelled out by the colder sub floor void cooling down the wall surface temperatures.

Additional modelling of the impact on moisture accumulation in floor timbers is necessary to have a holistic understanding of moisture risks associated with ground floor timbers pre- and post-retrofit, since risk is affected by the underfloor ventilation provision and the vapour permeability characteristics of the insulation installed.

EWI cut-outs

Commonly, "cut-outs" in SWI occur around obstacles such as gas pipes, to avoid the costs of removing and reattaching the obstacle. However, this can introduce a thermal bridge into homes.

Two EWI cut-outs were investigated in the case study homes. Where the cut-out is located close to another thermal bridge, such as a window reveal or external wall corner, the temperature factor was below the critical threshold. However, installing IWI at the discontinuity increased the temperature factor back above the critical value.

Where the cut-out was small and not near any other thermal bridges, the temperature factor behind the cut-out remained above the critical temperature factor.

Figure 2-3 Impact of retrofit on temperature factors at discontinuities

Impact of retrofits on overheating risk

Overheating in homes affects occupant comfort and health, and as the climate warms and heatwaves becomes more frequent, this risk will increase. Little is known about the level of existing overheating risk in UK housing and how this is affected by retrofitting homes. In DEEP, overheating risks in the 14 case study homes were assessed before and after their retrofits were installed using dynamic simulation modelling (DSM) of the homes. The assessment relied on the criteria of the Chartered Institute of Building Services Engineers' (CIBSE) TM59 document [9]; Criterion A (occupied rooms should not experience a difference between the operative and comfort threshold temperature greater than or equal to one degree (K) during the period May to September for more than 3% of hours) and Criterion B (bedrooms should not exceed 26°C for more than 1% of hours between 10pm and 7am). If the criteria are exceeded the building is considered at risk of overheating.

Only four of the 14 dwellings pre-retrofit passed (i.e., they did not exceed comfort thresholds) Criterion A, and one passed Criterion B. Following the retrofits, five dwellings passed Criterion A and four passed Criterion B. This suggests retrofits can be beneficial in reducing overheating, but it still remains a significant issue for most homes. It is important to note that this analysis used a worst-case scenario, with window opening restrictions and no shading at all. It also used a single design summer year (DSY1) weather file for the 2020s, as specified in the current TM59 guidance.

However, for two of the homes (56TR and 17BG) a 10-year average weather file was used to assess overheating. This showed that homes would overheat pre-retrofit if they were located in London, but not in Glasgow or Manchester. Post-retrofit, if shading and additional ventilation are also incorporated into a whole house approach, there would be no overheating risk in the homes at all, under the current climate.

Furthermore, pass-fail assessments, as discussed for surface condensation risk modelling, can lead to inappropriate decision-making. For example, overheating models do not consider the uncertainty of weather data or how representative these are for specific locations, variations in shading, construction make-up, internal gains, etc. They also do not consider many issues that affect comfort such as air movement, humidity, clothing values (i.e., the insulating potential of occupants' clothing), and occupant behaviour.

A more appropriate approach may be to evaluate relative change in overheating risk. Figure 2-4 shows the change in overheating risk for Criterion A of TM59 when retrofits are installed in the 14 case study homes. As can be seen, insulating the homes had a variable effect. Those homes that reduced solar gains entering the building (i.e., with solid wall and room-in-roof insulation), in addition to installing new windows with increased openable area (i.e., increased potential for natural ventilation) reduced over heating risks.

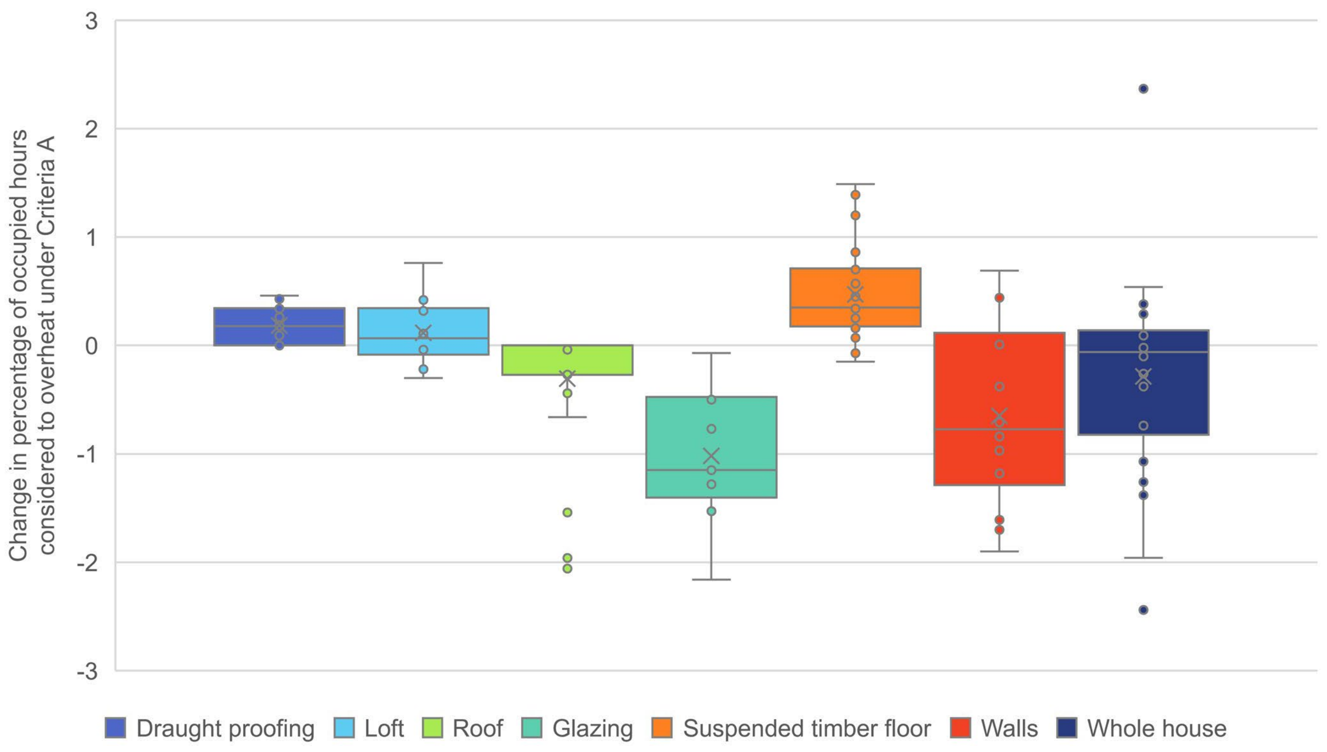


Figure 2-4 Change in the percentage of occupied hours considered to overheat under Criterion A for each retrofit stage across all case study rooms

As can be seen, installing suspended timber ground floor insulation led to an increase in the overheating experienced. It is thought this is because there is a beneficial impact of the cooler sub floor void in summer which is lessened when the floor is insulated. Similarly, when the air leakage in homes was reduced via draught-proofing, and when loft insulation was topped up, the homes were not able to lose heat as readily. This meant their overheating risk increased, albeit marginally.

Addressing discontinuities in the insulation, as required by the whole house approach, did not make any material difference to overheating risk in the homes. However, ensuring there is adequate ventilation and the potential for increasing ventilation beyond that required solely for fresh air (i.e., purge ventilation such as opening windows), was beneficial in further reducing risks. Thus, a whole house approach can reduce the chances of overheating, for example, by ensuring that even if window replacements are not part of the scope of a fabric retrofit, maximising the ventilation (i.e., removing window restrictors or introducing the potential for mechanical purge ventilation) should be considered.

To explore overheating risk further, additional model-based assessments were undertaken on two case study homes, 17BG (with window openings on only one façade and therefore limited to single-sided ventilation) and 56TR (where cross ventilation could be achieved by opening windows on opposing facades). These assessments used the same TM59 criteria but looked at the extent of overheating that was predicted to take place over 10 years of weather observations, rather than using a single test weather year. The assessments used the last ten years of weather observations for London, Manchester, and Glasgow, as well as future weather predictions of the warmer climate in 2060. The assessment also considered the effectiveness of two simple mitigation measures aimed at reducing overheating: increasing the level of natural ventilation in homes by opening windows wider and for longer (when advantageous) and installing external solar shading for windows.

The results of this assessment (Figure 2-5) showed that under the current climate, insulating all the home’s fabric elements via piecemeal approach (‘Post’) sometimes increased the risk of overheating compared to the uninsulated base case (‘Pre’) home, especially in London. This was primarily due to the suspended timber floor insulation reducing the beneficial cooling effect of the sub floor void in summer. The other retrofits had much less impact on overheating risk.

However, this risk was eliminated using increased natural ventilation combined with external shading. Under a future climate scenario, the whole house retrofit increased the risk of overheating in all locations. This risk could be almost eliminated in Manchester and Glasgow using increased natural ventilation combined with external shading. However, overheating still occurred most years in London.

If, as these results suggest, mechanical cooling will be required in some homes, whole house retrofit with the provision of adequate shading and ventilation would still be beneficial as it would reduce the energy demand for cooling in these cases. The case study home with cross-ventilation (56TR) had a lower overheating risk than the home which had only single-sided ventilation (17BG). This finding may also be relevant for flats with only one external facade and therefore no opportunity for cross-ventilation.

House	Criterion*	Current climate						Current climate with mitigation					
		London		Manchester		Glasgow		London		Manchester		Glasgow	
		Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
56TR	a	5	5	0	0	0	0	0	0	0	0	0	0
	b	8	8	2	2	0	0	0	0	0	0	0	0
17BG	a	4	**10**	0	**2**	0	0	0	0	0	0	0	0
	b	1	**3**	0	0	0	0	0	0	0	0	0	0

House	Criterion*	Future climate						Future climate with mitigation					
		London		Manchester		Glasgow		London		Manchester		Glasgow	
		Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
56TR	a	10	10	7	7	2	1	2	1	0	0	0	0
	b	10	10	10	10	6	6	7	6	0	0	0	0
17BG	a	10	10	6	**10**	1	**6**	8	**10**	0	1	0	0
	b	10	10	2	**3**	0	**1**	5	3	0	0	0	0

* The count for criterion a includes years when overheating occurred in the living room or in the bedroom during waking hours, while the count for criterion b includes years when overheating occurred in the bedroom during sleeping hours.

Figure 2-5 No. of years out of 10 when post-retrofit homes failed overheating assessments

Provision of adequate natural ventilation and external shading should, therefore, be important considerations for the whole house approach to retrofit. Without these, summertime overheating may become a risk. However, there are socio-technical barriers related to ventilation and shading around aesthetics, planning, construction details, noise, air pollution, and security. Further work to improve the design of ventilation openings and external shading should be carried out to address these issues.

Impact of IWI on interstitial condensation risk

Moisture accumulation in the walls of buildings can lead to severe damage and can affect the health of occupants. There are concerns that retrofitting homes with IWI will increase moisture risk due to interstitial condensation. It is difficult to measure moisture risk in the field as moisture can accumulate over many years and problems can remain hidden within the fabric of a building. In DEEP, hygrothermal simulation was used to analyse the moisture profile of solid walls over a decade of real weather in two locations with differing exposure to wind driven rain.

A validated hygrothermal software tool (WUFI Pro 6.5) was used to simulate the walls. However, there is no standardised way to define if a building has a moisture risk or not. There will always be inherent uncertainty in boundary conditions, the condition of the building, and in the thermophysical properties of the construction materials that make an absolute measurement of moisture risk difficult. However, it is possible to determine if risk is increased by the installation of IWI.

To assess moisture risk in DEEP, a metric to simulate the *relative* risk from installing IWI was developed (termed moisture risk RH.days; see section 2): the number of days during which the daily average RH at the critical location between the insulation and the external wall was above 80%. Retrofits of different thicknesses of IWI were compared to an uninsulated wall. The use of a vapour permeable wood-fibre IWI system (Figure 2-6, Model A) was compared with a vapour impermeable expanded polystyrene with an air vapour control layer (EPS with AVCL; Figure 2-6; Model B) and one using EPS without the AVCL (Figure 2-6; Model C).

Figure 2-6 shows installing IWI always led to an increased moisture risk, even when only a thin layer of insulation was applied, e.g., at a U-value of 1.1 W/(m^2·K), as adding IWI will always make the wall colder than it would have been in winter. Therefore, the relative humidity within the wall at critical locations will be higher, even if the moisture content remains the same. The more vapour permeable systems (A and C) had lower risk and it is hypothesised that this is because more drying occurs to the inside of the home and is removed by ventilation. Using vapour impermeable paint finishes may compromise this performance.

Increasing the thickness of the IWI increased the relative moisture risk in all cases. No safe limit exists for moisture risk and so a threshold insulation thickness cannot be quantified. However, the results for wood fibre insulation showed that the relative moisture risk increased more rapidly below a U-value of about 0.8 W/(m^2·K) [7]. This is similar to the threshold U-value of a renovated wall, according to the Building Regulations, of 0.7 W/(m^2·K) [8]. However, long-term field work is needed to determine a suitable threshold of risk and benefit, in different weather and exposure locations, before thinner IWI can be recommended.

These results suggest a more balanced approach may substantially reduce risks while only marginally reducing energy saving potential. For instance, the energy saved by IWI systems which achieve a U-value 0.3 W/(m^2·K) was 30%, while the IWI system which achieved a U-value of 0.8 W/(m^2·K) could achieve 20% reduction. This has implications for the revision of limiting U-values in Building Regulations to balance energy savings with moisture risk.

[7] 30 mm of wood fibre insulation was required to achieve this U-value.
[8] In the building regulations it is also stated that the 0.7 value can be lowered due to interstitial and surface condensation; compliance with Part C is required in this case.

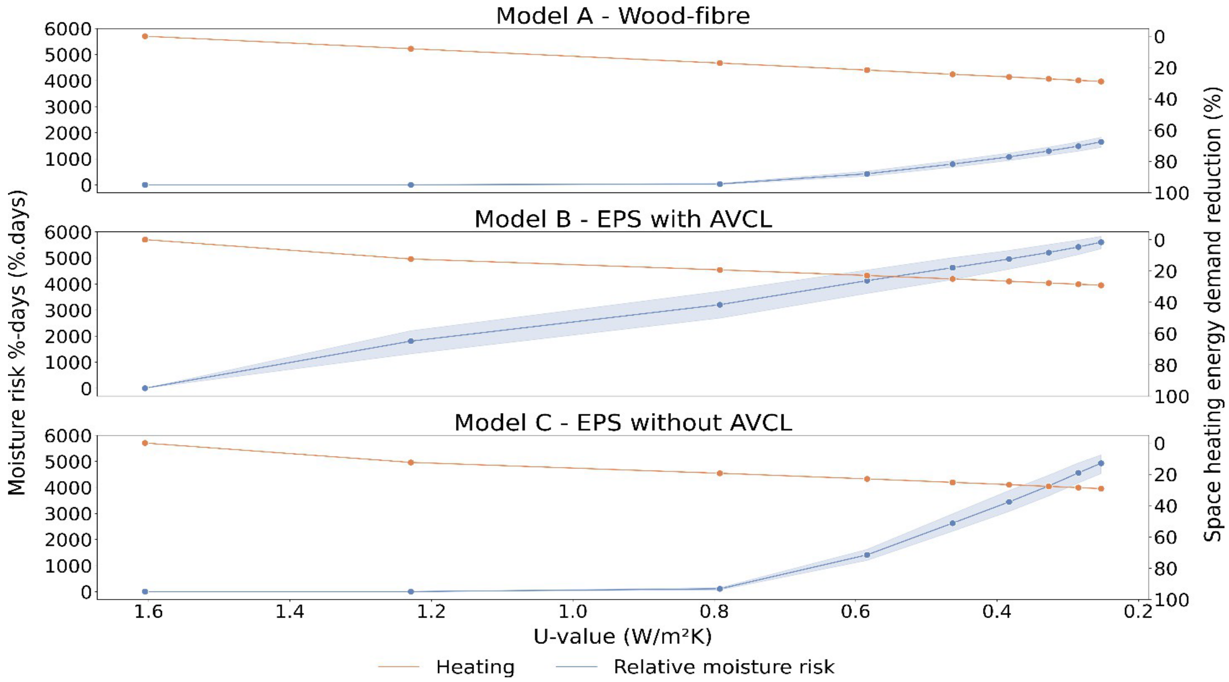


Figure 2-6 The impact of insulation thickness (U-value) on moisture risk RH.days and space heating energy demand for three IWI systems using London RWD file

An additional risk for IWI when installed via piecemeal retrofits occurs if the retrofit design does not consider interactions with adjacent elements, specifically if the IWI is not integrated into a continuous air barrier.

In this instance, warm moist air may be more likely to penetrate behind the IWI, either via suspended timber floors directly, or through penetrations and edges around the IWI where it is not adequately sealed. This exacerbates risks in piecemeal retrofits, highlighting the importance of thinner IWI to minimise risks. In whole house approach retrofits where risks are adequately considered, thicker IWI solutions may be acceptable.

3. How can building energy model inputs and risk assessments be improved?

Whole building thermal models are used to predict energy consumption and overheating risk in homes, while elemental models predict thermal bridging heat losses and surface and interstitial condensation risks associated with fabric constructions. There are several different modelling approaches, and software and models are commonly used with estimated or default inputs. This introduces uncertainty and reduces the reliability of the predictions they make. This has implications when models are being used to investigate energy savings and risks in homes. Therefore, understanding which input assumptions are useful, and identifying those which need improvement, can help ensure retrofits are effective and low risk.

Overpredictions of Energy Performance Certificates (EPCs) and the prebound effect
EPCs are based on Standard Assessment Procedure (SAP) calculations for the energy performance of homes. They are mandatory at the point of sale, rental, or where there are major refurbishment works to homes, including retrofits installed as part of policy schemes. When EPCs are used for existing homes they make use of default values for occupant profiles, set points, hot water usage, fabric U-values, air permeability, and thermal bridging heat losses using the Reduced Data SAP (RdSAP) calculation method. This means that in homes for which the default values are not appropriate, EPCs will not accurately reflect their individual level of thermal performance.

As part of the RdSAP calculation used in the EPC methodology, an HTC is calculated which estimates overall fabric heat loss. Comparison of the HTCs used in EPCs against those measured using coheating tests in the DEEP case study homes demonstrated that EPCs mostly overpredicted heat losses. This overprediction became less significant as energy efficiency improved. Across the case study homes, predictions made by EPCs overestimated the HTC by 42% on average, ranging between 7% lower and > 100% higher than the measured value in individual homes. The EPC overprediction was greater pre-retrofit than post retrofit. This aligns with other research suggesting EPC bands A and B had no significant difference between EPC and measured energy use while the over prediction for Band C homes was ~8% on average [1]. This phenomenon (over-prediction of energy use) is termed the ‘prebound effect’ and has implications for using EPCs to predict retrofit savings on a house-by-house basis in policy or finance models, as well as for occupant expectations.

Additionally, since occupants behave differently, it is feasible that the overestimation of fabric heat loss is lost in the ‘noise’ of in-use performance. For example, lower internal heat gains, combined with higher heating set points and frequently opened windows, could make it look like an RdSAP calculation with a high estimate of fabric heat loss is making an accurate prediction of annual heating energy consumption. In this example, it is the operation of the property that leads to the high annual heating consumption and not the fabric performance.

Improving EPCs by updating default assumptions with measured data
RdSAP does not allow default inputs to be updated by assessors, unlike the full version of SAP. However, in DEEP the Building Research Establishment's Domestic Energy Model (BREDEM) was used to investigate the impact of replacing defaults with real data on the EPC for specific homes. The impact on the homes' HTC of replacing default inputs for airtightness, U-values, and thermal bridging heat loss (y-values) with measured and calculated values is shown in Figure 3-1. The impact of this is that the EPC now predicts HTC closer to the measured values, though it still overpredicts. It can also be seen that in the original and updated EPC the overpredictions are larger for homes with higher heat losses.

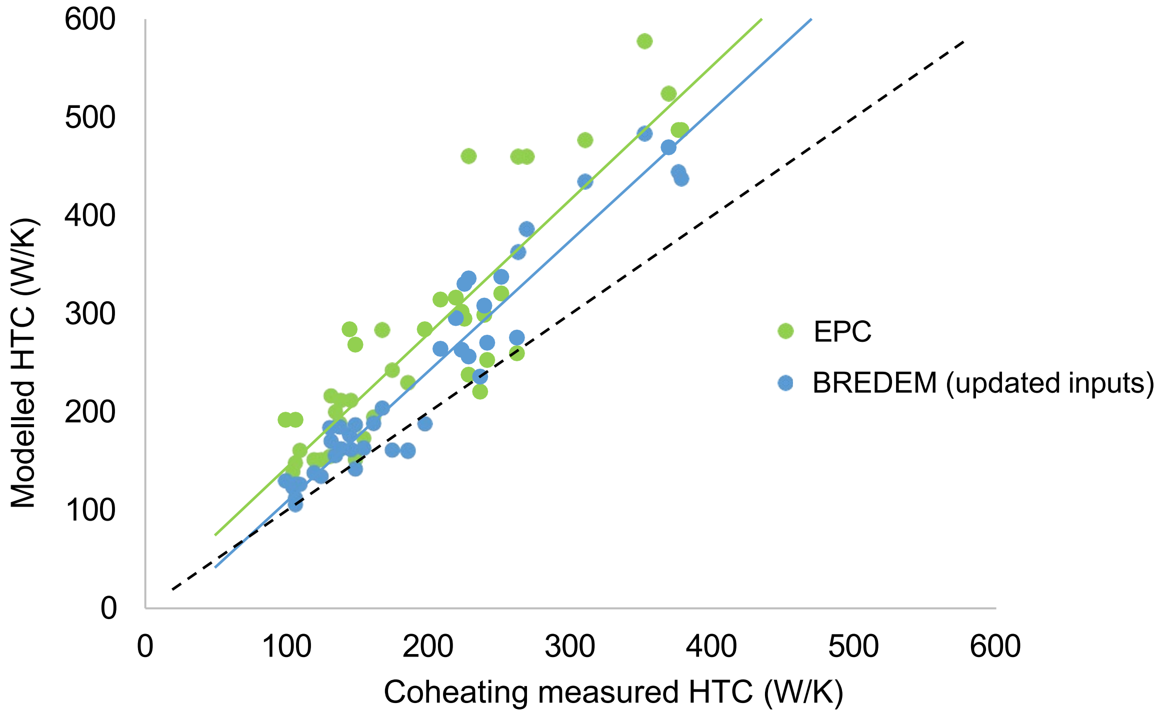


Figure 3-1 Comparison of measured HTC and modelled HTC with different inputs. Black dashed line represents 1:1 relationship between coheating and modelled results

Although the RdSAP and BREDEM model inputs were matched, the BREDEM model has marginally different HTC predictions from the EPC. On average this meant the BREDEM HTC predictions 34% higher than the measured values (RdSAP values were 42% higher). The RdSAP defaults assumed, on average, 20% more air leakage (background ventilation) taking place in the case study homes than was measured. Including the measured airtightness in the case study models reduced the average predicted HTCs across all the homes, meaning the modelled HTC was on average 27% higher than the measured values, although this varied by between 8% lower and 80% higher.

Post-retrofit the impact of replacing default airtightness is more pronounced, since EPCs only consider airtightness improvements following draught-proofing and suspended timber ground floor insulation. However, in DEEP other retrofits also reduced air leakage in homes, for instance in the five homes in which SWI was installed. In these, air leakage was reduced by on average 4%. Because air leakage varies substantially in homes, the impact of replacing default airtightness values for individual homes varies significantly. For some this brings the HTC predicted by the EPC much closer to the measured value, in others it moves further away, and in some instances, it has little impact. Moreover, background ventilation heat loss is a smaller component of whole house HTC, representing on average only 19% across the case study homes compared with 71% for plane element fabric heat loss, which is determined by U-values, with the remainder being thermal bridging heat loss.

U-values can be calculated where the fabric construction make-up is known or measured using heat flux density measurements. This can be an important consideration. For example, the EPC default wall U-values were found to be 15% higher (worse) than those measured in the case study homes as well as being higher than calculated U-values.

The difference between measured and default U-values was less significant for insulated fabric elements, which had a more consistent and predictable performance. The difference varied substantially for different elements, meaning the effect on individual homes of replacing default U-values cannot be simply predicted. As expected, incorporating measured U-values for all the case study homes reduced the HTC over prediction, meaning overall EPCs which use measured U-values predicted HTCs to be on average 21% higher than were measured across all the homes, down from 27% higher before this correction was undertaken.

In DEEP multiple heat flux density measurements were taken on the same element to ensure robust measurements were obtained. For example, in the case study home 09LT the external wall U-values varied from 1.7 to 2.4 W/(m^2·K) depending on the location of the heat flux plate. This was despite efforts to identify measurement locations using thermography to be representative of the entire element. Because of the stochastic nature of heterogeneous heat flow through elements, it is essential that multiple heat flux measurements are used when informing retrofit evaluations, and that area weighed U-values are used.

Measured U-values were found to be generally lower than calculated U-values and replacing defaults with calculated U-values achieved a slightly lower reduction in HTC, meaning the EPC predicted 24% higher HTCs than were measured. This indicates there were discrepancies between the assumed fabric make-up and real performance in-situ. Care must therefore be taken when calculating U-values to ensure the construction make-up is well understood, making it challenging to accurately calculate U-values for most existing homes.

Replacing thermal bridging default heat losses with calculated values also reduced predicted HTCs, on average by 4%, in the BREDEM models for the five homes for which bridging calculations were undertaken. The extent of thermal bridging heat loss, measured as a y-value, tends to increase as fabric elements are insulated. However, idiosyncrasies in the homes mean the difference ranged from 8% lower to 47% higher in some homes, depending on the different retrofit stages and the specific thermal bridges. For instance, in case study 56TR, a single thermal bridge was responsible for more heat loss than all the other bridges in the home combined.

Table 3-1 Modelled mean (and range) of HTC overpredictions for all 43 retrofit models

	Average HTC over prediction of models compared to measured		
	RdSAP	BREEDEM	DSM
Using all default inputs	42% (-7 to 102%)	34% (-4 to 86%)	13% (-22 to 62%)
Using measured airtightness	-	27% (-8 to 80%)	6% (-22 to 45%)
Using calculated U-values	-	24% (-19 to 60%)	5% (-24 to 38%)
Using measured U-values	30% (-5 to 71%)	21% (-11 to 51%)	6% (-15 to 32%)
Using calculated thermal bridging (18 models only)	-	17% (-14 to 47%)	-5% (-24 to 22%)

An alternative visualisation of the difference between the measured HTC values and the HTC values predicted by the models is shown in Figure 3-2. The RdSAP predictions use all the EPC defaults and are usually the least well aligned to the measured values, while the BREDEM and DSM predictions have updated inputs based on measured or calculated values. This illustrates that the model-predicted HTCs are higher than the measured values, though the gap diminishes as the fabric of the homes is improved through retrofitting, and some predictions are within the uncertainty of the measurement.

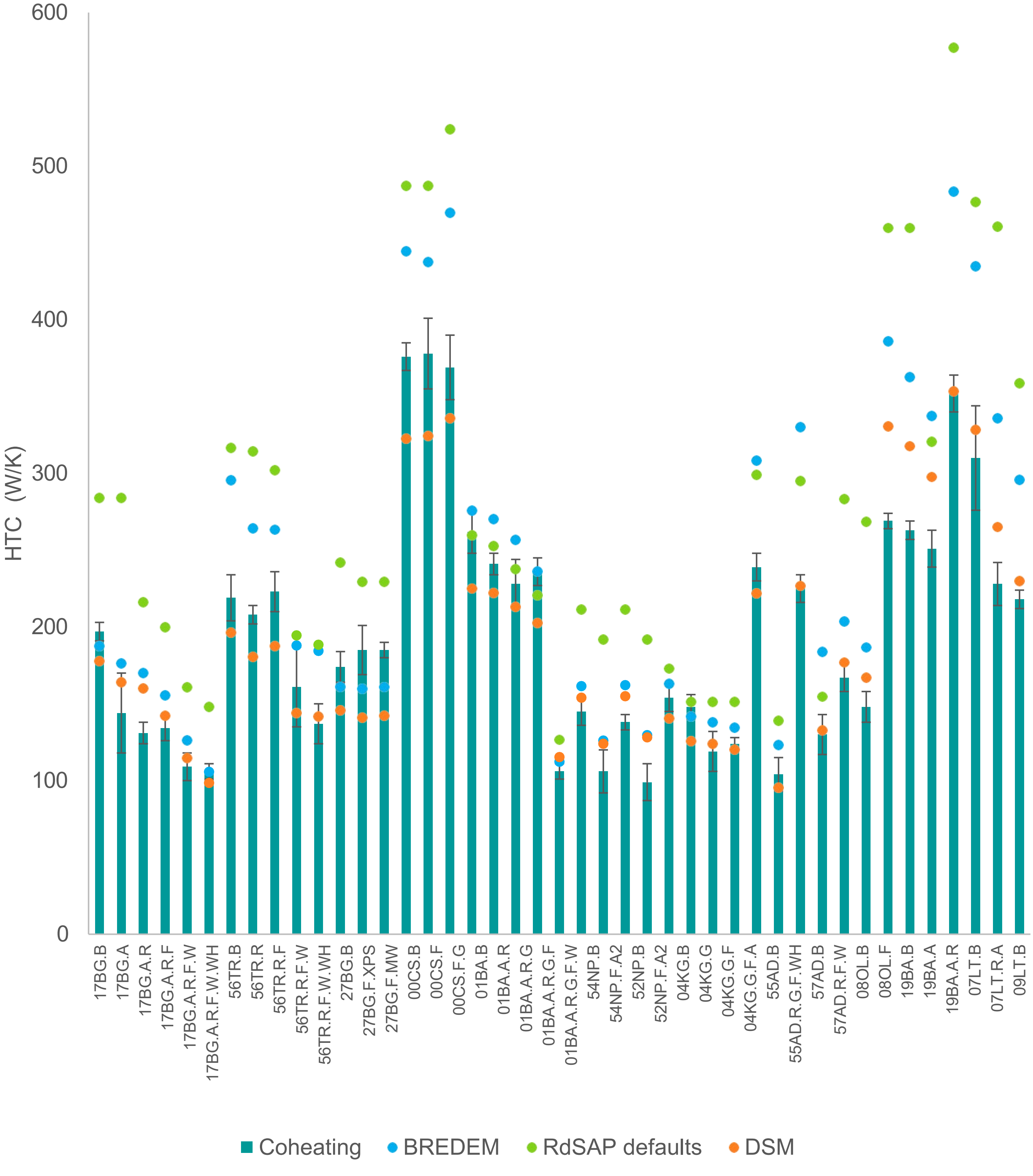


Figure 3-2 Measured and predicted HTC of case studies at base case and retrofitted stages

Figure 3-3 compares the measured HTC reduction achieved by the retrofits to the predictions from models. This shows that the reductions predicted by the EPC, which rely on default inputs, are often the highest. The figure also shows the impact of improving the predictions by updating the BREDEM and DSM models with measured airtightness values, measured U-values, and (for homes with SWI installed) calculated thermal bridging heat losses. While these are often more in line with the measured reductions, this analysis illustrates that predicted savings can still be very different and often greater to those experienced.

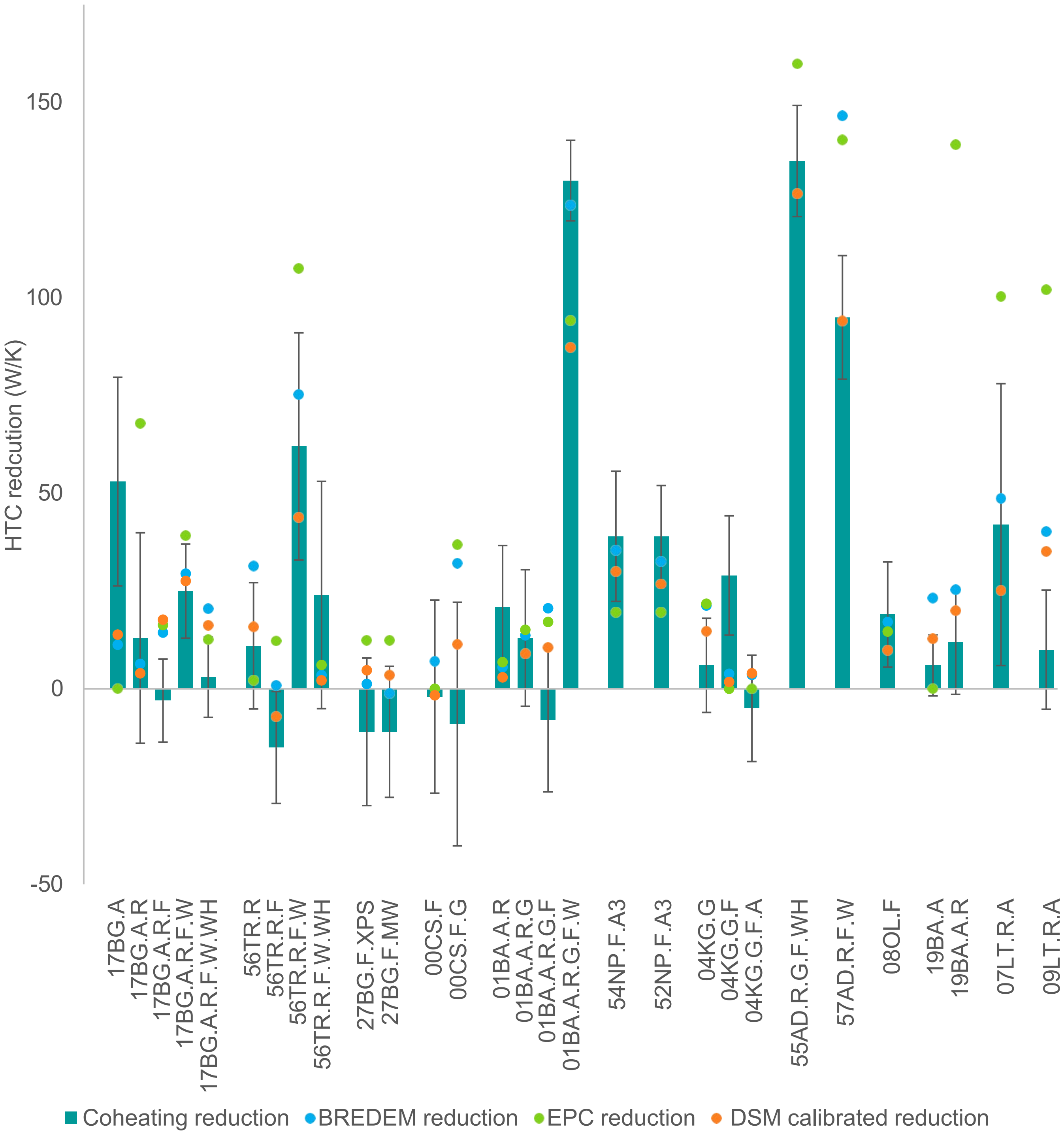


Figure 3-3 Predicted and measured HTC reductions achieved by the retrofits

Improving default input values to EPCs

Collecting real data to replace defaults is costly and not commonly undertaken. An alternative could be to provide a greater range of defaults and more flexibility for assessors to determine appropriate inputs.

For example, thermal bridging heat loss is represented in RdSAP as a y-value. This is set at a default of 0.15 W/(m^2·K) for most age bands in RdSAP, regardless of retrofit stage or house typology. However, calculated y-values for the case study homes ranged from 0.05 to 0.24 W/(m^2·K), equivalent to variations in HTC of between 6 and 50 W/K. Thus, it may be beneficial to create multiple default y-values to reflect specific building features, such as bay windows, the presence of SWI, or visible discontinuities. For instance, in one case study home the discontinuity between the SWI and the loft insulation resulted in heat loss up to 11 W/K. Additional work is required to understand the range of defaults needed.

An illustration of the variability in y-values calculated for the case study homes is provided in Figure 3-4, showing generally how thermal bridging can increase as insulation is installed, but that individual bridges in homes can cause significant bridging. It also highlights the scale of variation, and that the EPC default value is relatively high and perhaps more relevant to new build homes, which use the Appendix K of SAP linear Ψ-values to calculate thermal bridging at specific junctions [3].

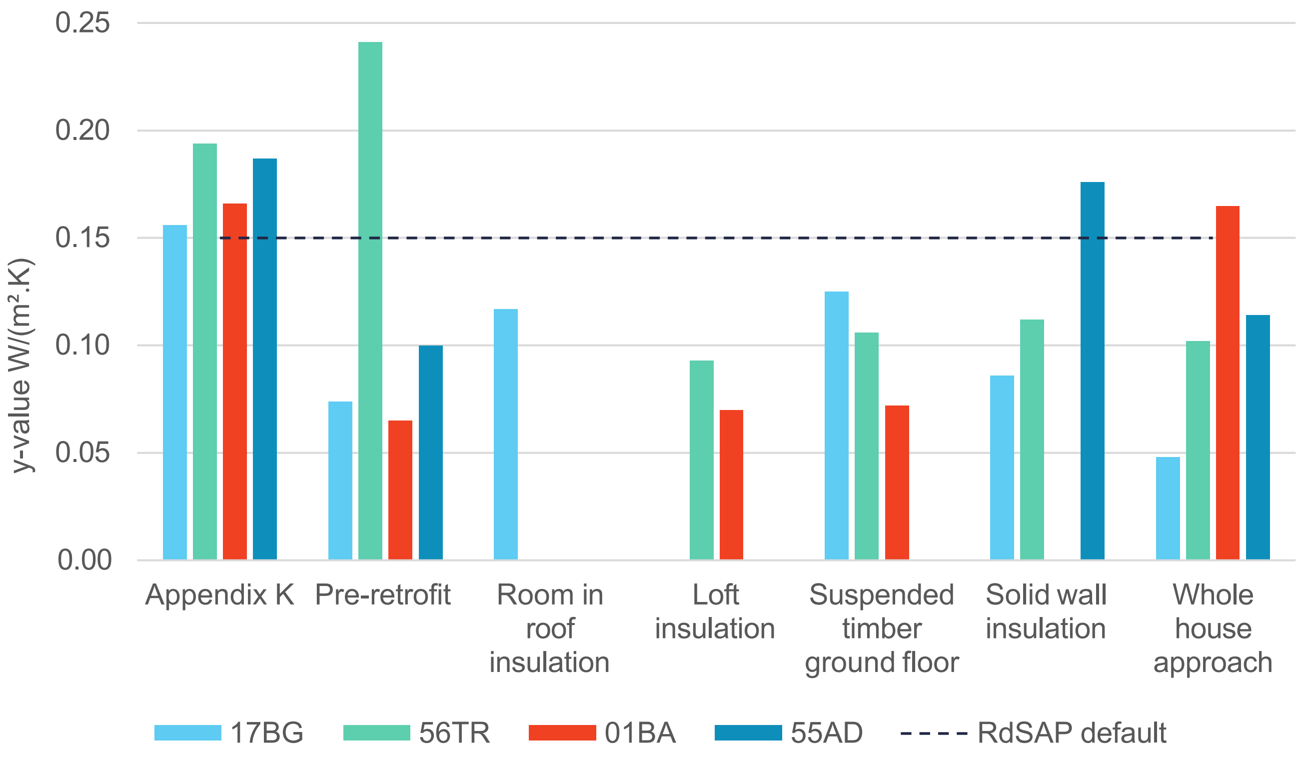


Figure 3-4 y-values for case study homes

Allowing a greater range of U-value inputs, for instance considering insulation thinner than 50 mm, would also substantially improve the accuracy of EPC predictions. One default U-value in RdSAP that was particularly inaccurate was for rooms-in-roof. For these, a simplified approach is applied by assessors which results in all fabric U-values being assumed to be 2.3 W/(m^2·K), and the geometry of the rooms and different elements is also assumed. In the case study homes, this resulted in significant overestimates of heat loss in EPCs. In some instances, twice the actual heat loss from homes was predicted. Moreover, removing modelling simplifications and shortcuts, and having a greater range of default U-values linked to specific construction types or construction features, could be a practical approach to improve EPC accuracy.

A comparison of measured, calculated, and default U-values for all elements in the DEEP case study homes was previously presented in Figure 1-5. This identified that the measured solid wall U-values ranged from 0.7 to 2.3 W/(m^2·K), suggesting the default of 1.7 W/(m^2·K) was not a good estimate for some homes. More research would be needed to understand what additional default U-values would be appropriate, e.g., for different construction types, retrofits, more refined age ranges, etc.

Another assumption in RdSAP, to simplify the process, is that internal walls and floors, fireplaces, kitchen units, and stair voids are not measured separately i.e., they are assumed to be part of a home's heated volume, making the home appear larger than it is. This is especially important as floor area is used to determine the level of inputs in homes (e.g., internal gains). Cumulatively, these internal features in a home can constitute a large volume. In DEEP this resulted in the case study homes' EPCs assuming, on average, 10% greater volume of air to heat than was measured. This resulted in an average 4.5% overestimation of space heating demand, though this varied significantly between homes. Requiring the volume of internal walls and other features to be accounted for in EPCs could improve accuracy.

Improving EPCs by using Dynamic Simulation Modelling
This project has identified that Dynamic Simulation Modelling (DSM) tends to predict lower HTCs than steady-state models like BREDEM (the calculation tool used in RdSAP to produce EPCs). This is illustrated in Figure 3-5. For homes with high levels of energy efficiency, both models report similar results, however, BREDEM tends to over-predict HTC more for homes with lower levels of energy efficiency, while DSM (DesignBuilder [5]) may even predict slightly lower HTC to the measured value.

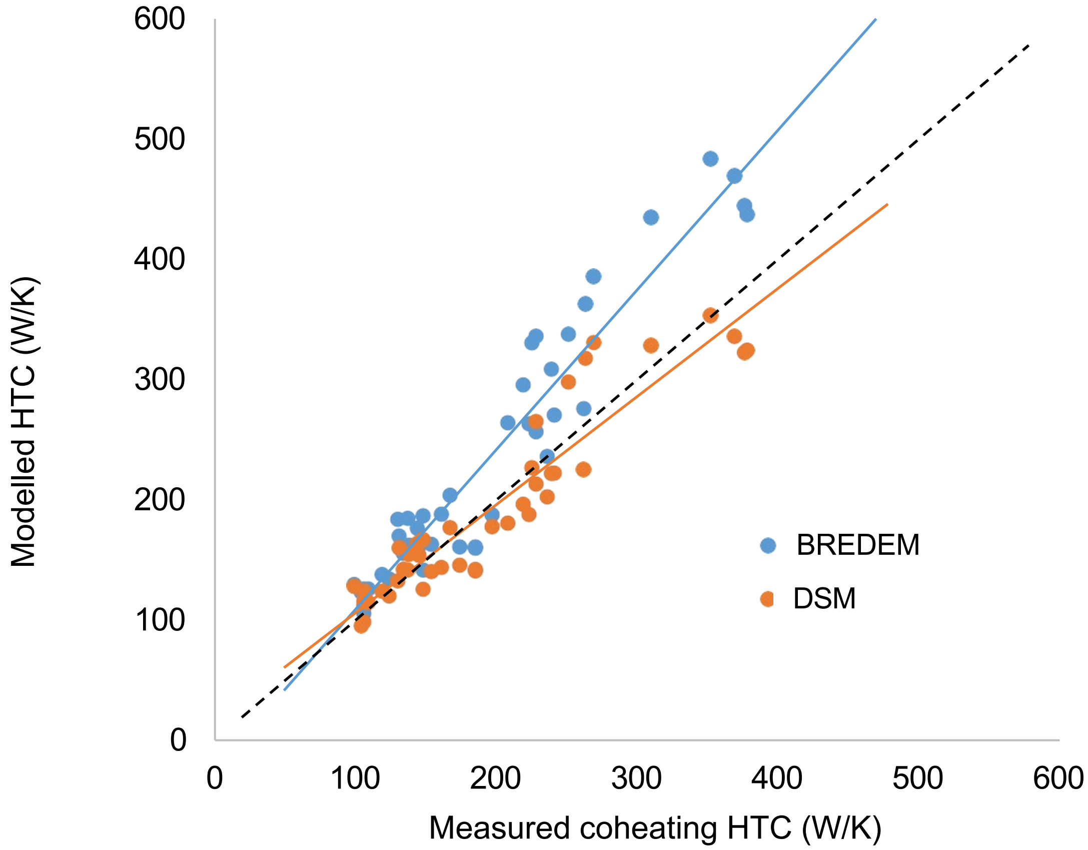


Figure 3-5 Comparison of measured and modelled HTC using different models, black dashed line represents 1:1 relationship

DSM differs from steady-state models like BREDEM, as it calculates heat transfer (and energy balances) in hourly time steps. Generally, DSM did not overpredict heat loss as much as steady-state models, while HTCs were on average <1 to 13% higher than were measured (occasionally, its predictions of HTCs were within the uncertainty range of the coheating test). There may be several reasons for its closer predictions, e.g., DSM's hourly resolution means it accounts for heat transfer and heat storage through building fabric in the context of weather conditions at each time step, including internal and external surface temperatures. This is compared with the steady-state approach of using an average day from each month to calculate heat demand, using mean daily values for all inputs; these typical days are then extrapolated to predict the annual energy consumption.

Additionally, for annual energy predictions, DSM accounts for internal gains using a different methodology to steady-state models, even when the total internal heat gains from people, lighting, and equipment are matched to those in the RdSAP calculations. Again, this is because DSM uses hourly time-steps to calculate the heat demand and energy performance dynamically. These differences mean DSM may be more representative of real-world conditions and could produce more accurate EPC scores. Thus, DSM may help inform retrofit policy, improve the implementation of RdSAP, and support decision-making.

DSM is also used for overheating assessment, and potentially for energy flexibility assessment, both of which are becoming more prominent concerns. Therefore, there could be complementary benefits to this type of modelling approach. Non-domestic energy models and large or complex dwellings can already use DSM for Building Regulations compliance. It may be possible to extend this to homes, although there would likely be resource implications for domestic EPC assessors.

Improving EPCs by incorporating different occupant behaviour

Occupancy profiles are standardised in EPCs to allow homes to be compared to one another. However, when using EPCs to predict retrofit savings, the occupancy profiles become more important and can affect the accuracy of predictions. In DEEP, nine different occupancy types were assessed using DSM, by altering the hours of occupancy and number of people assumed to be in the home.

A large variation in space heating demand was found between high and low energy users, which manifests in the potential retrofit savings. EPCs may be more useful if a range of predicted energy savings were reported for retrofits based on different occupancy profiles. This would allow occupants to understand the impact of their behaviour (high or low energy users) when making decisions and interpreting their EPCs. More research is needed to understand appropriate range of occupancy profiles to capture the most useful categorisation of energy users in UK homes.

Using 10-year weather files to improve moisture and overheating risk assessment
As mentioned, a significant problem with assessing moisture and overheating risks using models is that they rely on counting how frequently predicted values exceed a threshold. Uncertainty in the model inputs that represent weather, occupant actions, and the physical properties of construction materials can all change the outcome. The assessments are particularly sensitive to variations in the weather, and therefore results are not representative of specific situations. In DEEP this problem was largely overcome by developing a methodology to use ten years of weather observations, termed Recent Weather Decades (RWD), instead of just one year, as is often the case in models. This approach could also be taken to produce future weather decades (FWD).

Since each year of weather produces a slightly different result due to this natural variability, where results were close to the moisture or overheating risk threshold, the models cross the threshold in some years and not in others.

This approach gives a more robust risk assessment, for instance as shown in Figure 2-5, overheating assessments showed that the case study home 17BG could overheat in London 4 out of 10 years, but post retrofit this would be 10 out of 10 years. This level of confidence could not be gained using single year assessments. Conversely when the results were very much below or above the threshold, the risk assessment could be more confidently made as it was less affected by the variability (error) in the modelling.

RWD could be applied to EPCs to make their predictions more robust and describe how the performance of homes and retrofits varies between years. The RWD and FWD files developed for this project could be made available to modellers for locations around the UK and used in simulations to ensure that the energy savings are achieved, and the unintended consequences of retrofit are avoided.

Establish metrics and thresholds to improve moisture and overheating risk assessment
While absolute model outcomes for overheating and moisture risk are uncertain, models can be used more reliably for comparative analysis. Thus, risk assessments could adopt new comparative metrics. Such metrics would reveal the relative performance of different retrofit options, for example, “option A is better than option B”. This removes some of the problems of systematic uncertainty that make declaring a construction to be ‘moisture safe’, or saying a home will not overheat, challenging.

To better define the presence of moisture risk for IWI retrofits, a new comparative metric was developed (RH-days) that describes the number of days during which the daily average RH at the critical location between the insulation and the external wall was above 80%. A higher number indicates a higher risk of problems related to interstitial condensation.

This metric can be readily calculated using hygrothermal simulation software. Thresholds for this new metric are not yet defined but should be based on empirical evidence gathered from longitudinal field trials, since the evolution of moisture problems after a retrofit is a slow process. Similarly, new metrics and thresholds for overheating and surface condensation risk could be developed to better inform decision-making when designs result in borderline risks which may be above the threshold in some situations but below it in others. These metrics could be compatible with the 10-year weather files and used together form a set of risk assessment methods that are less sensitive to uncertainty in the weather and in the input parameters chosen.

Improving thermal and hygrothermal simulations using measured material properties
UK bricks have different material properties according to how, when, and where they were made. This means the thermal conductivity of bricks (which is the main determinant of heat loss), differs between homes. Eight bricks were tested in DEEP. U-values for a solid wall, incorporating the measured thermal conductivity of each brick, were calculated. As shown in Figure 3-6, six had U-values for the external wall much higher than the 1.7 W/(m^2·K) assumed in RdSAP software used for generating EPCs. Five exceeded the book value threshold in CIBSE Guide A [10], while the average was 2.1 W/(m^2·K). The values also differed to those derived by in-situ measurements taken in the four case study homes in the sample: 01BA, 17BG, 56TR and 57AD.

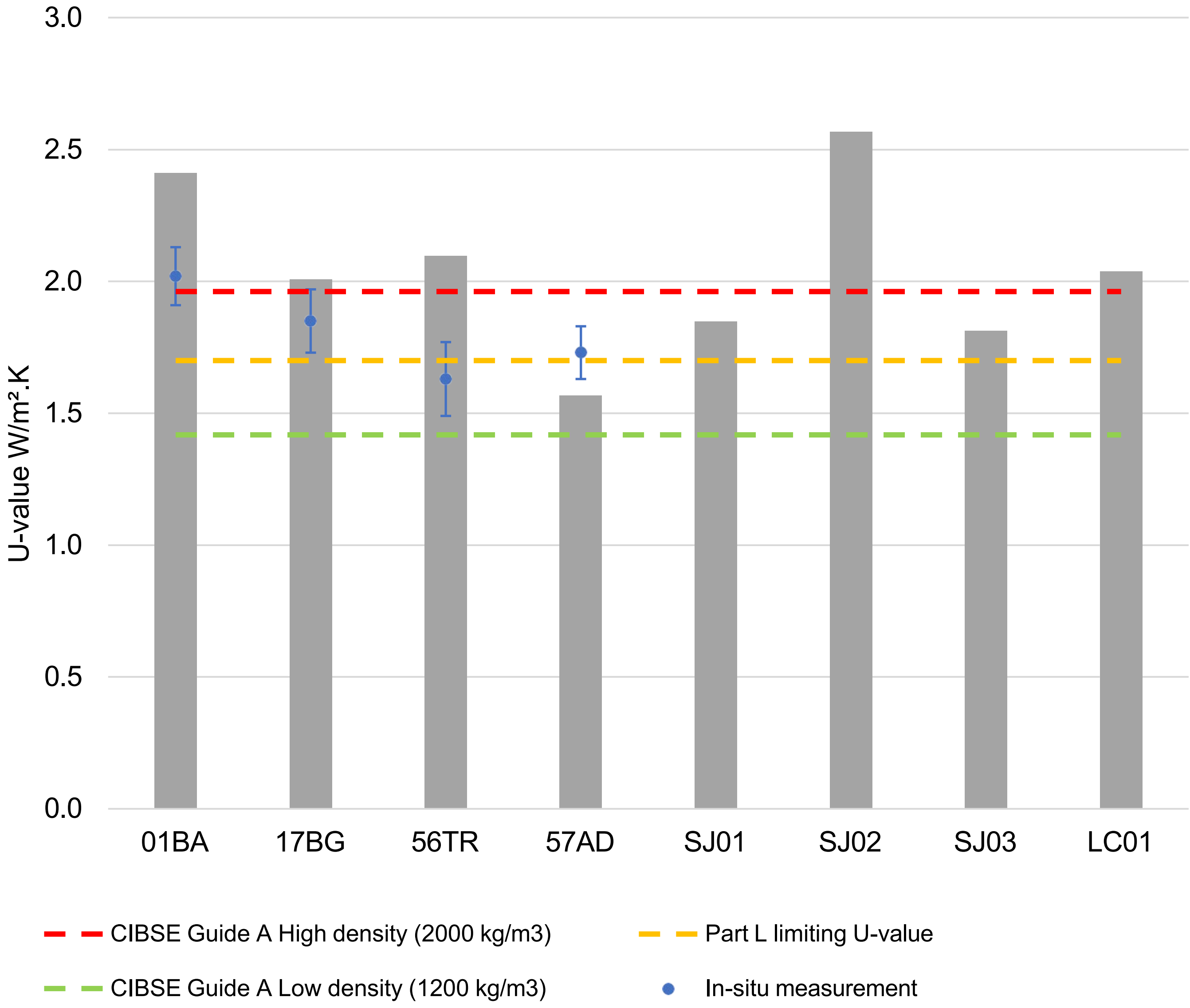


Figure 3-6 Calculated solid wall U-value (W/(m²·K)) of measured samples (grey) compared to in-situ measurements, book values and part L limited U-value

This evidence further highlights that some solid walled homes will have higher heat losses than are assumed in RdSAP. However, the variation in thermal performance of the bricks becomes insignificant once the solid walls are insulated. The analysis also revealed that, due to variability in brick material properties when uninsulated, seven of the eight walls would have surface condensation risks. When insulated, however, brick variability is less significant to the whole fabric heat loss.

Two of the eight bricks were found to be at risk of excessive moisture accumulation when uninsulated, due to their hygrothermal properties, while another two bricks were at risk of causing rot in embedded timber. This variability is a concern as it adds further uncertainty to models when attempting to predict moisture risks. The results do, however, suggest risks of excessive moisture accumulation and timber rot are generally low in uninsulated solid walled homes, but that in some parts of the country, inherent moisture risks may exist in homes.

Book value default material properties for bricks are commonly used in simulations. DEEP found that two of the three book values, contained in modelling software and standards, resulted in predictions of significantly more moisture accumulation risk than when using measured brick data, i.e., the book values overestimated risks.

Using data of actual brick material properties when modelling moisture risk can make risk assessments more accurate. However, it is rare that properties of individual bricks can be measured, so book value defaults will likely still be required. The creation of a greater range of defaults to cover a wider range of UK brick types, and guidance on which values to select in different scenarios, should improve assessment of moisture risk.

4. What are the procedural implications for achieving a whole house approach to retrofit?

Whole house approaches to retrofit must consider that all homes are unique, even those of identical construction (e.g., pairs of semi-detached homes). Construction quality varies, and over time, they may have been changed from their original construction. For instance, having dry lining, alterations to heating and ventilation systems, structural alterations, layout changes, and extensions. Thus, the whole house approach requires that each home's unique construction context is fully understood to ensure effective energy efficiency improvements, while minimising technical risk.

Establish an airtightness strategy for the retrofit
Adequate ventilation provision in homes is already a strong pillar of the whole house approach to retrofit and much guidance exists on this, including Part F of the Building Regulations for England and Wales. The DEEP project investigated uncontrolled ventilation, i.e., air leakage in homes, which should be considered alongside a home's ventilation strategy.

Excessive air leakage can limit the effectiveness of retrofits. As well as increasing heat losses, poor airtightness can also increase the likelihood of moisture-laden air entering the building fabric, which is not desirable. Out of the 14 retrofit case study homes, air leakage was predicted to contribute between 8% and 36% of a home's HTC, depending on the air leakage measured and the stage of retrofit (pre-retrofit homes tended to be leakier). This is illustrated in Figure 4-1, which shows the disaggregated heat losses based on U-values measured by heat flux plates, the blower door test to measure air leakage in each home, and thermal bridging heat loss[9].

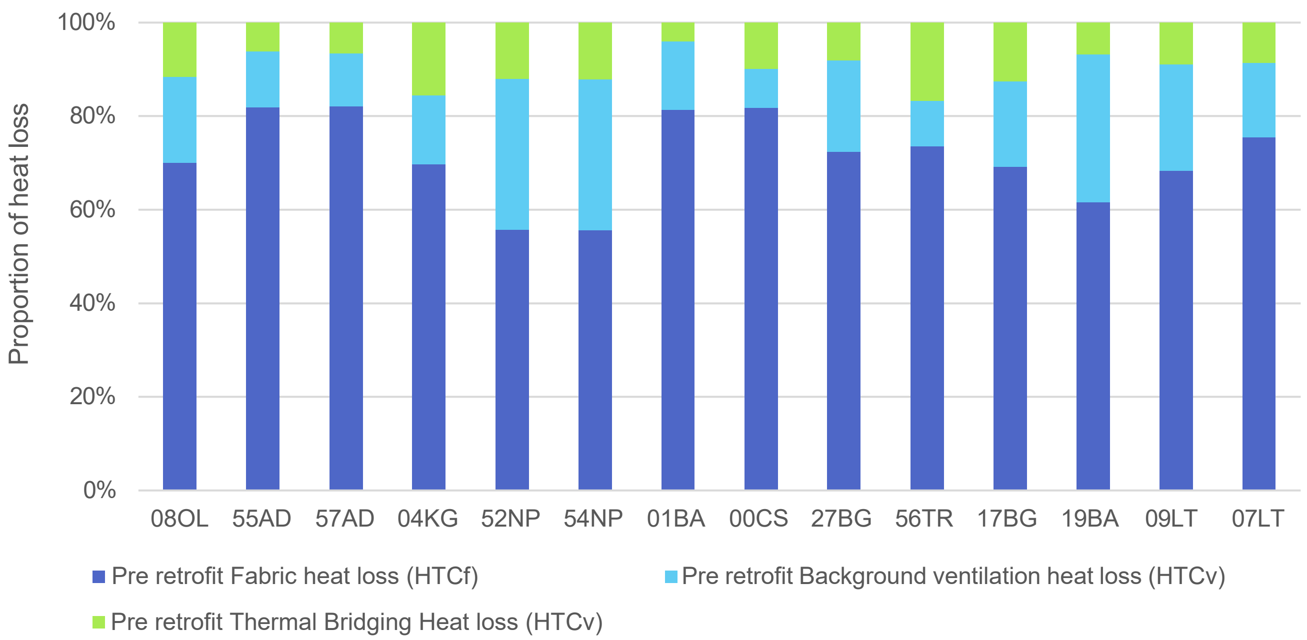


Figure 4-1 Disaggregated heat losses in baseline case study homes

[9] HTCb was calculated for 17BG, 56TR, 27BG, 55AD and 57AD, all other homes use RdSAP defaults

As fabric retrofits are installed the importance of background ventilation heat losses, and thermal bridging, becomes more significant. This was observed in the DEEP case study homes where SWI retrofits were installed, as shown in Table 4-1.

Table 4-1 Change in relative heat losses for 5 case study homes which had SWI installed

	Fabric plane element	Background ventilation	Thermal bridging
Pre-SWI retrofit	78%	13%	9%
Post-SWI retrofit	64%	20%	16%

Around 10% of the 146 homes tested as part of wider DEEP airtightness surveys had high levels of air leakage, with measured air permeability over 15 $m^3/(h \cdot m^2)$ @ 50Pa. The majority of the 77 solid walled homes tested in the project had air permeability ranging from 6 to 19 $m^3/(h \cdot m^2)$ @ 50Pa (though the sample ranged from 0.9 to 25 $m^3/(h \cdot m^2)$ @ 50Pa).

Furthermore, it was not usually possible to predict which homes had excessive air leakage without testing. An airtightness test, preferably using air leakage detection, should therefore be used to assess the ventilation requirements, both pre- and post-retrofit.

Similar air leakage pathways were found across all homes, but the severity of leakage varied. Usually both direct (e.g., via unsealed penetrations through the walls) and indirect (e.g., leakage via inter-connected internal voids before exiting the home) were present. Existing homes tend not to have a clearly defined continuous primary air barrier, as there is for new build homes. For instance, wet plaster provided the air barrier on the walls, but no membranes or seals existed to continue this air barrier across the floor or at ceiling junctions.

Discontinuities in the air barrier were observed to be air leakage pathways in the case study homes. Attempts at achieving a continuous primary air barrier in the case studies were challenging and disruptive (e.g., requiring removal and subsequent replacement of skirting boards, floor finishes, boxed-in services, bathroom and kitchen fittings, and plasterboard finishes).

This has implications for training and skills in the industry, and for individual retrofits. Traditional draught-proofing activities undertaken in the DEEP retrofits were not successful in minimising uncontrolled ventilation in homes and showed that improving the airtightness of a home is not a ‘fit-and-forget’ retrofit. All subsequent work and installations also need to take their effects on airtightness into consideration, highlighting the need for more sophisticated approaches.

Embed home repair and maintenance into the retrofit plan and budgets
When works are undertaken it is likely that repair and maintenance issues will be identified. These are important considerations in the whole house approach. Repair costs were one of the most significant additional costs faced by the DEEP case studies. These are shown for each home in Figure 1-23. On average additional costs constituted 26% of the retrofit cost but could be as high as 38%. Several repair and maintenance issues were observed in the case study homes, as shown in Figure 4-2. These included rebuilding garden walls, repairing chimneys, fixing rainwater, and plumbing leaks, servicing boilers, repairing damaged plaster, and reinforcing roof timbers. Undertaking some of these activities will contribute to safeguarding the structural integrity and longevity of the building.

Figure 4-2 Examples of repair issues in DEEP case study homes (Top left; incomplete party wall, Top right; damage to masonry, Bottom; leak in roof)

The costs of undertaking these repairs may or may not be considered part of the retrofit budget. However, the retrofit is likely to be the point at which the damage is discovered, and the repair needs to take place. This has implications for household retrofit budgets, as well as how general home improvement and domestic energy efficiency policies interact.

Include knowledge of previous retrofits in decision-making
Effective surveys should be capable of identifying retrofits that have previously taken place during a home's lifetime. However, identifying previously installed retrofits is not always possible without destructive surveys or thermography to observe anomalies in thermal performance. Undertaking retrofits without these surveys means existing condensation risks in homes may be retained in the new retrofit. For instance, unsealed polystyrene-backed plasterboard IWI had previously been installed with an air gap between the board and the external wall in several DEEP homes. This approach increases the risk of interstitial condensation. Existing retrofit measures should also be considered in energy saving predictions of the new retrofit to avoid the prebound effect. For instance, if homes have pre-existing thin IWI, any additional or replacement wall insulation will yield diminishing returns. If this is not considered in an EPC it will overpredict savings from the new insulation.

Adapt heating systems to consider heat loss reductions from fabric improvements
Investigations undertaken during DEEP at the UoS Energy House demonstrated how reduced heating demand from improved building fabric affects hydronic heating system efficiency, as pre-existing boilers and radiators can then be oversized. Increased boiler cycling and higher water return temperatures reduced condensing boiler efficiency by 5% following a major retrofit (SWI). For a major retrofit this could mean a loss of 3% of the energy savings that could have been achieved by the fabric retrofit.

Reducing the boiler flow temperature setpoint to provide better agreement between the heat output of the existing radiators and the post-retrofit heat load of the dwelling can mitigate post-retrofit oversizing. In addition, installing Class V boiler controllers, i.e., those which can modulate boiler output, (rather than on-off controllers) can reduce the impact and should be considered (for boilers that are not capable of modulation) following solid wall retrofits.

The methods used to calculate fabric heat loss and size heating systems require improvement to enable heating systems to be optimised for a dwelling's post-retrofit heat load. Matching heat output to demand is also critical for heat pumps, which require an appropriate heating curve to be selected to achieve good control of space heating and optimal efficiencies. This will be more important as heat pumps become installed more frequently, especially if they are installed in tandem with fabric improvements. The whole house approach to retrofit should consider the entire dwelling as a system and the impact on heating system performance considered when any retrofit is planned.

Improve risk assessments and guidance
Evidence on additional activities required in the DEEP case study retrofits to avoid unacceptable risks are summarised in Section 2, describing steps commonly undertaken to limit thermal bridging heat losses or reduce condensation and overheating risk in homes. These should be expanded upon through further research on other house types, constructions, and retrofit designs, so that evidence-based guidance can be provided on which activities are likely to be essential to avoid excessive thermal bridging, moisture, and overheating risk on a broader range of house and retrofit typologies. It may be possible to develop risk profiles and recommendations for specific situations that installers can follow, akin to the accredited details used in Building Regulations.

Using risk profiles could achieve cost reductions for relatively simple design solutions, where issues are low risk, as well as differentiate the situations where this would not be appropriate and more case-specific solutions are needed.

However, more holistic appraisals of risk would be needed before this could be implemented, including investigating the impact on surface condensation, interstitial condensation (where appropriate), moisture accumulation and overheating. Moving towards more holistic risk profiles rather than individual risk thresholds is especially important since the concept of risk is not well understood and can seem ambiguous, i.e., solutions can be judged as low risk for one risk factor (e.g., surface condensation) but high risk for others (e.g., interstitial condensation).

The assessment methods used to evaluate risk may also need to be updated. For instance, developing risk metrics which do not follow pass or fail thresholds but allow a buffer around borderline results, or comparative assessment where option A is better than option B. Uncertainty in risk assessments should also be better accounted for, for instance by simulating models over multiple years to understand how likely certain risks are.

Also, model boundary conditions used often do not, or cannot, account for realistic scenarios for how homes are used in practice. These may need to be revised to consider a broader range of scenarios such as underheating, high levels of RH, air movement through fabric, and more extreme weather conditions. Given that risk assessments in their current form are subject to significant uncertainties, the broader whole house approach requirements to improving ventilation alongside any retrofit should help to minimise any risks that are present in homes around moisture and overheating manifesting as problems.

***Retrofit ready* building and maintenance work**

To ensure measures are not detrimental or creating future barriers, the whole house approach should consider what future retrofits may be needed in the home (and document the works undertaken at the time) to achieve future energy efficiency standards. This means that if individual measures are installed or general building and maintenance work is undertaken, they should be designed to make future retrofits less disruptive to install. For general building work, this could include extending rooflines when making roof repairs to accommodate future EWI or installing airtightness barriers between floor and wall junctions when replastering walls.

In DEEP, examples of this included fitting windows into boxes so that they can be replaced more easily in the future, since removing windows and doors often leads to severe damage to plasterwork. This also makes it easier for windows to be moved in line with future EWI. Additionally, it is important to allow sufficient clearance to accommodate IWI or EWI to be installed in the future without the glazing being covered or the opening mechanism being impaired. Further, deep or over sills should be considered (or sills that can be replaced simply) to allow sufficient clearance for EWI to be installed in the future. The same issues apply to installing new external doors, where sufficient floor clearance to accommodate future floor insulation should also be considered.

For EWI it is important that external structures such as gates and fences allow sufficient clearance for EWI to be installed in the future without the need to relocate these structures. For IWI one of the main barriers is that new kitchens, bathrooms, and other wall-mounted items need to be removed. So, when these are being replaced, IWI installation should be considered at the same time. Similarly, where penetrations through the external wall are made, they should be accessible, so that future airtightness works may take place without major disruption, e.g., removing baths, sinks, boxed-in services etc. Also, since the lifetime of homes exceeds that of retrofits, insulation materials should be installed so that they can be replaced at the end of their expected lifetime.

5. Are measurements of retrofit technical performance robust?

Building performance evaluation (BPE) tools measure technical performance and risks of homes and retrofits. Different methodologies have strengths and weaknesses which should be considered when interpreting the results. DEEP has undertaken a significant amount of testing and identified important considerations for future use of BPE tools.

This section discusses some of the observations about BPE tests undertaken during DEEP. These include 43 coheating tests, 410 heat flux plate measurements, and 118 blower door tests, in addition to thermographic surveys and surface temperature measurements. Comparisons between established scientific tests and alternative commercial tools were also made, including 84 low-pressure pulse tests to measure airtightness in homes and 50 QUB tests which provide an overnight assessment of HTC.

Commonly, the blower door test, with leakage detection, is used to identify and quantify air leakage in homes. The low-pressure pulse test is becoming more widespread as an alternative. Heat flux density measurements to quantify in-situ U-values of fabric elements are rarely used outside of scientific investigations but can provide useful data on rate and heterogeneity of heat flow through fabric elements. Further, the whole house HTC is a metric becoming increasingly used, for which the coheating test is the scientific measurement tool. New commercial alternatives are also emerging, including overnight tests, as well as those using smart meter data from occupied homes via smart meter-enabled thermal efficiency ratings (SMETERS[10]).

Beyond fabric testing, in-use monitoring of homes can provide useful data on their real-world performance, including air quality, internal temperatures, humidity, comfort, and energy consumption. These investigations require longitudinal monitoring approaches which were outside the scope of DEEP. Nonetheless, they have potential to give useful information on the differences in technical performance and risks of piecemeal retrofits versus the whole house approach, as well as to validate modelled predictions.

[10] https://www.gov.uk/government/publications/smart-meter-enabled-thermal-efficiency-ratings-smeter-technologies-project-technical-evaluation

Comparing low- and high-pressure airtightness measurements
The low-pressure pulse test is an alternative to the fan pressurisation (blower door) method for establishing the air leakage rates of homes. It has been incorporated into CIBSE TM23 and accepted for Building Regulations new home compliance testing [6]. Its suitability for use in existing homes to support retrofit is not well explored.

In DEEP 84 pulse tests in 50 homes were successfully undertaken. More were attempted but were not always successful; this was a particular issue in the least airtight homes (i.e., >15 $m^3/(h \cdot m^2)$ @ 50Pa) and those homes in some disrepair. However, the later model pulse kit (not available until near the end of DEEP) and additional expansion tank mostly resolved the issue.

Of the 50 homes where a valid pulse test result was achieved, comparisons of the mean of all the pulse and blower door tests showed a very good correlation (around 1% difference).

However, the range in variation between individual pulse and blower door tests for the same home could be large, i.e., the pulse test result for any single home could be very different to the blower door result. In some instances, the pulse result was 20% greater than the blower door result, in other instances it was 80% lower. The relationship is illustrated in Figure 5-1.

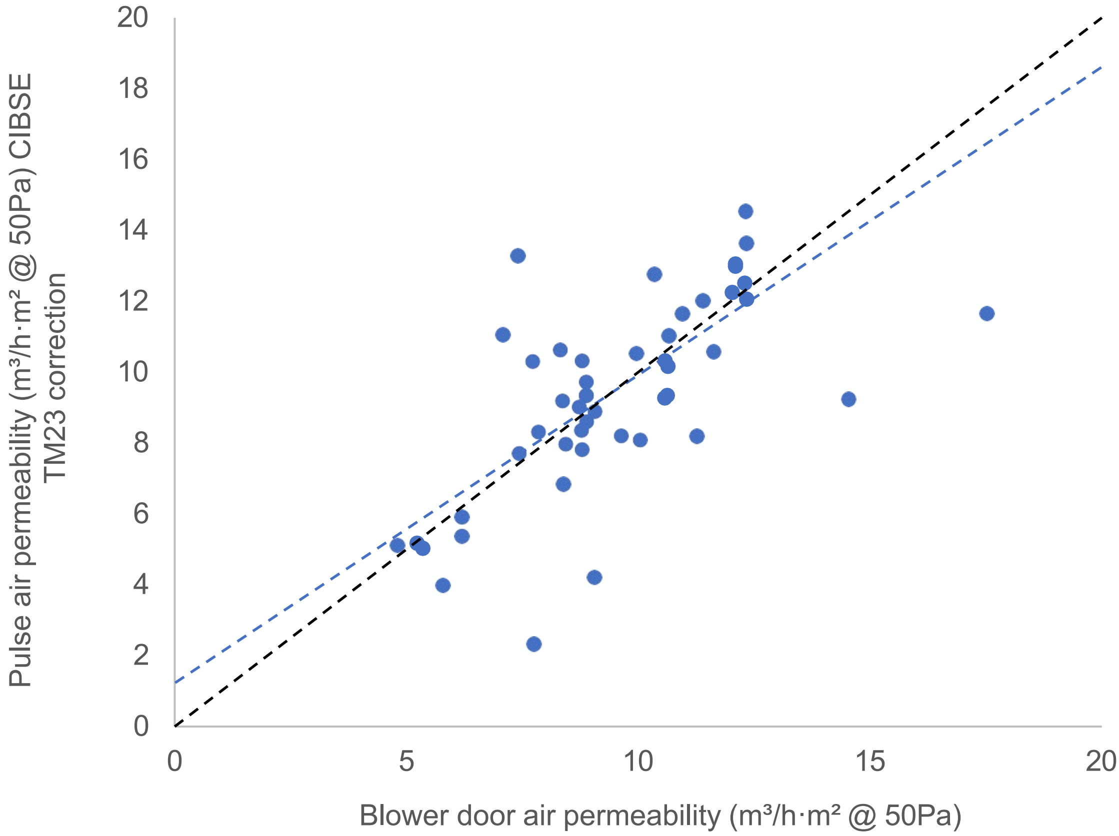


Figure 5-1 Comparison of blower door and pulse test air permeability (black line = 1:1 relationship)

Accounting for inter-dwelling air exchanges when measuring airtightness
As the blower door test induces high pressure differentials in homes, it may cause air exchange that is specific to the test, rather than observed under natural conditions. Additional tests were carried out during DEEP to further investigate part of this phenomenon.

Pressurisation tests were undertaken in adjoined dwellings simultaneously (co-pressurisation tests), removing pressure differentials across the party element that only exist under individual dwelling test conditions. Holding both homes at the same pressures (within 1.0 Pa of each other over a 10 second average) negated any inter-dwelling air exchanges.

This revealed that inter-dwelling air exchanges made up, on average, 17% of the total blower door test value (ranging from 2 to 28%) as can be seen in Figure 5-2, suggesting there is an overprediction in the regular blower door tests being undertaken in homes with attached neighbours.

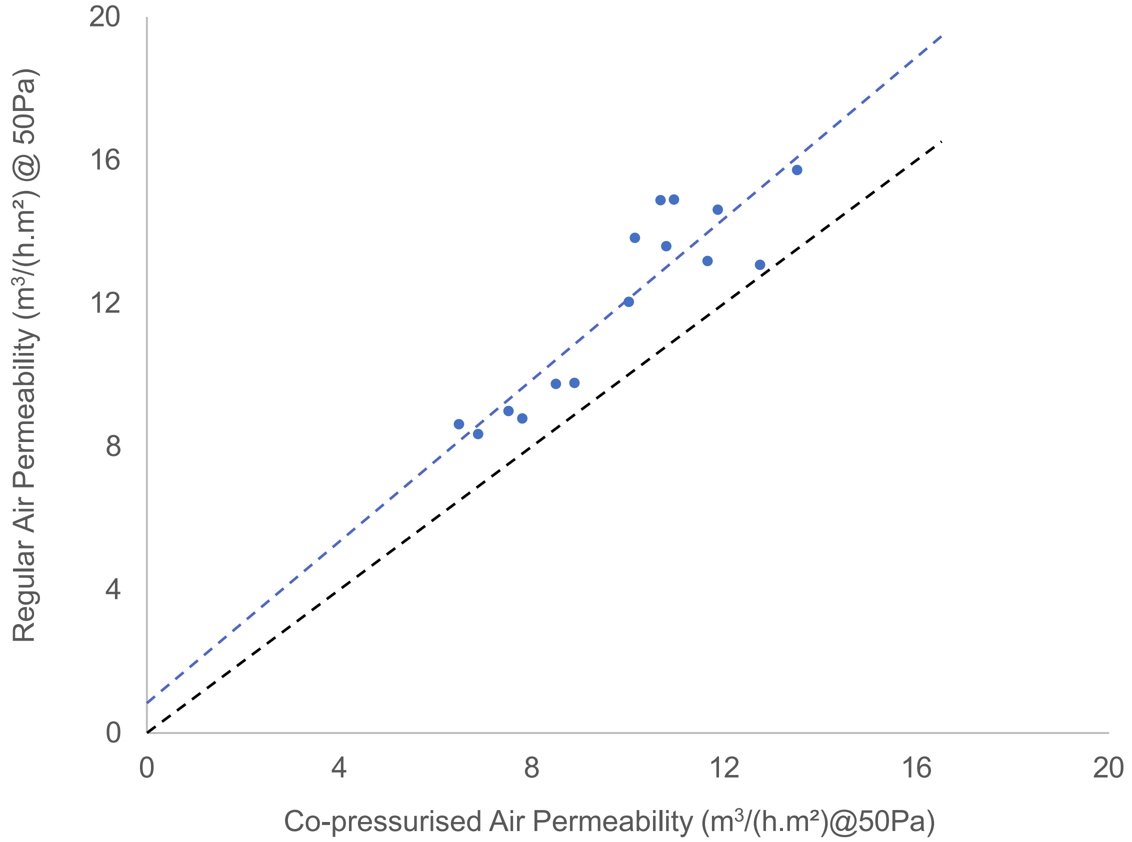


Figure 5-2 Comparisons of pressurisation and co-pressurisation tests (black line = 1:1 relationship)

This has significant implications for all blower door tests undertaken on similarly constructed adjoined properties as those in DEEP, and possibly all adjoined homes (over 75% of the UK housing stock [11]). This overestimation of inside-to-outside air leakage in attached homes means calculations of ventilation heat loss and assessments of the need for mechanical ventilation may not be robust.

Avoiding spot measurements when measuring fabric heat loss

Energy assessors conducting EPC assessments do not measure heat loss from the building fabric. However, where more detailed investigations are taking place, heat loss measurements could be used to inform energy models and designs.

Heat flux density measurements derived from Heat flux plates (HFPs) installed in the case study homes were useful in disaggregating whole house heat loss, explaining the relative amount of heat loss from certain elements, and identifying the performance gap of retrofitted insulation, which may be caused by discontinuities in insulation layers. The case study reports outline the specific heat loss of different elements pre- and post-retrofit for all the DEEP case study homes. An average of this disaggregation across the five case study homes which had SWI installed, pre- and post-retrofit, is shown in Figure 5-3. This also highlights that walls can be the most significant source of heat loss in homes before, and even after, SWI is installed.

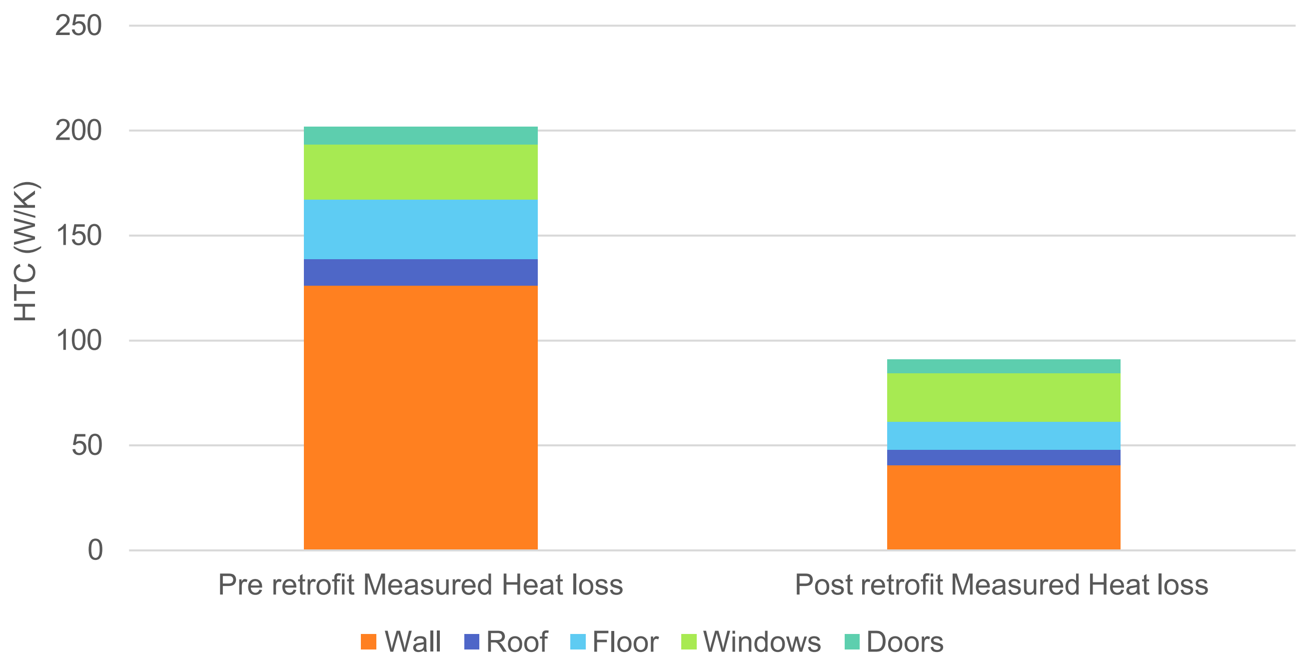


Figure 5-3 Fabric heat loss for five case studies before and after retrofits including SWI

The coheating test provides some of the best conditions in the field for driving monodirectional heat flow through construction elements, and therefore enabling reliable heat flux density measurement. However, there were several instances where a reliable heat flux measurement could not be attained from individual sensors. The reasons for these failures include solar gains, heat emitters on the neighbouring sides of a party wall, unusual fabric constructions, or excessive air movement within the building fabric. The intermittent nature of some of these interferences only became apparent upon analysis of initial results. Thus, relying on individual heat flux measurements could be misleading, even when using thermal imaging to position sensors. Instead, average U-values from multiple heat flux density measurements for each fabric element should be used to provide robust U-value estimates.

Where necessary, area weighting of elements may be needed (e.g., if there are discontinuities in insulation) to avoid misleading results, though this adds cost and complexity to the process. Problems of this nature make it difficult for practitioners to use heat flux measurement outside research projects.

Figure 5-4 highlights heterogenous heat flow that can take place in fabric elements. Ideally multiple heat flux measurements are needed to provide a weighted average heat loss through each element. Thermography is therefore a complementary tool for heat flux measurements.

Figure 5-4 Heterogenous heat losses through fabric caused by variations in construction (top, missing insulation in a stud wall, bottom, varying construction in party wall)

Thermography is also useful when coupled with pressurisation tests to identify the location of air leakage. However, interpreting thermographic images to determine if anomalies in surface temperatures are caused by the emissivity of the surface, reflections, thermal bridging, air movement, or moisture in the fabric etc., requires training of practitioners.

Comparing coheating and overnight whole house heat loss measurements
Overnight whole house heat loss test (QUB) tests were undertaken in 50 homes, and over the sample achieved HTC values within 15% of the coheating test, though this varied between 1 and 47%. Most QUB tests reported slightly lower HTCs than the coheating tests regardless of the building form or stage of retrofit. The statistical uncertainty associated with QUB tests is similar to coheating tests, with average uncertainty of 2.7% across all the tests, ranging from <1 to 10%. However, the precision of repeated QUB tests was 17% relative to the mean when multiple tests were conducted, i.e., the separate tests tended to give similar results within this range.

The relationship between QUB and coheating is illustrated in Figure 5-5. Other attempts to measure the HTC using different technologies were undertaken in the DESNZ SMETERs program, where agreement ranged between 14% and 33%, indicating that QUB is among the best performing alternatives to the coheating test [12]. However, since the SMETERs were evaluated against an adapted coheating test that did not conform to the standard protocol [13], and tests were performed on homes with different characteristics to the DEEP case studies, the results are not directly comparable.

The uncertainty of all HTC measurement methods determines what limitations they have in providing data on the performance of buildings and retrofits. These results indicate that overnight tests can be usefully deployed to understand the approximate HTC of homes to compare with models, as well as identifying changes in HTC resulting from major retrofits. In DEEP, the overnight tests successfully identified the impact of SWI in the case study homes. QUB tests may, though, have limited use for measuring performance pre- and post-retrofit in homes that achieve modest heat loss savings, i.e., within the uncertainty range of the test (e.g., loft, ground floor, window, or airtightness retrofits). It is possible that repeating overnight tests in homes could improve their ability to identify the impact of less significant retrofits.

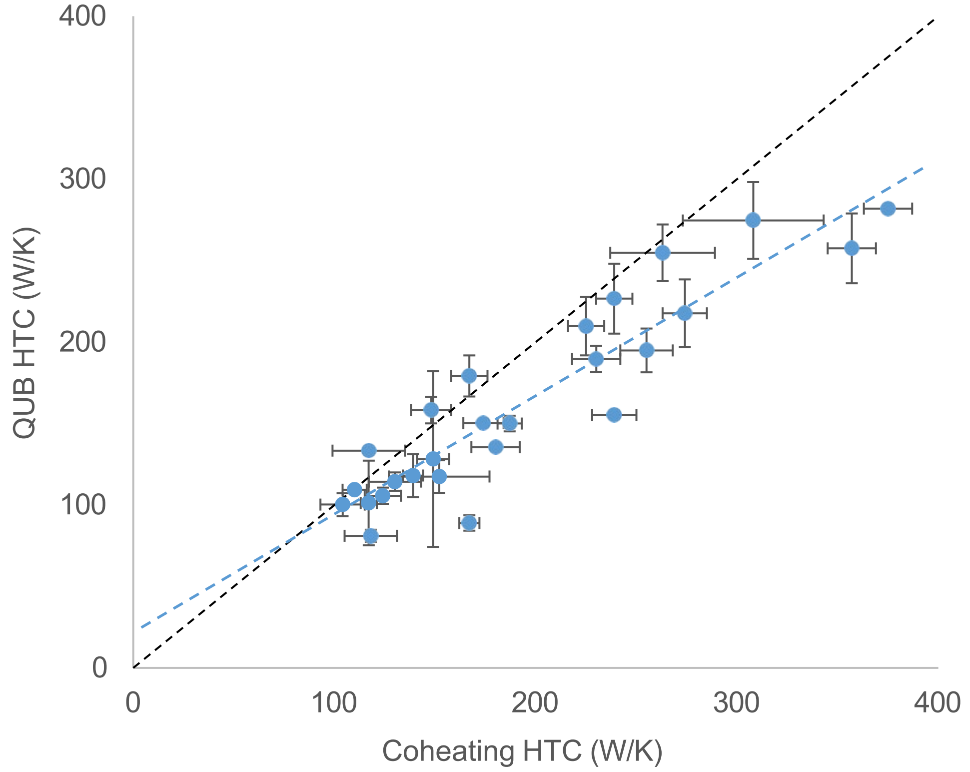


Figure 5-5 Comparison of case study home HTCs measured by QUB and Coheating (black line = 1:1 relationship)

Understanding uncertainty in pre- and post-retrofit measurements
Measuring the performance of homes is challenging, since there are many factors affecting heat losses that are difficult to measure, but which need to be accounted for. For instance, the amount of solar or party wall heat transfer can only be estimated from proxy measurements. Other influences like changing exposure to wind and rain (how wet the fabric becomes), are often not possible to approximate at all. Hence longer test durations are often needed to improve the robustness of the estimates.

This has implications for all HTC measurement tools, including those that take place with occupants in-situ and therefore have additional user behaviour variables to account for (opening windows, varying occupancy etc.). The uncertainty associated with the measured values therefore varies per test and must be considered when quoting an HTC value to understand if it is useful in assessing the performance.

Historically, the uncertainty of the coheating test has been in the region of 8 to 10%. In DEEP the uncertainty ranged from 2 to 18%, with a mean of 6%. Since 20 out of 39 coheating tests had an uncertainty of between 2 and 6% and 30 out of 39 had uncertainty lower than 10%, the DEEP coheating tests are among the most accurate field trial experiments undertaken and there is a good degree of certainty in the results.

The variation found in the coheating HTC uncertainty illustrates that there is no single uncertainty value for an HTC test. Each individual test is subject to its own idiosyncrasies and specific environmental conditions, meaning that a bespoke uncertainty value for every test is needed. This is an important consideration since applying the average uncertainty of 6% for the coheating tests in DEEP, to all the coheating tests undertaken, would give misleading results on which retrofits achieved statistically significant reductions in HTC, and which did not.

Despite the low uncertainties achieved, the coheating test was still only able to measure a statistically significant improvement in 13 of 27 individual retrofits. Where a statistically significant improvement could not be detected, the most likely cause was simply that the retrofit did not have a large impact on HTC. Detecting the impact of individual, small retrofits therefore presents a considerable challenge to the field of building performance evaluation. This challenge is important for all HTC measurement methods, where high uncertainty bounds could result in tests being unable to detect HTC improvements even on large retrofits. Overcoming this challenge may require measuring the HTC of cohorts of homes rather than house-by-house or testing over much longer periods of time. More work is required to understand how the uncertainty and cost of measuring HTC can be reduced, as well as to define the boundary conditions of tests in the context of measuring retrofit performance.

Conclusions

The DEEP project makes a significant contribution to knowledge to promote safe and effective retrofits in solid walled homes. The project provides valuable data to support the whole house approach to retrofit. It gives specific guidance on critical issues for minimising risk and maximising impact when retrofitting solid walled homes. The project also outlines how energy models and risk assessments can be improved, as well as how to measure performance of homes and retrofits robustly.

Building performance evaluation tests were undertaken before and after 41 different fabric retrofits were installed in 14 case study solid walled homes. Additionally, a series of retrofits were installed in a home inside an environmental chamber to replicate the case studies in controlled conditions and investigate the effect of retrofits on heating systems. These evaluations, along with thermal modelling of fabric junctions, describe changes in heat loss and thermal bridging (which affects surface condensation risks) in the homes, comparing the piecemeal and whole house approaches to retrofit.

Energy models, including Energy Performance Certificates (EPC), were used to predict reductions in fuel bills resulting from retrofits, as well as to evaluate changes in overheating risk in the homes. Furthermore, hygrothermal simulations were undertaken specifically to explore interstitial condensation risk related to internal wall insulation (IWI). The impact of the retrofit approach on internal conditions (background and purpose provided ventilation, relative humidity, comfort, indoor air quality etc) and occupant experiences or behaviour, however, were not investigated. These are important components of the whole house approach to retrofit. The findings should therefore be considered in the context of how these other factors may also affect risk in homes. Despite focussing on technical performance and a limited range of risks, DEEP is still one of the most extensive investigations into retrofitting homes to date, and the results provide useful insights for practice and policy.

The report introduced five research questions related to the benefits and risks associated with retrofitting solid walled homes, the whole house approach to retrofit, and how modelling and measurement of retrofit technical performance and risk can be improved. The main findings and implications for each question are discussed here:

1. Effective retrofits for solid walled homes
In the DEEP case study homes, the reduction in whole house heat loss from installing retrofits varied substantially, seeing HTC reduce by between <1 and 60%, depending on the starting condition of the home and specification of the retrofit, as well as the assumptions made when creating models. Solid wall insulation (SWI) was predicted to reduce HTC between 10 and 60%, and household fuel bills by between 7 and 38%, substantially more than other retrofits. Loft, room-in-roof, and ground floor insulation, new windows, and draught-proofing retrofits had more variable success, reducing HTC between <1 and 27%, and fuel bills by between <1 and 8%. SWI is therefore the most impactful measure and saves more energy than all other measures combined. The savings observed are based, however, on a small sample of case study homes so do not represent savings across all UK homes.

Tests performed on the home in the environmental chamber also identified a potential unintended consequence of installing SWI, where the efficiency of the home's gas boiler can be reduced by around 5%. Boilers run most efficiently when their output is matched to the heat demand, so by reducing the heat demand from retrofitting, a mismatch between boiler output and demand is created. To counter this loss of efficiency, modulating controls may be installed or the boiler flow temperature setpoint can be reduced to match the lower demand. This highlights that the whole house approach must also incorporate consideration of the impact on services, even when fabric-only measures are being installed.

2. Reducing technical risks for retrofits in solid walled homes
Between 66 and 89% of junction lengths in the uninsulated solid walled homes had a temperature factor (f_{Rsi}) lower than the critical value of 0.75. This means it is likely that uninsulated solid walled homes have underlying risk of surface condensation. However, whether condensation, damp, and mould will manifest in homes is determined by other criteria not assessed in DEEP. For instance, relative humidity (RH) and air temperatures, provision of ventilation and air movement next to cold surfaces.

Insulating the solid walls reduced thermal bridging in the uninsulated homes and saw the junction lengths with f_{Rsi} <0.75 reduce to between 16 and 22%. Thus, SWI reduces the average risk of surface condensation when installed as a single measure, though when it is installed via a piecemeal approach, some individual bridges will become worse. Removing these discontinuities, as required in the whole house approach, saw the proportion of junction lengths with temperature factors below the critical threshold to drop further, to between 1 and 8%, indicating that the underlying risk was almost removed from the homes.

The uncertainty in the assessment methods means pass-fail assessments may not be appropriate, i.e., junctions which are marginally below the critical threshold can have similar risk profiles to junctions marginally above it. Post retrofit, the case study homes had many junctions with borderline temperature factors equal to, or marginally above, the critical threshold. It is important these are not considered "safe" and that broader surface condensation risk management as part of the whole house approach is included in the retrofit design. For example, ensuring the ventilation and heating system can deliver adequate ventilation and heat into homes, and allows air movement around the junction. Additional investigation around the appropriateness of pass-fail risk assessments may be needed, as well as guidance to help explain the implications of temperature factors, especially when they are close to the critical threshold.

Overheating risks in the 14 case study homes were assessed according to the thresholds outlined in Criteria A and B of CIBSE TM59. Only four of the 14 dwellings were shown to not overheat (i.e., "passed") according to Criterion A, and one passed Criterion B. Following the retrofits, five dwellings passed Criterion A and four passed Criterion B. These pass-fail criteria are again simplistic, since there is uncertainty in the models around weather, and occupant behaviour, as well as the fabric construction. All the retrofits that reduced solar gains entering homes (SWI and room-in-roof insulation), and the installation of new windows which increased the amount of natural ventilation in the homes, were successful in reducing overheating in the homes even where they failed the TM59 criteria.

This suggests that when new windows are installed in homes, they should maximise their openable area. Additionally, fabric-only retrofits should consider increasing the potential for purge ventilation in homes to counter overheating risks as part of a whole house approach. Furthermore, simulations identified that overheating risk could be removed entirely from retrofitted homes where shading of windows was provided in addition to increasing levels of natural ventilation.

These measures were also predicted to reduce risk from homes in a future warmer climate in 2060, except for homes in London, though this would reduce their potential future mechanical cooling needs. As mentioned, models used to assess risk can have large uncertainty, for example the representativeness of assumed weather files, inconsistencies in the assumed construction of the home, unknown internal gains, and variations in occupant behaviour. To account for this, Recent Weather Decades (RWD) were developed so that the number of years in which risks manifests over a decade could be calculated, providing a more robust and comparative evaluation, rather than assessing overheating risk over one year.

RWDs were also used to assess the risk of interstitial condensation occurring when IWI is installed. It was found that installing IWI increases the risk of interstitial condensation, although the increase in risk is lower up to a U-value of 0.8 $W/(m^2 \cdot K)$, and mitigations are available. The limiting value in Building Regulations for insulating solid walls is currently 0.3 $W/(m^2 \cdot K)$, and although this will achieve more heat loss savings, it has a greater risk of interstitial condensation. Additionally, vapour open systems (Woodfibre and EPS without an air vapour control layer, AVCL) were able to dry to the outside and inside and had substantially lower risks at lower U-values compared to EPS with AVCLs.

IWI with U-value of 0.3 $W/(m^2 \cdot K)$, as required in Building Regulations for England and Wales for SWI, achieved a 30% reduction in space heating compared to 20% for 0.8 $W/(m^2 \cdot K)$. However, its risk of interstitial condensation was higher. This suggests regulations are causing a perverse incentive for high risk SWI retrofits. If installed via a whole house approach, IWI should be sealed to the adjacent elements to avoid warm moist air penetrating behind the insulation and condensing on the cold solid wall substrate. In practice this is difficult to achieve, and although homes should have good ventilation to ensure internal air is not laden with moisture, a balanced approach for IWI between risk and performance is preferable.

3. Comparing modelled and measured performance

The RdSAP model, which is used to generate EPCs, predicted much higher whole house heat losses than measured in the case study homes by, on average, 42% (though this ranged from 7% lower to 100% higher). Overestimates were larger in the uninsulated homes. This meant the HTC reductions predicted by RdSAP were on average 46% higher than were measured, i.e., the “prebound effect”. However, the prebound effect was not always observed, and in some instances, EPC predictions were lower than were measured. These findings are based on a small sample of case study homes and more investigations are needed to explore if this finding is replicated across a representative sample of UK homes.

One reason for the overprediction was that default input values in EPCs for background ventilation, fabric, and thermal bridging heat losses, were generally higher than those measured. The defaults also suggested there was almost 20% more air leakage in homes than was measured. Wall U-values were assumed on average to be 15% higher (more heat loss) than measured. The default thermal bridging heat loss (applied as y-values) was more variable; the default y-value could be between 60% lower and 70% higher than calculated y-values, depending on the retrofit stage and specific thermal bridges observed.

Updating default inputs with real data was found to reduce the extent of over-predictions from 42% in the base EPC using RdSAP to just 17% when using BREDEM. The scale of over prediction was very variable across the homes and varied from -7% (i.e., the EPC predicted lower heat loss) to 102% (i.e., the EPC assumed double the heat loss that was measured). Replacing default inputs with measured data also reduced the variability of the overprediction across all the homes to between -14% and 47%.

Assessor conventions around calculating geometries also affected the accuracy of predictions, specifically around the measurement of internal walls and the assumptions used to quantify heat losses from rooms-in-roof. This can result in 100% over-predictions of HTC.

DSM-predicted HTCs were closer to the coheating values than steady-state models. However, differences for individual homes were still very variable, and predicted HTCs could be between 24% lower and 62% higher than were measured, depending on which inputs were updated. Across the sample of homes, the average difference between predictions and measured HTCs was between <1 and 13%, depending on which defaults were updated. DSM could therefore appear to improve predictions of thermal performance of homes, and retrofit measures, and was less likely to cause the prebound effect.

These results are based on a limited number and range of homes, and so cannot be extrapolated to the general housing stock. However, the observed over-prediction of heat loss, even when measured inputs are used, suggests that EPCs are exposed to systematic errors, which require more investigation.

Further analysis to explore the uncertainty in models was undertaken by comparing different material properties of bricks. The results suggested that U-values of uninsulated brick walls ranged between 1.57 and 2.57 W/($m^2 \cdot K$), so in some instances are considerably different to the default 1.7 W/($m^2 \cdot K$) used in EPCs. When the walls are insulated the difference in the brick material properties has a negligible impact on the U-value. Moisture risk too was found to vary in the bricks depending on their moisture characteristics, meaning some homes have underlying risks while others do not. It may therefore be beneficial to investigate the variability of brick material properties to see how this could improve risk assessments and energy performance predictions.

4. What are the procedural implications for the whole house approach?

The research has identified gaps in guidance to support the industry to deliver the whole house approach to retrofit. Risks can often be ambiguous, and lack of clarity can lead to barriers to adopting, or inconsistencies in implementing, the whole house approach. Several themes are outlined that could provide the focus of future work.

The first is to improve retrofit surveys, encouraging more airtightness testing with leakage detection. With better surveys better designs can be produced and these should always have airtightness strategies which consider the air barrier in a home, to ensure retrofits address air leakage in homes beyond the specific retrofit being installed. Since 10% of homes tested in DEEP demonstrated excessive air leakage (air permeability >15 $m^3/(h \cdot m^2)$ @ 50Pa) this would ensure excessively leaky homes are identified and improved.

Retrofit surveys should also identify previous home alterations and there should be a process to capture future retrofits. The DEEP case studies found examples of changes that affected risks and thermal performance of the homes and future retrofits. For instance, the installation of polystyrene-backed plasterboard with an air cavity but without adequate sealing, or sloping roofs being partially insulated. Knowledge of alterations will help ensure existing issues can be resolved or beneficial adaptations can be considered in future designs. Better data would also support planning for future retrofits, to ensure that work carried out today does not impede future work, as well as identify any additional costs for repair and maintenance needed.

Designs for retrofit fabric improvements need also to consider changes required by services to ensure they are operating efficiently. In DEEP, savings from SWI were reduced by 3% when boiler flow temperatures were not adapted. This may require fabric retrofit teams to upskill or work more closely with heating professionals.

Airtightness failures, as well as general home maintenance and repair, need to be addressed when undertaking retrofits. In the case studies, numerous maintenance and repair issues were identified during the retrofits that may have gone unnoticed and caused significant issues in later years. Rectifying these issues was responsible for around a quarter of the retrofit costs in the DEEP project. This should be considered when planning retrofit budgets and policy.

The case studies demonstrated that there are many uncertainties around the risks of retrofits, especially at the junctions between insulation and the fabric. To some extent each risk was bespoke to the specific junction, however, some general guidance around risks for common situations may be useful to support installers. Risk assessments themselves were found to be inadequately categorising risks (i.e., safe vs. unsafe), and unable to describe risk profiles effectively, or only assessing one risk at a time. Better guidance on which risks need to be assessed, and how, would be helpful for installers and designers and more sophisticated risk assessment tools and methods may be needed.

5. Are measurements of retrofit performance robust?

A considerable amount of building performance evaluation (BPE) testing was undertaken in DEEP and some considerations for interpreting the results of BPE tools have been identified. One of the most significant is that the induced pressures experienced during blower door tests may be forcing air to move between test homes and adjacent homes.

This is significant as it implies the blower door tests overstate the airtightness of solid walled homes - by on average 17%. Additionally, it may mean that homes are experiencing less internal to external air exchange, and so the assessed amount of fresh air provision and heat loss calculations are overstated. Since thousands of blower door tests are being undertaken in the UK every year, this is a significant finding that warrants further investigation.

The low-pressure pulse test correlated very well with the blower door test across the entire sample of tests. However, results for individual homes could be very different. This is a concern in the context of retrofit, where information on specific air leakage rates and pathways is needed to inform airtightness strategies, thus more investigation on the different approaches is needed.

The overnight QUB test achieved reasonably comparable HTC results to the coheating test, being within 15% of the measured result and with low levels of uncertainty (average of 2.7%). The precision (repeatability) of the test was shown to be on average 17% relative to the mean when multiple tests were conducted. This suggests there is some potential for assessing the energy performance of homes via overnight tests, where a substantial reduction in heat loss is made (e.g., SWI), where multiple tests are undertaken, or where multiple homes are being assessed to evaluate retrofit success at a cohort level.

The use of thermography and heat flux plates was essential in identifying the idiosyncrasies associated with the case study homes. For example, discontinuities in the insulation layer of previously installed insulation, as well as air movement causing bypasses or direct air leakage. Interpreting the results is challenging and could lead to erroneous assumptions about the homes, which was especially the case for heterogeneous heat flow through building fabric where the reliance on individual and a small number of heat flux plates may under- or overestimate heat loss from the fabric. The use of these tools can therefore support retrofit delivery, but caution is needed to ensure they are implemented appropriately.

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