Department for
Business, Energy
& Industrial Strategy

LEEDS BECKETT UNIVERSITY
LEEDS SUSTAINABILITY
INSTITUTE

DEMONSTRATION OF ENERGY EFFICIENCY POTENTIAL

Literature review of benefits and risks in domestic retrofit practice and modelling

Prepared by the Leeds Sustainability Institute at Leeds Beckett University

BEIS Research Paper Number 2021/014

February 2021

Authors

Dr David Glew
Dr Jim Parker
Dr Martin Fletcher
Felix Thomas
Dominic Miles-Shenton
Dr Matthew Brooke-Peat
Professor David Johnston
Professor Chris Gorse

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

Contents

Executive Summary

Leeds Beckett University has been commissioned by the Department for Business, Energy & Industrial Strategy (BEIS) to undertake a literature review to identify current knowledge gaps regarding the performance and risks associated with retrofits. This review forms part of the Demonstration of Energy Efficiency Potential (DEEP) project and provides the evidence to justify the research strategy adopted in fulfilling and maximising the outputs of the project. The salient findings from the review of previous retrofit research projects are as follows:

Loft Insulation and Room in Roof Retrofits: A large proportion of lofts have been insulated and this tends to reduce space heating bills by between 2% and 4%. However, there is some evidence of poor installation, material degradation and disturbance in-use which increases the risk of thermal bridging and condensation on ceilings under lofts. There is limited building performance evaluation (BPE) data on rooms in roofs; however, limited studies have identified that they are poorly performing and difficult to achieve an adequate thermal retrofit. To investigate this, DEEP will gather data on loft insulation quality and undertake before and after BPE investigations on loft insulation and room in roof retrofits.

New Windows and Doors: There is little data on the current performance of windows and doors installed in homes in the UK, however, studies suggest that upgrading windows can reduce space heating fuel bills by between 5% and 15%. Infiltration rates have been observed to be both improved and worsened when windows are upgraded. DEEP will survey infiltration around different window types in a range of existing homes and undertake before and after BPE investigations on a series of window and door upgrades.

Cavity Wall, Partial Fill & Cavity Party Wall Insulation: Cavity wall insulation (CWI) is one of the most common retrofits and shown to reduce space heating bills by between 7% and 9%. However, it is also responsible for the vast majority of complaints by homeowners because of its potential to cause damp. Some studies suggest partial fill insulation is highly susceptible to performance issues caused by wind washing and air looping, where installed incorrectly. Topping up partial fill insulation with CWI has been observed to fix the problem. There are a variety of different party walls, some of which are affected by a heat bypass and where this happens, insulating the party wall can reduce fuel bills. DEEP will undertake borescope investigations on a range of cavity walls to inspect the quality of retrofitted cavity full-fill insulation, as well as the state of any partial fill cavity walls that are surveyed.

Solid Wall Insulation: Solid Wall Insulation (SWI) retrofits are not widely undertaken. SWI is particularly difficult to detail appropriately and research projects have identified this leads to discontinuities in the insulation; the gaps in the insulation introduce thermal bridges into homes. Since SWI dramatically reduces heat loss, this also increases the extremity of any remaining thermal bridging which can increase surface condensation risk in these areas. This is a particular problem since uninsulated solid walls are generally already considered to be at risk from surface condensation. Additionally, internal wall insulation (IWI) has also been found to introduce the risk of interstitial condensation, increase water accumulation in walls and introduce surface condensation risk in adjoining properties, although breathable and thinner types of IWI reduce this risk. DEEP will survey a number of uninsulated and insulated solid walls to identify barriers to installation and problems related to retrofits. It will also undertake before and after BPE on a range of solid wall retrofits and model a range of scenarios to explore condensation and water accumulation risks. It will use modelling to investigate the impact of different solid wall retrofit options, including applying SWI to different types of cavity walls.

Airtightness Improvements: Excessive infiltration undermines the energy performance of homes and retrofits. While the housing stock average airtightness levels may be around 11.48 $m^3/h/m^2$ @ 50 Pa (slightly worse than new build limit) research studies have found examples of extreme air leakage in particular house types (e.g. steel frame homes) and linked to particular building characteristics (e.g. unsealed dry lining and suspended timber floors). Retrofits often include airtightness improvements, however, its contribution to energy efficiency as an individual retrofit measure is not well understood. DEEP will undertake airtightness testing to evaluate air leakage in a range of housing archetypes. It will also undertake BPE before and after airtightness-specific retrofits to quantify how these can reduce the heat loss from homes. Building energy models will also evaluate how airtightness may undermine other retrofits.

Ground Floor Insulation: Ground floor retrofits are rare despite there being around 10 million uninsulated suspended timber ground floors and evidence suggesting insulating these could reduce heat loss in homes by up to 20%, depending on how much infiltration is taking place through the ground floor. DEEP will survey existing uninsulated and insulated floors to identify any barriers to installation or performance issues. When installing thermal upgrades, DEEP will undertake before and after BPE on a range of ground floor retrofits to explore the potential performance and identify possible risks related to moisture build-up in the under-floor void.

Multiple Measure and Deep Retrofits: Although multiple measure and deep retrofits can achieve greater savings than single measures, they are rare, meaning homes tend to have piecemeal retrofits spread over many years. How multiple measures combine to reduce heat loss is not well understood, though deep retrofits have been observed to reduce heat loss in homes by over 50%. It is not well understood how retrofit measures are currently designed and installed to interact, or how the risk of condensation and moisture accumulation are affected , when measures are installed in combination. DEEP will undertake several phased deep retrofits on a range of solid wall homes to replicate current practice and to understand the contribution of each individual measure's contribution to the whole system performance. This will identify mitigation strategies to reducing risk during these piecemeal retrofits and compare performance when undertaking a deep retrofit all at once. Modelling will also be used to identify which approach suffers from the largest performance gap and to quantify the risks to households, such as increased surface condensation risk.

Following this review of retrofit measure performance, it appears there are knowledge gaps around the following specific heat loss mechanisms:

- Insulated elements not effectively interfacing (e.g. loft and cavity wall insulation);
- Discontinuities in insulation (e.g. where obstructed by services or building features);
- Thermal bypasses and air looping around insulation; and
- Infiltration affected by, and its effect on, other retrofit performance.

Additionally, knowledge gaps have been particularly evident for the following retrofit types and scenarios:

- Less common retrofits (e.g. ground floor, room in roof and airtightness retrofits);
- Piecemeal versus deep retrofit performance; and
- *Inter-house* and *whole-house* considerations for single measure retrofits.

Retrofit modelling techniques and input assumptions have also been reviewed in this project and the following main issues have been highlighted:

Whole building modelling: Reduced data Standard Assessment Procedure (RdSAP) is a steady-state model used to predict retrofit performance for policy via Energy Performance Certificates (EPCs). However, its input data is not detailed and often fixed to default assumptions, and this reduces the accuracy of its predictions. Steady-state models that allow for more detailed inputs and dynamic simulation models (DSM) are more accurate. DEEP will explore which RdSAP inputs and default assumptions could be improved to make RdSAP more useful for retrofit evaluations.

Building fabric in whole building modelling: Default U-values, y-values and infiltration assumptions in RdSAP have a large influence on the model's accuracy. DEEP will validate existing defaults and define uncertainty in these where possible.

Modelling overheating risk: Retrofitting homes affects overheating risk which may be more problematic as the climate warms. DEEP will evaluate the usefulness of the SAP summer-gains-check and compare this with alternatives used in PHPP and DSM analysis.

Occupancy and internal heat gains: Occupant behaviours (including heating hours and heating set points), and the level of internal gains generally, are fixed in RdSAP, thus the impact of different occupant types on retrofit payback cannot be assessed in these calculations. DEEP will predict the extent to which RdSAP over or underestimates the performance of different retrofits for different occupant types.

Weather files used in models: Full SAP models can use localised, postcode-specific weather data whereas RdSAP is limited to 21 UK regions. The impact of this on model accuracy, as well as the impact of using hourly weather data in DSM, will be evaluated in the DEEP project.

U-Values: RdSAP uses default U-values based on building characteristics, which is one of the largest areas of uncertainty in the calculation. DEEP will explore the benefits of having a wider range of defaults for RdSAP assessors to identify.

Thermal bridging: In homes with lower heat loss, the relative proportion of heat loss via bridges increases. Additionally, retrofits can introduce new bridges into homes via discontinuities in insulation. Thus, changes in thermal bridging in post retrofit models may be particularly important. However, it is not clear if bridging defaults in RdSAP reflect this reality. DEEP will undertake modelling of thermal bridging pre- and post-retrofit in a range of different house archetypes and retrofit types to estimate what defaults may be more appropriate for use in RdSAP calculations. It will also undertake thermal bridging modelling to quantify the risk of surface and interstitial condensation that may occur in common retrofit scenarios.

Hygrothermal Behaviour: Models which predict water accumulation and risk of rot in construction fabric use databases of materials with assumed properties of density, porosity and water content, etc. which affects the accuracy of the model predictions. Data from field measurements can be collected to improve accuracy but is costly and time consuming. DEEP will undertake testing of common UK wall types to widen the range of defaults for modellers to choose from and evaluate how sensitive model predictions are to different material properties. DEEP will also use hygrothermal simulations to undertake scenario analysis for common retrofit scenarios to quantify risk of moisture accumulation.

This review has highlighted issues with current approaches to retrofit modelling, and specific areas where there may be knowledge gaps for investigation in the DEEP project, thus research activities will include:

- Comparing steady state retrofit model predictions with dynamic simulation models
- Systematically describing input variables to which steady-state models are most sensitive
- Evaluating how appropriate current default input values and conventions are
- Assessing whether steady state models can be made more accurate by altering inputs
- Exploring the benefits and practicalities of DSM for retrofit modelling
- Comparing measured properties of common materials with those used in models
- Identifying key model inputs and variables that need updating or refining; and
- For common retrofit scenarios, quantifying the risk of surface and interstitial condensation, timber rot and overheating, and describing the potential for mitigation.

1 Introduction

Domestic retrofits have the potential to reduce fuel bills and improve thermal comfort and quality of life. Although millions of retrofits have taken place in UK homes, concerns have been raised around the actual performance of retrofits being less than their design specification suggested that they would achieve (performance gap) and furthermore around possible risk being introduced into homes (unintended consequences). This document reviews the evidence base on retrofit to identify critical issues and inform how future policy could support safe and effective retrofits. Specifically, the review interrogates what factors may need to be considered when undertaking both ***single measures*** *and* ***deep*** *retrofits in the context of adopting a whole-house approach to retrofit.*

1.1 Literature review approach

The aim is to provide a review of current domestic retrofit performance and risk and identify and discuss the critical factors that make different types of retrofit project more, or less, likely to succeed. In doing so, it will specifically highlight how these issues may be considered in the context of a whole-house approach to retrofit.

Based upon this review, the potential of different retrofits will be evaluated and critical areas for policy consideration and future research areas highlighted. The review is divided into two main categories:

1) Review of the retrofit performance gap and unintended consequences identified in field and modelling studies; and

2) Review of modelling inputs which support retrofit performance goals and investigate condensation and moisture accumulation risks.

These sections are followed by a Conclusions chapter, which provides a final comment on the lessons learned on current approaches to retrofit practice and modelling.

The review starts with an introduction to retrofit policy in the following section to understand how this operates in the context of the whole-house approach and *deep* retrofits.

1.2 Introduction to retrofit and UK policy

Retrofitting homes can reduce fuel bills, improve comfort [1-4] and have wider benefits to the nation’s health, wellbeing, fuel poverty reduction and climate change targets. The UK Government has therefore supported retrofits via a range of policy initiatives since the early 1990s. More recent schemes from the last decade are listed below:

- 2000 to 2005 Warm Front Scheme / New Home Energy Efficiency Scheme (HEES);
- 2002 to 2005 Energy Efficiency Commitment (EEC) scheme;
- 2005 to 2008 EEC2;
- 2008 to 2012 Carbon Emissions Reduction Target (CERT);
- 2009 to 2012 Community Energy Saving Programme (CESP);
- 2013 to 2015 the Energy Company Obligation (ECO);
- 2013 to 2015 Green Deal;
- 2015 to 2018 ECO2 and ECO2 transition (ECO2t); and
- 2018 to 2022 ECO3.

In ECO3, Government sets an overall energy efficiency target, and the scheme is implemented, overseen and regulated by Ofgem. Energy customers fund ECO3 through their fuel bills, which energy companies are then obliged to invest, thus improving the efficiency of the housing stock. Retrofits also take place outside of national policy, most notably installing loft insulation, and often when other improvements are being made to homes. Policy funded schemes are thought to account for the greatest proportion of retrofits [5], though there is a limited amount of data on private sector retrofits. Retrofits undertaken outside of policy would not normally be required to achieve the same standards (e.g. PAS 2030 and PAS 2035) as those funded by policy initiatives. Consequently, Part L1B of the Building Regulations [6] is currently the only mechanism for setting standards outside of the ECO schemes.

In order to estimate the number of retrofits taking place outside of policy we can compare data on national household insulation with retrofit policy data. According to the English Housing Survey (EHS) between 2013 and 2018 (period of ECO1 to 2t) the proportion of homes with loft insulation (LI) rose from 37% to 38%, equivalent to 200,000 homes; and the proportion of homes with cavity wall insulation (CWI) and solid wall insulation (SWI) combined rose from 46% to 49%, equivalent to 580,000 homes in England [7]. Conversely it was reported that, for retrofits installed via ECO 1, 2, and 3 for the whole of the UK, there were around 500,000 LI retrofits and 1.5 million homes have had CWI or SWI over the same period [5, 8, 9].

This indicates that the scale of retrofits taking place outside of ECO is relatively low. However, reporting methods for the EHS and ECO are different and EHS only provides data for homes in England and is based on a nationally representative sample and so may not provide the full picture. This means numbers are not directly comparable but indicates the scale of installations taking place. While policy may be the main route for retrofitting homes, more data may be needed to understand the scale of retrofit taking place in owner occupied homes as these make up the largest proportion of the housing stock. Additionally, research has found that retrofits delivered and driven by communities, as the main decision makers, may have greater potential to promote cultural, behavioural or attitudinal change among householders, which may be needed to achieve retrofits on a mass scale [10, 11].

1.2.1 The scale of retrofit in the UK

Government policy on domestic energy efficiency has been successful in that millions of homes in the UK have been retrofitted, as shown in Figure 1-1.

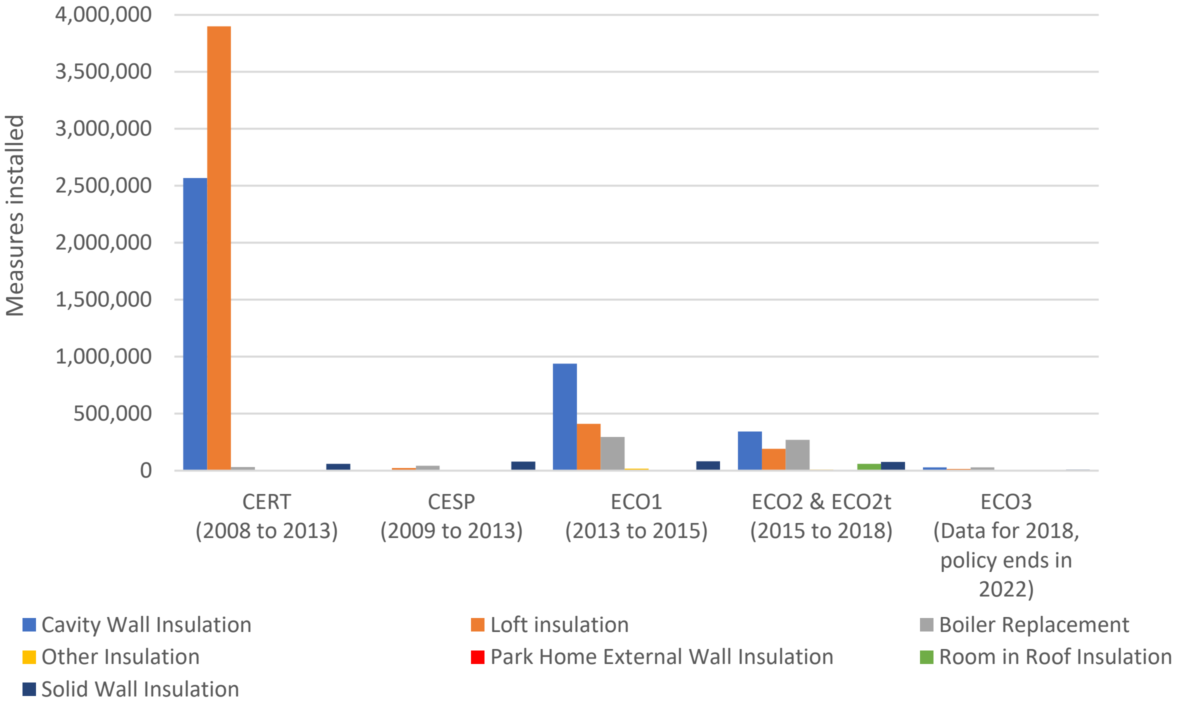

Figure 1-1 Retrofits installed under recent schemes [5, 8, 9]*

The eligibility criteria for the ECO and CESP schemes were more restrictive than CERT and focussed on hard to treat homes and fuel poor households, which resulted in these schemes retrofitting substantially fewer homes. In addition, as shown in Figure 1-2, there was also substantially less funding available for more recent ECO policy, which also impacted on the potential number of homes that could be retrofitted.

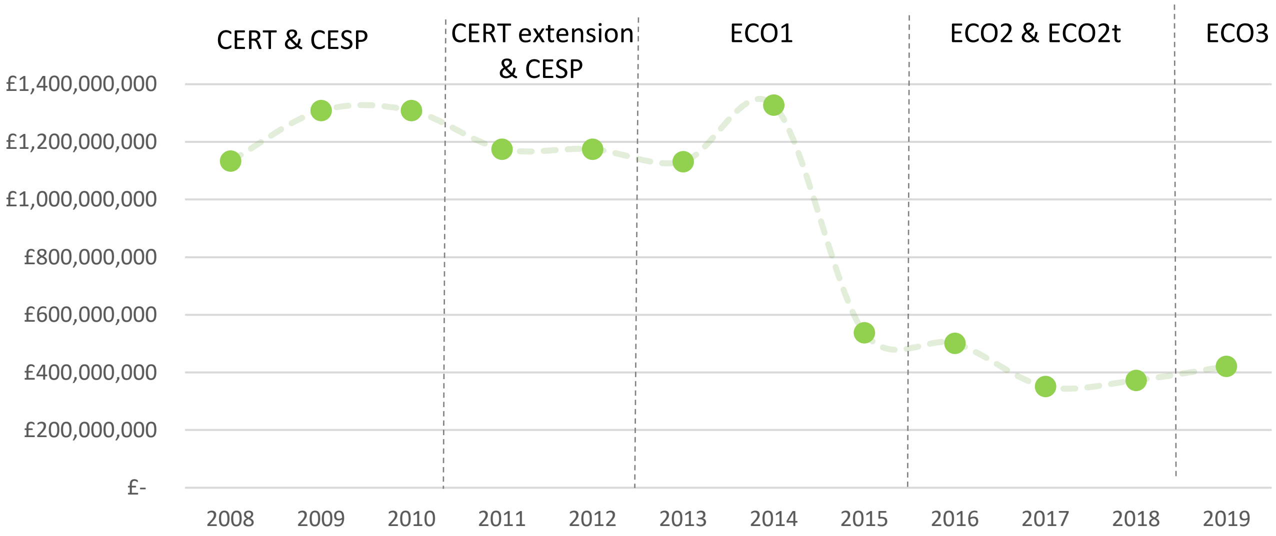

Figure 1-2 Average annual delivery cost of retrofit policy† [12, 13]

---

* Including DIY Loft installations under CERT

† Total CERT cost of £3.4bn averaged between 2008 to 2010, total CERT extension cost of £2bn averaged between 2010 and 2011, total CESP cost of £702m averaged between 2009 and 2011

Figure 1-2 shows that average annual spend on ECO2, ECO2t and ECO3 was roughly a third of that during CERT, CESP and ECO1. Consequently, CERT and CESP collectively delivered over 6.5 million installer-provided retrofits and 2.8 million DIY loft insulation retrofits over 5 years [14] and ECO1, which focussed on fuel poor and hard to treat homes, only installed retrofits in around 1.7 million homes over 3 years. Conversely, ECO2 and ECO2t installed retrofits in homes in just under 1 million homes over 4 years. A more detailed overview on falling installation rates associated with the ECO schemes is shown in Figure 1-3, where HTH refers to Help to Heat obligation in the ECO2t.

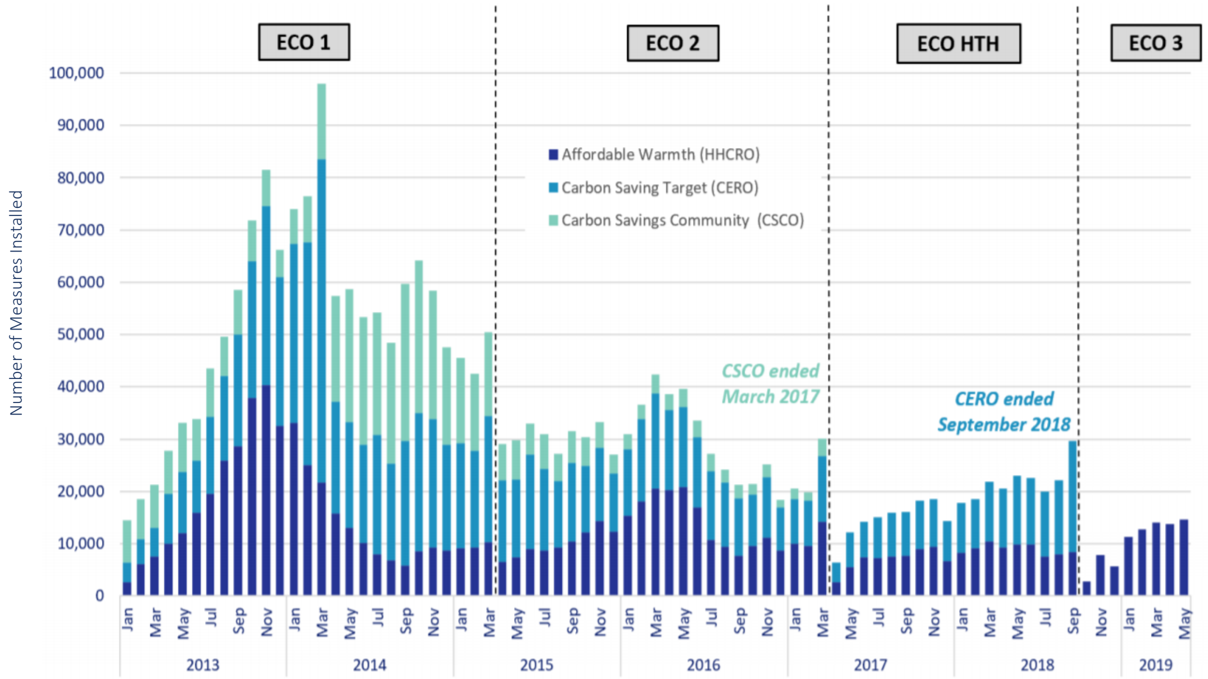

Figure 1-3 Measures installed over time under ECO [15]

Currently retrofits are delivered by energy companies based on house by house eligibility and how much energy bill saving may be achieved. This may reduce the potential for undertaking community or neighbourhood-scale retrofit programs, since some houses in a community may not meet all the eligibility criteria and so may require householder contributions. If community wide retrofit programs are necessary to achieve the Net Zero policy goals [16] and 2050 carbon targets, this suggests that changes in ECO design, or complimentary policies will be required [17, 18].

In addition to national policy support, Government has also funded several smaller scale retrofit projects such as the Department for Energy and Climate Change's (DECC) Low Carbon Community Challenge [11] and the Technology Strategy Board's Retrofit for the Future program [1] among others. These were aimed at understanding retrofitting on a neighbourhood scale, and designed to improve the performance of individual retrofits, respectively. The retrofits delivered under these programmes are well studied, though may not be representative of the types of retrofits which are more frequently installed in the UK. The common types of retrofits installed under government schemes are discussed in the following section.

1.2.2 Types of retrofit installed under policy

The term *retrofit* can be used to describe any measure installed in a home which reduces fuel bills, usually by reducing space heating demand. In ECO, since 2013, around 2.6 million measures have been installed in almost 2 million homes [19], indicating that the majority are *single measure* retrofits. This represents an inefficiency associated with the schemes, since finding suitable homes can be costly and time consuming due to the eligibility criteria set for households by legislation. Additionally, undertaking partial retrofits means that householders are less likely to have further retrofits in the short to medium term [20]. There is also concern that the current practice of single measure retrofits may make it more difficult to embed a whole-house approach to retrofit and more importantly, may lead to performance and risk implications [21].

In contrast a *deep retrofit* refers to homes that have many measures installed simultaneously. This commonly involves upgrading space and water heating and lighting services, as well as fabric and airtightness enhancements. There are several standards of deep retrofit in the market, which define their own level of performance against key performance indicators, for instance EnerPHit [22]. However, whole-house retrofits do not necessarily have any set performance requirements, instead specific projects may set their own success criteria [23]. This review is interested in how both single measures and deep retrofits can be undertaken as part of a strategic *whole-house approach* to retrofit*.*

A detailed picture of the types of retrofits that have been installed more recently is included in Figure 1-1. This indicates that (excluding DIY lofts under CERT) CWI is the most common retrofit, followed by boilers and LI, and that these three make up almost all measures installed. Significantly, SWI retrofit rates are relatively low, perhaps as a consequence of the fact that there are fewer solid wall dwellings in the UK than cavity wall dwellings. They may also be less cost effective and technically more challenging, and thus more likely to lead to unintended consequences [24].

Energy companies are currently responsible for finding eligible households, as well as arranging and installing the retrofits. Retrofit policies, as mentioned, are administered by Ofgem, who also provide quality assurance through Technical Monitoring (TM) on behalf of the Department for Business, Energy and Industrial Strategy (BEIS). Installers in ECO must be appropriately qualified and on a national register (PAS 2035) [25]. Despite these processes being in place, TM and several other research projects have identified multiple instances of poor quality [26]. This concern prompted the Each Home Counts (EHC) industry-wide review into the standards for retrofit [21], which made recommendations for ECO3 centred on the need to adopt a whole-house approach to retrofit.

Specifically, the EHC review recommended more stringent standards rather than addressing the policing of its existing standards. However, policing of existing standards appears to be one of the major problems, as shown in Figure 1-4. Thus, requiring more challenging standards may have the perverse effect of further reducing compliance rates and increasing the incidence of poor-quality installations.

Energy companies select technical monitoring companies to inspect their work. Under this arrangement technical failure rates have not improved. TM data from previous Ofgem schemes indicate that ECO1 had higher failure rates than ECO2. However, as identified in Figure 1-4, ECO2 failure rates were increasing over time, suggesting that between 5% and 10% of energy company led retrofits do not meet the required standards, possibly affecting between 130,000 and 260,000 homes during the period [19].

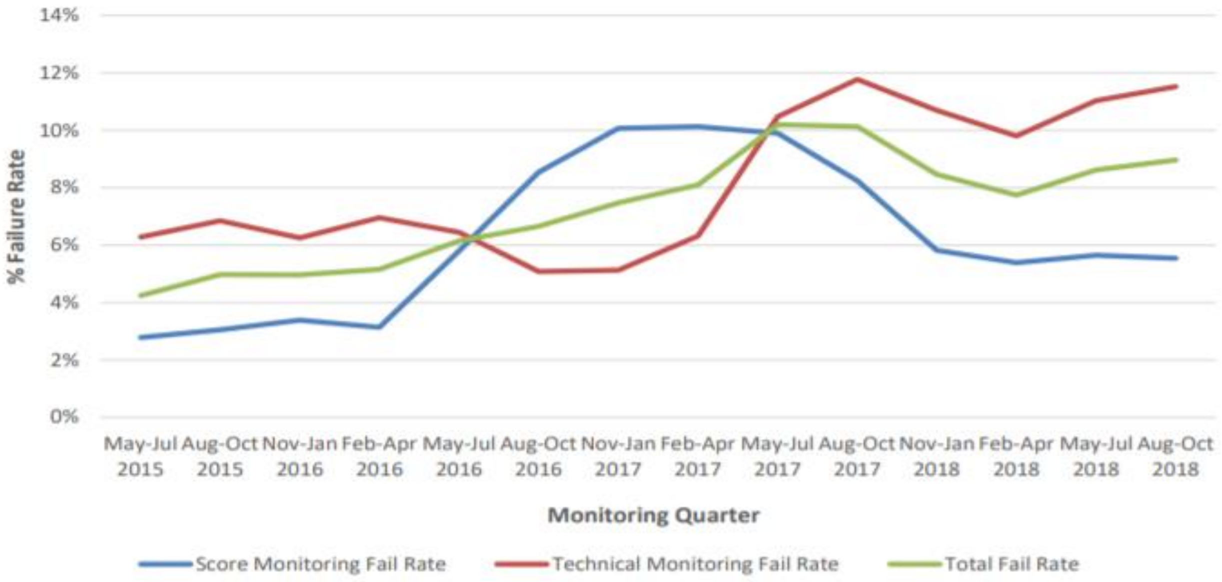

Figure 1-4 Ofgem technical monitoring compliance failure rate in ECO2 [9]

Energy companies commission registered installers via competitive bidding on a house by house or project by project basis to undertake retrofits. It has been observed in one study, that this competitive bidding process pushes prices down meaning installers cannot afford to provide the installations at the quality required, while others are avoiding ECO work because profit margins are low and administrative burdens are high [27].

1.2.3 Summary of UK retrofit policy

The following points summarise the state of retrofit policy in the UK:

- Most retrofits are thought to take place via policy, the size of the retrofit market outside of policy is likely to be substantially smaller, though there is relatively little data on this.
- Eligibility criteria around fuel poor households, hard to treat homes and reduced funding levels have reduced retrofit installation rates.
- The annual spend on ECO2, and ECO3 is roughly a third of the annual spend on ECO1 and CERT.
- Current retrofit installation rates will not meet Government carbon reduction targets for dwellings.
- Deep retrofits are rare, usually only a single measure is retrofitted in each home.
- CWI, LI and boiler replacement making up 95% of all measures installed as they are perceived to be the most cost effective on a house by house basis.
- Up to 10% of retrofits fail technical monitoring.

This chapter provides the current policy context; identifying that a whole-house approach to retrofit has hitherto not been incentivised and describing some of the consequences of this. The following section will investigate, in more detail, the benefits and problems with specific retrofit measures observed in the literature. It also identifies opportunities for a whole-house approach to improve outcomes for retrofits.

2 Retrofit performance and risks

The performance of domestic retrofit is evaluated annually and nationally in the National Energy Efficiency Database (NEED) via fuel bills. It is also evaluated less regularly and generally more intensively, by different types of in-use monitoring and building performance evaluation (BPE) field trials. This section presents the knowledge gained from these evaluations, discussing the reasons behind trends in retrofit performance and exploring the underlying causes of underperformance and why unintended consequences occur.

2.1 Introduction to retrofits and the whole-house approach

Retrofits could involve installing a single, or multiple measures in a home. Indeed, an individual home may receive a series of single measure retrofits over time. Installing a combination of measures achieves greater savings [3, 28-30] and in controlled conditions, multiple measures that are installed separately in a home can have the same benefits as undertaking a whole-house retrofit all in one go [31]. However, in reality, multiple installations performed over an extended time may not lead to the benefits of a whole-house retrofit performed as a single undertaking. Due to the benefits of a considered and more integrated design, that is encouraged with a whole-house approach this should achieve greater energy savings than installing separate measures piecemeal [1, 4, 32-35].

A whole-house approach should also lead to fewer instances of unintended consequences, such as overheating, cold bridging and condensation risks [4, 36-40], and the payback periods associated with such retrofits may reduce as future energy prices increase [41]. However, the specific benefits to energy savings, risk mitigation and costs of whole-house versus piecemeal retrofits have not been explored in any detail. This section presents evidence on the benefits and limitations of individual retrofit measures in more detail, specifically in relation to their role in a whole-house approach to retrofit.

2.2 Loft insulation

Loft insulation is one of the most common retrofits and is installed in an estimated 16.2 million homes, equating to approximately two thirds of all properties which have lofts [42]. The prevalence of LI in the UK housing stock has, in part, been achieved via government policy support. LI represents 23% of all ECO retrofit measures that have been installed and 9% of all Affordable Warmth measures [15]. This support may be well justified as LI has the potential to provide a substantial reduction in heat transfer, with individual field trials measuring U-value improvements of between 6% and 87% [43-45].

The causes for this variation may be related to the quality of installation, the existing level of energy efficiency of the home, the number of other measures that have taken place in the home or whether there were disturbances to the LI after installation had taken place. In terms of the impact on fuel bills, evaluations in the Government’s National Energy Efficiency Database (NEED) reveal a typical energy saving of 3.9% may be achieved [42].

Of the 8 million homes that have uninsulated lofts, around 5.8 million of these homes are considered *easy to treat*, i.e. there are no obvious obstructions to the retrofit. Thus, despite the success of LI retrofits there remains a significant untapped potential for energy saving [42].

The remaining 2.2 million uninsulated lofts are considered *hard to treat* or unfillable; therefore, achieving minimum energy performance standards in these homes may be problematic. Previously, *easy to treat* lofts were perceived to be simple to do, particularly *cold ventilated loft* systems, where insulation was usually laid both between and over the ceiling joists [46]. This was considered a *fit and forget* retrofit measure [47]. Indeed, 2.8 million DIY loft retrofits were funded under the Government's CERT policy [48]. However, evidence suggests that the *fit and forget* approach to loft insulation is not appropriate. Little has been done to investigate the long-term performance, performance gaps or risks associated with DIY and installer retrofits on a national scale.

Case study investigations have, however, raised several issues of concern regarding retrofit quality [49]. When combined, these may result in underperformance and undermine the success of LI retrofits in homes or lead to unintended consequences.

Classification of such issues include:

Issues causing thermal bridging and increasing condensation risk in rooms below lofts

- Gaps at hard to reach areas, such as at the eaves.
- Missing insulation and discontinuities in the thickness of the insulation around service penetrations, particularly light fittings.
- Discontinuities around the loft hatch.
- Discontinuities in the insulation layer up, over and around cold water storage tanks and feeder tanks.
- Inaccessible areas (porches, extensions, etc.).
- Joists running close to walls, meaning insulation cannot be fitted between the wall and joist.

Issues causing underperformance

- Irregular depths across the loft area.
- Insufficient depths due to installation of boards on top of joists for storage and access.
- In-use compression from stored items on top of mineral fibre.
- Disturbance of insulation to maintain or install services.
- Dust and dirt compromising insulation integrity.
- Leaks or condensation, saturating insulation.
- Excessive packing around ventilation openings.
- Uninsulated or unsealed loft hatch.
- Insulation in the roof space only partially installed, not unrolled or unpacked.

Issues increasing condensation risk in the cold roof

- Covering over loft ventilators with insulation.
- Over-stuff of insulation into ventilated eaves.
- Penetrations into wet rooms not sealed.

These issues can cause thermal bridges on the ceilings below lofts, increase heat loss, cause underperformance and present a potential risk of surface condensation, mould growth and material decay [36]. An example is shown in Figure 2-1, where thermal bridging is observed at the eaves because the LI is not fully extended to the wall cavity and has not been connected with the CWI. This can be rectified by adding extra LI to ensure continuation between roof and wall insulation, as shown in Figure 2-1. Such an approach may or may not require an extension to the roof eaves.

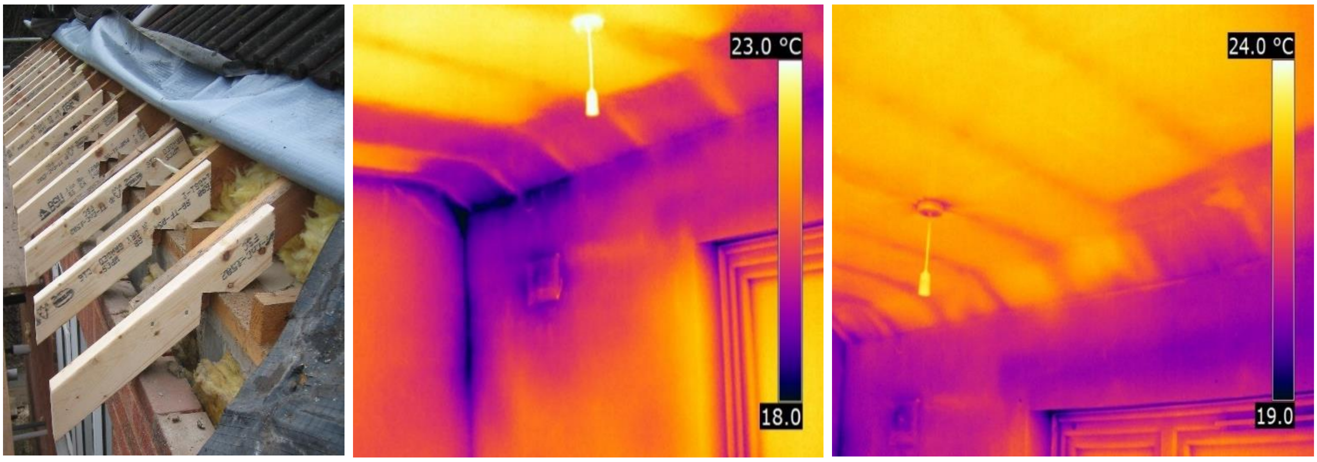

Figure 2-1 Extension of eaves to ensure continuation between the LI and CWI (left) causing thermal bridging on the ceiling eaves (centre) which can be avoided by joining the LI to the CWI (right) [50]

The implications of these thermal bridges may not, initially, be visible to householders, installers or the TM assessors, but they do become apparent when discolouration, mould or damp manifests over time. This is a concern for loft installation, specifically avoiding a discontinuity between the wall and loft insulation. Equally, TM assessors may not identify the fault, and it may not necessarily be clear if it is the responsibility of the LI installer or the CWI installer to ensure that the discontinuity is treated. Furthermore, installing LI correctly first time is especially important since building fabric and space heating systems are not generally upgraded or rectified but are left unchanged until there is a noticeable failure [51]. This is an example of the benefits of a whole-house approach to retrofit, even when measures are installed individually.

The issues that cause underperformance listed here may also introduce some (though perhaps less severe) thermal bridging. Additionally, some of these are introduced after the retrofit has taken place. For example, householders may use the loft for additional storage or services may be installed in via loft spaces (electrical cables, water and gas pipe and water tanks), both of which can disturb the LI (illustrated in Figure 2-2). This indicates that LI should not be a *fit and forget* measure and current LI practice may not be robust [52, 53]. Thus, a whole-house approach needs to consider issues that may affect performance and risk post installation.

Figure 2-2 Loft insulation removed and piled to one side following rewiring of electrical cables and removal of a water cylinder from the loft space and variability in LI performance

There is some evidence of deterioration in LI performance over time as illustrated in the NEED data shown in Figure 2-3, though it appears to suffer less than other retrofit measures. However, because the savings in NEED are based on metered gas use, which is affected by many things not accounted for in the assessment process, as well as non-space heating energy use, some fluctuation in the results is to be expected. Therefore, there is some uncertainty over the amount that loft insulation (and other retrofit measures) deteriorates over time and more data is needed to understand the scale and extent of this.

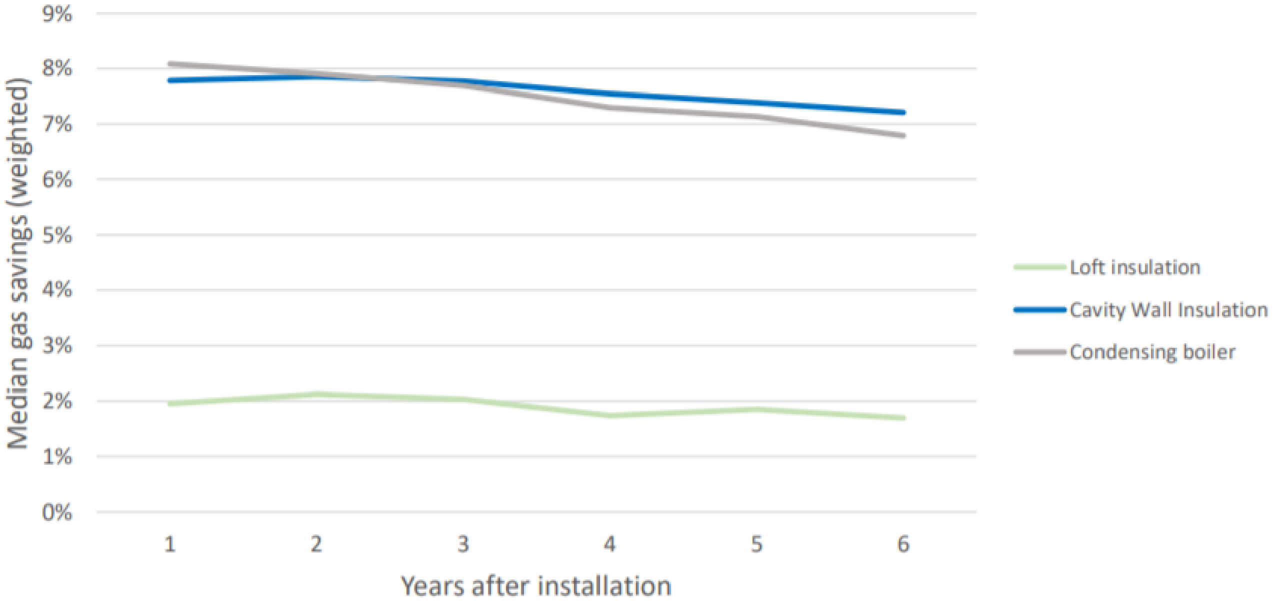

Figure 2-3 NEED analysis showing the energy saving potential of installed retrofits diminishes over time [54]

The data indicates that despite two thirds of lofts being insulated, there may be scope to top-up or rectify these to achieve greater savings. Loft top-up where there is over 100 mm of pre-existing LI is classified as a valid ECO measure. However, the law of diminishing returns means that loft top-up retrofits are predicted to achieve lower fuel bill savings than first time LI. Nevertheless, evidence of disruption to loft insulation and incomplete installations presented above suggests there may be a benefit in providing additional support for loft top-ups or systems that are less susceptible to these problems as a means of rectifying performance and reducing chances of condensation in cold lofts or on the ceiling of rooms below the loft.

Finally, an unintended consequence of LI is the loss of ventilation when insulation is installed over vents without alternatives being provided [55]. This could cause poor air circulation, stagnant air, condensation and mould growth. The situation is exacerbated by warm moist air infiltrating the loft from the habitable space. Roof timbers may be exposed to an increased risk since they are not routinely visible nor inspected. Structural roof timbers exposed to condensation are a particular concern and more research is required to investigate this.

Loft insulation: implications for DEEP

Loft retrofits have been considered a ‘low hanging fruit’ and easy to address for retrofit policy. However, the literature suggests that loft insulation may be underperforming due to poor installation, material degradation and disturbance in-use. In turn, this also exacerbates the risk of thermal bridging and condensation risk on ceilings under lofts and can reduce the ventilation in lofts, leading to moisture issues. DEEP will investigate historic loft retrofits to better understand in-use performance degradation, explore how loft and wall insulation junctions interact and model condensation and underperformance risk resulting from imperfect installations. The research will also use case study data to measure the reduction in space heating demand achieved via loft insulation.

2.2.1 Room in roof insulation

Compared to lofts, less is known about *room in roof* retrofits where insulation is added at or above the rafter level. Typically, the installation of insulation between the rafters aligns closely with converting a loft into a habitable space. Room in roof insulation (RIRI) case studies suggest whole-house heat loss can be reduced by 20% which is as much as SWI [27]. RIRI can also substantially improve both U-values and airtightness [56], however, few RIRI retrofits have taken place in policy [57]. The potential energy savings for RIRI retrofits is large, but care needs to be taken since rooms in roofs have complex geometry presenting challenges when attempting to maintain airtightness and insulation continuity at junctions. Interfaces and junctions typically affected include areas between the knee walls, dormer cheeks, sloping roofs, flat roofs, party and external walls [56]. An example is shown in Figure 2-4.

Figure 2-4 Complexity of room in roof geometry and uncertainty around requirements causing partial retrofits and inconsistent fabric performance [27]

Installers working under the ECO framework are required to hold certification for the specific measures they install, e.g. LI installers hold LI certification. However, currently a RIRI specific certification scheme does not exist, so installers working on RIRI retrofits require multiple individual certification schemes when undertaking work on the different elements present (flat roof insulation, sloping roof insulation, party wall insulation and internal wall insulation).

The current situation adds confusion, making it not only difficult for installers to evidence their competence, but just as importantly, making it difficult for householders to understand if their installers hold the correct certification. This situation can lead to only some elements being insulated, as evidenced in Figure 2-4.

Partial approaches to thermal insulation can increase the potential for introducing unintended consequences. For example, failure to insulate the celling behind the knee wall will introduce thermal bridging into the ceiling below, as in conventional LI retrofits.

Failure to insulate knee walls or dormer cheeks will introduce thermal bridges into the room in roof itself. The combination of interacting elements in RIRI is an example of how a whole-house approach to retrofit should benefit householders. If policy and technical barriers to RIRI can be overcome, there may be a substantial opportunity for RIRI retrofits in the UK. Data are needed on the number of properties in the UK housing stock with rooms in roof, though these will likely be a subgroup of the 3 million homes with lofts that are considered *hard to treat*.

Room in roof insulation: implications for DEEP

RIRI retrofits are less abundant than LI retrofits, though may potentially provide much greater annual fuel bill savings for households. This is because rooms in roofs typically have poor thermal performance and complex geometry, while insulating them is not straightforward. In addition, they also have relatively onerous installer requirements, as a RIRI specific certification scheme does not exist, so installers working on RIRI retrofits require multiple individual certifications. DEEP will survey existing rooms in roofs to explore performance levels and will use case study retrofits to measure the benefits and risks of RIRI.

2.3 New windows and doors

Traditionally, windows and doors and associated reveals often have higher condensation and mould growth risks, and despite comprising a proportionally small area of a home’s surface area, windows are often a substantial region of heat loss. Thus, they are particularly important element to target for retrofit, however since they are often installed as part of a wider retrofit project, studies often do not report their specific contribution to reducing heat loss.

One study by Ahern et al. [58] found that, when modelling relatively modern houses with cavity walls built between 1978 and 2006, single glazed windows caused the most heat loss of any building element (91 W/K) and installing double glazing as part of a whole-house retrofit could reduce this heat loss by a third. However, although the absolute savings achieved by retrofitting windows could be the same, the percentage savings may not be so large in older, inefficient or solid walled homes, since heat loss through the walls and the roof in these dwellings is likely to dominate the overall thermal performance. There are multiple window retrofit options available to householders, which include:

- Upgrading single to double glazed units; this is a common thermal upgrade in homes [59] which has been observed to reduce whole-house heat loss by up to a third [60], depending on the glazed area and thermal efficiency of the house;
- Adding secondary glazing to single glazed windows, which has been shown to successfully reduce energy consumption as part of broader retrofits [43];
- Upgrading existing secondary glazing to a more efficient specification, which could achieve savings (including fabric and ventilation heat loss) of 7.1% [61];
- Replacing double glazing with higher-spec double glazing (i.e. changes in gas fill and coatings) or triple glazing which has been estimated to save 15.3% [62]; and
- Increasing the number of panes [63] if frames are thermally broken and the edge of the glazing incorporates an insulated spacer bar.

There is little research that compares the effectiveness of individual door or window retrofits. However, window retrofits may be expected to reduce U-values and in some instances improve airtightness in homes, which in turn has been observed to reduce heating and cooling demand by 5% to 15% [64] depending on efficiency of the windows and rest of the house. Installing new windows inevitably reduces the conductive heat loss, as newer units tend to have lower U-values. However, installing new windows has also been observed to improve airtightness performance, potentially significantly reducing infiltration in a property [65-70]. Conversely, depending on the quality of the retrofit, infiltration can actually increase. For example, if the new window doesn’t fit the opening and is not appropriately sealed, or in the case of replacing sash with casement windows, if redundant sash boxes and frames are covered over rather than being removed or insulated a thermal bypass can result. Figure 2-5 shows a substantial bypass at the head of the replaced sash windows. While the sash boxes at the sides have not resulted in a heat loss mechanism, presumably being effectively treated, a failure to seal and insulate the connecting recesses at the head and the bay window stud, below the sill of the window, results in substantial heat loss.

Figure 2-5 Excessive infiltration around window frames after sash windows replaced by casement windows and the resulting gaps have been boxed in, allowing air exchanges via the unsealed tops of the boxing in (unpublished image from [27])

The quality of the window installation can substantially affect its overall performance. However, identifying underperformance is difficult since draughts are not clearly visible and may only be felt when the wind speed increases. Consequently, TM for window installations in ECO, including Competent Persons Scheme assessments, may not always identify where problems exist, unless they incorporate measures to identify any potential air leakage points and pathways, such as smoke detection and infrared thermography.

The areas of window and door reveals are substantial (including the frame, lintel, sill, threshold, jambs and surrounding reveals), and when acting as a thermal bridge, can contribute up to 40% of the total bridging heat loss in a dwelling and can result in significant condensation issues [71-73]. Calculation of the heat losses attributable to these regions is typically done using thermal models, due to the complexity of measuring thermal bridging, although it may be qualitatively evaluated in the field using thermal imaging [62]. The insulation of reveals and the positioning of windows in line with wall insulation to ensure a continuous insulation layer is important in maximising savings [74, 75] and avoiding possible risks introduced by thermal bridging, as shown in Figure 2-6.

Accredited Construction Details (ACD) suggest that there should be a minimum 30mm overlap of the window with the insulation [76] as this can reduce thermal bridging by 50%. However, in order to minimise bridging, the window should be installed in line with the insulation [77]. In retrofit scenarios difficulties can arise when attempting to overlap the insulation, as complications around water tightness and restricted access or space can present buildability issues. In some instances, windows have been fitted into boxes fitted into walls in order to future proof them for future wall improvements. While not currently required in the guidance this, in addition to consideration of the insulation of reveals, are examples of how a whole-house approach could impact on window and door retrofits.

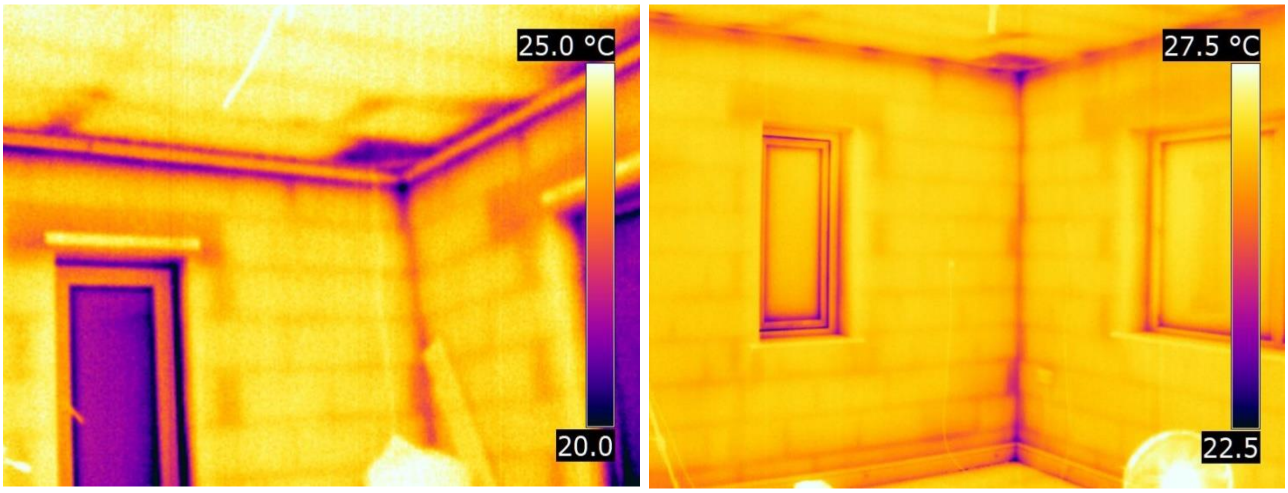

Figure 2-6 Thermal bridging at reveals around old double glazed window located on external leaf (left) replaced by new triple glazing window unit in an thermally broken frame, relocated post-retrofit in line with external wall insulation (right) resulting in less thermal bridging and a warmer window pane (unpublished image from [78])

Door retrofits are not common in ECO and perhaps motivations for replacement are likely to be due to aesthetics or security requirements, rather than to improve energy efficiency. However, doors tend to be among the worst performing thermal elements of a dwelling, with U-values measured around 3.6 to 4.0 W/m^{2}K. Fortunately their relatively small area means they will not contribute much to a dwelling’s total heat loss, though more research is needed to quantify this. In dwellings, the impact of doors leading directly into habitable space, closed porches or entrance halls has also received limited attention.

New build homes are expected to have doors that achieve a limiting U-value of 2.0 W/m^{2}K [79] and it is recommended that retrofitted doors should achieve 1.8 W/m^{2}K [6], though studies have shown retrofits have previously improved door U-values to 1.7 W/m^{2}K [66]. Whilst common practice is to replace the entire door and frame, it is possible to apply insulation products directly to the existing door where there is a desire to retain external aesthetics, with U-value reductions of 79% observed in a field study [43].

In the Building Regulations, basement doors are considered equally to external doors since they separate the conditioned space from a non-conditioned space. However, it is not clear how many homes have external quality doors to the basements. The implications of this are difficult to quantify since there is little data captured on the number of homes with basements.

Doors share the same limitations identified for windows, and, similarly, they can also reduce conductive heat loss in homes when new doors are installed with lower U-values and reduce the convective heat loss by reducing draughts around frames. However, it is difficult to capture data on the improvement in airtightness achieved by door retrofits since often the blower door test used to quantify air leakage is installed in the door. Therefore, its performance and seals cannot be evaluated unless there is another door (or large window) in the property or an alternative test is performed. A further complication unique to doors is the presence of key holes and letterboxes, which provide a potential source of thermal bridging and air leakage, although keyhole covers can be used to mitigate against this.

Further approaches to improve the performance of doors and windows include proprietary draught stripping products which are installed onto existing door and window edges. Although these can be installed under ECO, very few of these are installed nationally and their impact is not well studied. These draught proofing retrofits, however, only address the seal between the frame and the door or window, they do not address air leakage around the frame or windowsill, which is often a major area of infiltration. Thus, the draught proofing measure in ECO provides only a partial sealing of doors and windows.

Openable trickle vents are often integrated into windows, designed to provide control over the provision of fresh air into homes when needed (*ventilation)*. However, they are often poorly sealed, leading to additional air changes when not required (*infiltration)*. Thus, there are multiple areas where airtightness around doors and windows could be improved which are not conventionally part of policy funded retrofits. There has been little work to investigate the impact of these issues which collectively may have considerable implications. This is an example of something that could be considered when adopting a whole-house approach.

Although DIY draft proofing measures for windows and doors are some of the cheapest retrofit measures that can be undertaken, conversely, full window and door retrofits are among the most expensive retrofit measures to install in homes [80, 81]. Despite their cost, they are still popular retrofits (especially windows) and the installs take place outside of policy frameworks. The popularity as a retrofit is perhaps a result of their perceived ability to enhance aesthetics and house prices. However, windows and doors also tend to have a shorter physical life than other parts of the building fabric [82], and thus may be replaced more often.

Upgrading from single to double glazing may be common, though upgrades to triple, even quadruple or high-performance double glazing are less so. This may have implications for future minimum energy performance regulations. It is not known if homeowners regard older existing double glazing as already efficient or if there are barriers that are unique to triple or quadruple glazing that restrict installation. For example, the units are substantially heavier, may require additional costly structural support and have thicker frames which may limit their potential to be retrofitted and could be considered less aesthetically pleasing.

New windows and doors: implications for DEEP

Upgrading from single-glazed or older double-glazed windows to higher performing double, triple, quadruple or secondary glazing can reduce space heating fuel bills by between 5% and 15%. However, performance may be compromised by workmanship issues. A whole-house approach should consider if reveals need insulating if windows can be relocated to accommodate future wall insulation and should seal around the frame and other areas prone to infiltration. DEEP will investigate the integrity of glazing and door retrofits installed in homes and use case studies to quantify the impact of different glazing and door retrofits in homes.

2.4 Wall insulation

Walls commonly represent the largest heat loss area of a dwelling and have rightly received significant attention with regard to retrofit, representing 41% of all ECO measures and 9% of all Affordable Warmth measures [15]. The following sections identify different wall types, how these may be retrofitted and what problems and opportunities have been encountered.

2.4.1 Cavity wall insulation

Cavity walls generally consist of two parallel connected masonry ‘leaves’ separated by an air gap, usually around 50mm, though this varies considerably. Traditionally, the cavity was left empty to prevent moisture travelling through to the inner surface of the wall. However, filling these cavities is now viewed as an effective way of improving the thermal performance of homes. Retrofit of cavity walls usually involves penetrating the outer skin and pumping an insulant, such as mineral wool or polystyrene bead, into the cavity to provide additional resistance to heat transfer.

CWI is one of the most common retrofit measures in the UK; approximately 13.8 million properties have had CWI, equivalent to 70% of all cavity wall properties [42]. Of the 5.3 million homes without CWI, 4 million are defined as *easy to treat*, indicating substantial potential for further energy savings. Conversely, 1.3 million homes are classified as *hard to treat* cavity construction [42], often due to location, obstructions, construction type or cavity width. Improving the thermal performance of these homes may be more problematic and would benefit from a whole-house approach.

NEED suggests CWI resulted in a consistently high mean energy saving, varying between 7.1% and 9.5% [83], and is therefore one of the most effective single-measure retrofits [84]. CWI performance is also relatively robust; reduction in heat losses have been observed in multiple studies on homes with different occupancy or heating patterns and at different times of year [85]. However, although CWI is a key contributor towards reductions in space heating energy use, research has found a CWI performance gap [62]. This can occur where there are obstructions to sprayed insulation, for example, wall ties, cavity trays and mortar debris, which can cause uneven distribution of insulation, or even uninsulated sections of wall in some cases. These inconsistencies have been confirmed via thermal imaging surveys and borescope investigations [62]. An example of missing insulation is shown in Figure 2-7.

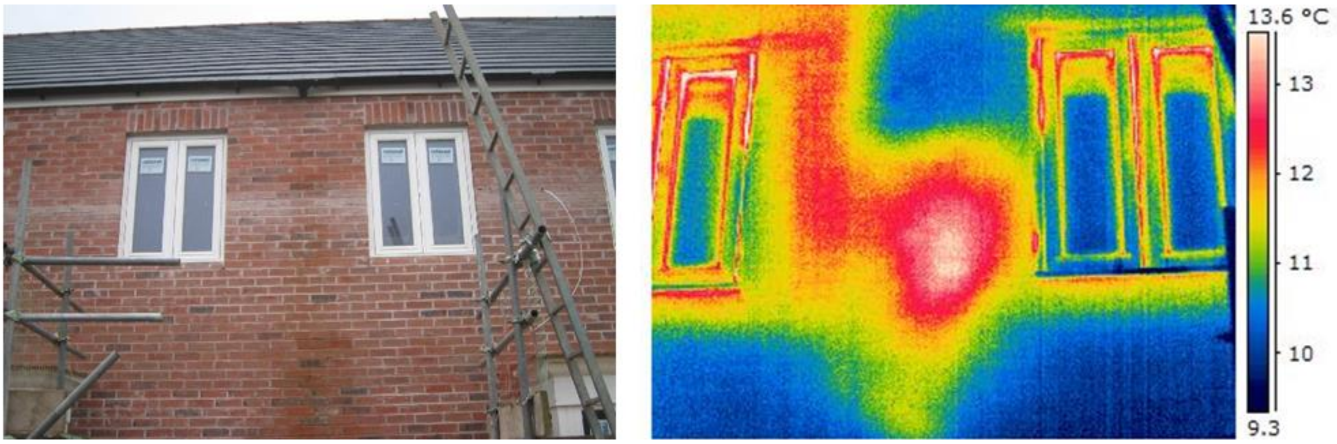

Figure 2-7 Areas of missing insulation following CWI retrofit visible as a hot spot during an electric co-heating test [77]

Heat flux through filled cavity walls has been measured to show variable performance of CWI retrofits and found lower performance near locations of thermal bridging, such as at wall perimeters, penetrations, doors and windows [44]. These areas of low performance may introduce lower internal surface temperatures with a consequent increase in surface condensation risk.

Field investigations into the performance of CWI retrofit are typically done immediately following its application, with underperformance primarily attributed to installation [44, 62, 85]. Comparatively little is known about the performance of CWI over time. However, a small number of studies have shown a decline in performance over time, with the reduced performance resulting from a number of occurrences, including moisture saturation, material settlement and deterioration [86-88]. This deterioration is also shown in the NEED data in Figure 2-3. However, more information is needed on the scale and extent of this deterioration to understand if it was worthwhile embarking on a program of CWI removal and replacement.

Problems may be more likely to manifest in properties located in exposed regions of the UK since these are more susceptible to moisture penetration and transference across the cavity, especially where walls are west facing. Although it is recommend that CWI should be limited in exposed areas installations do still occur and *water penetration* is the main cause of complaints and claims against CWI [89].

An additional complication for cavity walls, which is less well understood, occurs where homes have been extended and resulted in one or more external cavity walls becoming internal walls. If these were uninsulated they can act as a thermal bypass [62]. Thus, in conventional CWI retrofits where this has happened, if these walls are not also filled or capped, this heat loss mechanism will continue to operate and undermine the retrofit performance. With a whole-house approach this complication may be identified and the bypass should be addressed. Additionally (as discussed in Section 2.2), with a whole-house approach, the installers should also ensure the CWI connects with the LI to avoid thermal bridging.

2.4.2 Partial fill cavity wall top-up insulation

Although cavity wall insulation was first introduced in the UK in the 1970’s, it was not until the 1990’s that is became a regulatory requirement for all new dwellings. In these dwellings, the cavity walls tended to include a layer of insulation within the cavity, fixed to the inner leaf. This meant these were *partially filled* and retained a residual cavity to avoid moisture ingress risks. There are estimated to be 1.6 to 2.4 million dwellings in Great Britain with such constructions [90].

While considered an improvement over empty cavities, there are unique energy performance problems with this type of construction. These are related to air movement around and through the partial fill insulation layer when it is not fitted correctly to the inner skin of the cavity, as shown in Figure 2-8. This has been recognised as a problem for some time [91], and where it occurs, air looping (where heat occurs via convention within the construction) and wind washing (where unconditioned air that is driven by the wind passes through or behind the thermal insulation layer, reducing its effect) can occur. Hens et al. [92] measured U-values of cavity walls and found that U-values can increase fivefold (0.21 W/m^{2}K to 1.03 W/m^{2}K) due to not taping up joints or sealing around the perimeter of the insulation panels [93].

Figure 2-8 Examples of partial fill insulation which is poorly fitted to the cavity inner leaf [44]

It has been suggested that retrofitting CWI could rectify this problem and have substantial potential for additional insulation savings [44]. In one study of recently constructed houses [94], the reductions in the whole-house heat transfer coefficient following the filling of the residual cavity were observed for an end terrace and mid terrace dwelling, with 90% of the benefit being attributable to the elimination of the air looping and wind washing, and 10% from the improved U-value of the wall. It is important to consider that models of partial fill top-ups would therefore greatly underestimate savings where partial fill insulation boards were poorly affixed.

Consequently, there are two mechanisms at work that may improve the performance of partial fill CWI retrofits: 1) adding insulation to improve thermal resistance and, 2) inhibiting air looping and wind washing. The limited literature on partial CWI retrofits suggests the potential energy savings from filling residual cavities could be considerable. However, it is not known if the same results may be achieved with an acceptable payback period. Some installation issues have also been observed with partial fill top-up retrofits. This is often caused by poor adhesion of the original partial fill boards to the inner leaf (e.g. caused by mortar snots) affecting the distribution of the top-up insulation. In addition, cavity trays can also cause gaps that top-up insulation cannot fill. Furthermore, partial fill CWI retrofits may also suffer from the same moisture ingress in exposed areas as CWI [95, 96].

2.4.3 Cavity party wall insulation

Homes with external cavity walls can also have a cavity party wall between adjoining properties. Party wall thermal bypass has recently been observed and identified as a heat loss mechanism [97, 98]. There are a variety of party wall types available, which affect the extent to which the bypass operates. For example, some party wall cavities are open at the loft level and may have the most severe bypass behaviour operating, some party walls extend up to the roof ridge and have a less extreme bypass, while party walls which are fully sealed or capped at the loft level may have almost no bypass. Cavity party walls can also connect to the underfloor void, external wall cavity and outside through gaps around floor joists, which extend into the cavity, and through gaps in the internal leaf of masonry that also extend into the cavity.

Cavity party wall insulation (PWI) may be retrofitted in a similar manner to CWI, but with the purpose of minimising the party wall bypass, rather than increasing the thermal resistance of the party wall. The U-value of a cavity party wall was previously considered to be zero, however, some studies have shown there is some heat loss through this element, and current building regulations now require new build party walls to have a U-value of 0.2 W/m^2K where a party wall is sealed at the loft level, and 0.5 W/m^2K if the cavity extends the roof ridge [6, 99, 100]. As observed in the partial fill CWI retrofits, PWI retrofits have a stabilising effect on party wall thermal performance [94], as illustrated in

Figure 2-9. While PWI retrofits have received relatively little research, field trials have observed that when this bypass is removed, whole-house heat loss can be reduced by 8%, though it is not clear if this is heat loss to the neighbour or to the outside [56].

PWI is a retrofit measure in ECO, though relatively few retrofits have yet taken place. It is estimated that there may be 6.6 to 8 million uninsulated cavity party walls in the UK, indicating that there is some potential for energy saving via PWI across the housing stock, though, it is not known how many of these may have an active bypass or how many are already capped. PWI may become significant as other building elements are upgraded and may become more common where a whole-house approach is adopted, for instance, it may be relatively simply installed along with conventional CWI.

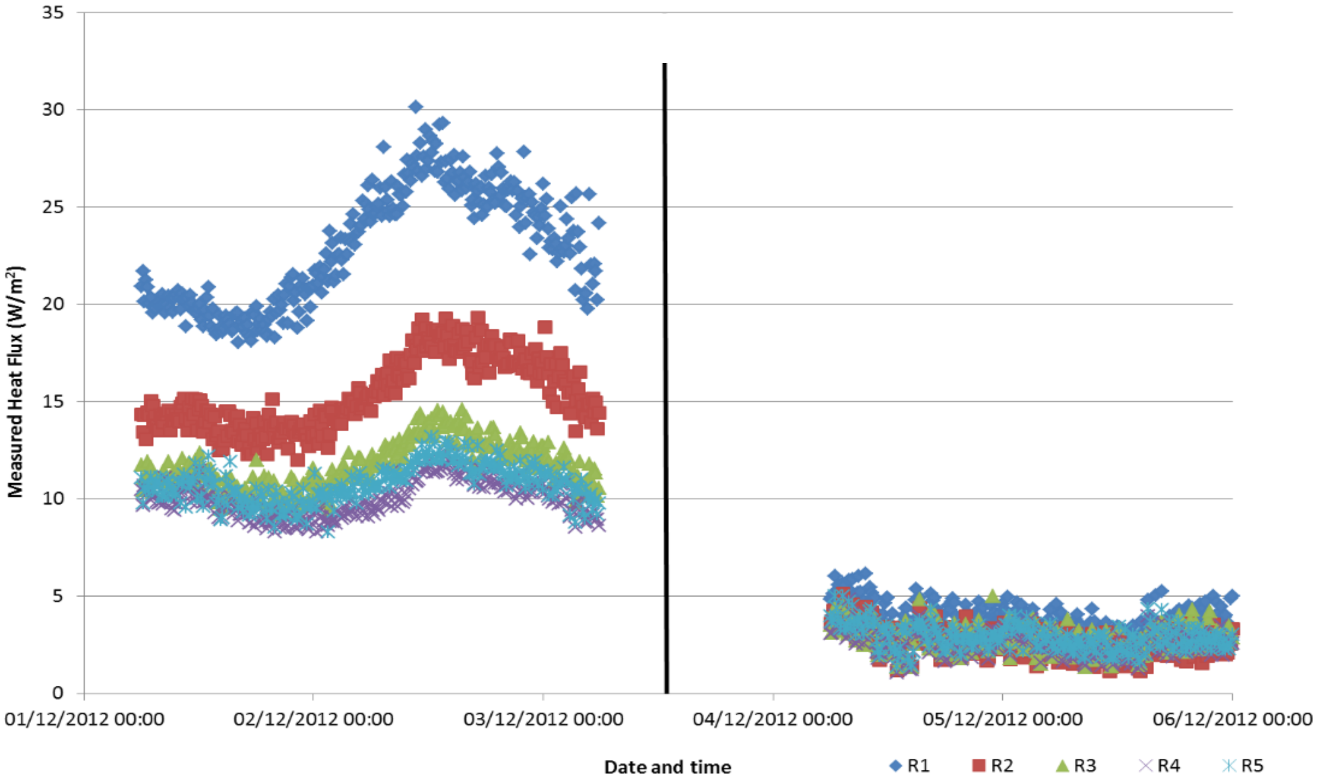

Figure 2-9 Individual heat flux plates (R1 to R5) identified by different colours showing party wall heat loss fluctuates pre-retrofit, particularly where the party wall and cavity external wall junctions (dark blue and red dots) due to air exchange between the walls (left). Post retrofit the heat loss by air bypass is removed and heat flux falls and stabilises (right) [101]

Cavity Wall Insulation: implications for DEEP

Retrofitting cavity walls, cavity partial fill and cavity party walls has the potential to reduce fuel bills. However, if it is not undertaken correctly, it can introduce unintended consequences and underperformance. Following CWI retrofits a deterioration in performance has been observed, and DEEP will use borescope investigations to evaluate the condition of historic CWI retrofits and their impacts on homes.

2.4.4 Solid wall insulation

Before cavity walls became the standard approach to house building, homes were built with solid walls from a wide range of materials and styles. Commonly, solid walls have two parallel courses of masonry (usually brick but can include block or stone) with cross bonding courses to tie the leaves of masonry together. In some old stone walls (mainly over 150 to 200 years old) the cavity between the internal and external leaves can be 100 mm to 200mm wide or more and filled with a loose rubble fill.

Typically, all masonry solid wall types are treated on the assumption that they form a homogeneous structure. In practice, this is not the case as there are a variety of air spaces ranging from a narrow (10mm) continuous cavity between internal and external leaves to small isolated air pockets. This creates a complex structure that can have a wide range of thermal characteristics.

Air movement through solid walls is particularly concerning for the application of rigid board SWI. Although panels should be sealed at the edges this does not always happen meaning air can flow around the insulation, reducing its efficacy as shown for an internal wall insulation (IWI) retrofit in Figure 2-10. Lack of adequate sealing around external wall insulation (EWI) has also been observed, which would result in air circulating between the EWI and external brick and could result in underperformance [50]. The direct air leakage via finger cavities in solid walls is relatively under-evaluated. Behaviours are likely to vary due to the different bonding patterns and wall materials used.

Figure 2-10 Thermal image taken under depressurisation illustrating a direct air leakage around the edges of internal wall insulation which is not adequately sealed [56]

Other solid wall types include post-war system build and non-traditional homes. These include solid and no-fines[‡] concrete panel structures, and there are also various timber, concrete and steel frame and panel homes. It is estimated that there are 450 post-war non-traditional system build types and around 1.5 million total non-traditional dwellings [102]. Thus, there are many different types of solid wall in existence in the UK. The type of wall construction influences its thermal performance and recent revisions to the estimated U-value of an average uninsulated solid wall have dropped from 2.1 W/m^{2}K to 1.7 W/m^{2}K for inclusion in Government retrofit modelling [103]. Reducing the predicted U-value also reduces the potential savings that may be anticipated from SWI retrofits.

Retrofit of solid walls generally involves attaching insulation directly to the internal or external wall face, known as IWI or EWI respectively. At the end of December 2018, 752,000 dwellings had some kind of SWI, equivalent to only 9% of properties with solid walls and so it is estimated that there are 7.7 million uninsulated solid wall dwellings [42]. Case studies have found that the application of SWI results in significant reductions in heat transfer between 13% and 68% [28, 56, 62]. NEED analysis suggests SWI resulted in a more modest median energy saving of 13.2% [54] which may be an indication that SWI suffers from a substantial performance gap, though this is still the highest saving of all insulation measures evaluated in NEED. The reason for the SWI performance gap may be due to unrealistic assumptions about the performance of the uninsulated wall, an overestimation of savings using RdSAP due to assumptions about the space heating hours and indoor temperatures, poor installation and changes in occupant behaviour post-retrofit [50, 103].

The literature highlights workmanship as one of the primary reasons for SWI underperformance, along with extensive evidence of poor detailing (or lack of adequate designs) for installers to follow, leading to thermal bridging and water ingress [104-108]. This is

---

[‡] No-fines is used to describe concrete constructed from coarse aggregate and Portland cement that does not contain any fine material, such as sand or fine aggregates. It is considered to be a non-traditional method of construction.

particularly the case for installing EWI around complex building details which may not have common design solutions, as shown in Figure 2-11. Beyond performance gaps, reports of moisture-related product failure have also been observed with IWI [109]. In addition, one study identified that 90% of solid wall homes may have pre-existing damp issues on at least one wall which may be exacerbated with the addition of insulation, which may act to slow the rate that the wall will dry out [27].

Figure 2-11 Complex construction features causing EWI detailing to create discontinuities in insulation and introduce thermal bridging [110]

A particular feature of solid wall homes is that they often have air bricks to provide ventilation for fresh air or for open flued appliances. Whilst these may no longer be needed if alternative ventilation is provided, e.g. trickle vents, a closed flue or mechanical ventilation, a whole-house approach to SWI should consider the continued provision of adequate purpose-provided ventilation. Unfortunately, in some instances, vents are obstructed or covered, as shown in Figure 2-12. Thus, a retrofit may inadvertently reduce purpose-provided ventilation rates which could impact on indoor air quality and occupant health.

Figure 2-12 Room ventilation (left) which has been covered over by IWI retrofit (right) [110]

The majority of SWI retrofits that have been undertaken in the UK are EWI, perhaps as external installation limits disturbance to occupants and can achieve economies of scale when treating multiple adjoined homes. However, some homes cannot have EWI retrofits. For instance, there may be poor access for scaffolding or restrictions on the potential to change the external facade of the building, which makes it unsuitable for many traditional buildings.

IWI offers an alternative retrofit approach, although is less common and has limitations. EWI is generally preferred to IWI as it neither reduces the floor area of homes, nor introduces the risk of interstitial condensation and timber rot [27], which is of particular concern for IWI, if installed with a non-breathable vapour control layer [109]. However, novel, often thinner, IWI products may be able to overcome some of these practical barriers to installation and introduce lower levels of risk than conventional IWI [27], though these have not been installed at scale.

Discontinuities in IWI commonly occur at the intermediate floor void, behind built in kitchens and bathrooms and around services and utilities. A survey of 100 homes identified that in 95% of cases there was at least 1 wall mounted obstruction to IWI [27]. A further complication that this project identified was that following an IWI retrofit is the impact on adjoining uninsulated properties' party wall surface temperatures. This means that when a house has an IWI retrofit, there is an increased risk of condensation for their neighbour's house. Thus, the concept of the *whole-house* approach may need expanding to an *inter-house* approach.

Solid Wall Insulation: implications for DEEP

SWI retrofits have substantial potential to reduce fuel bills, though they are susceptible to performance gaps and may introduce thermal bridging and condensation risks linked to the complexity of wall details. Since SWI drastically improves the thermal resistance of solid walls, where discontinuities in insulation do occur, thermal bridging may be extreme. Interstitial condensation risks associated with IWI need careful consideration, as does the concept of moving beyond a whole-house to an *inter-house* approach. DEEP will use house surveys to investigate these issues as well as undertaking SWI retrofit case studies and models to explore how insulated solid walls interact with other elements and retrofits.

2.5 Airtightness improvements

Air leakage is defined as the uncontrolled fortuitous exchange of air both into (*infiltration*) and out of (*exfiltration*) a building envelope, space, or component through cracks, discontinuities, and other unintentional openings. This is not to be confused with *purpose provided ventilation*, which is the intentional air exchange to manage moisture levels and ensure healthy indoor air quality. The airtightness of a dwelling is affected by gaps and cracks in the building fabric, which typically appear at openings, penetrations and junctions. If a dwelling has a poor level of airtightness, this may lead to excessive energy use and thermal discomfort. It may also cause enhanced risk of poor air quality where infiltration occurs through damp parts of the building, or where interstitial condensation occurs, such infiltration may allow mould fragments and spores to enter habitable space, presenting health issues [111].

Building Regulations require that new build homes must have their airtightness assessed (though not all homes in a development currently require testing) [79]. However, this is a relatively recent requirement. As such, comparatively less is known about the airtightness of existing dwellings in the UK, which varies dramatically based on building age, form and construction type.

Work undertaken by Stephen, some 20 years ago, found that the average air permeability of a sample of 384 existing dwellings was 11.48 $m^3/h/m^2$ @ 50 Pa [112]. This is slightly worse than the maximum level permitted for current new build dwellings [79], but is significantly higher than that currently observed in new build dwellings of ~4.5 $m^3/h/m^2$ @ 50 Pa [113]. It also falls well short of the standards required for low energy homes, which use mechanical ventilation and heat recovery (MVHR) systems [34]. However, the available data points to a very wide distribution, with many dwellings having values in excess of 15 or even 20 $m^3/h/m^2$ @ 50 Pa [112]. Studies have shown that air leakage can be reduced by 50–70% by undertaking general and targeted airtightness work [65, 67, 95] including:

- Replacing or sealing around window and door frames;
- Sealing loft hatches;
- Repairing defects in plaster;
- Sealing gaps in, around and between the boards of suspended timber floors;
- Sealing service and other penetrations through the building fabric; and
- Sealing around dot and dab plasterboard finishes.

Homes with wet plastered walls tend to have lower air leakage rates than those with plasterboard [56]. There are no data available on the number of homes with plasterboard versus wet plaster, however, it is likely that older homes have wet plastered walls. This is significant when considering wall retrofits, as one study found no change in airtightness following IWI retrofits in homes with wet plaster [27].

Although improving the airtightness of a house may be perceived as a relatively simple task, care and attention to detail is required by retrofit installers [114]. Most fabric retrofit measures influence air movement in some way [61] and include installation processes intended to maintain or improve airtightness.

However, these are often done poorly [50] due to a combination of factors ranging from lack of awareness of performance issues to be considered, to poorly specified materials and workmanship [66].

Evidence in the literature suggests that where an explicit air barrier was detailed as part of the retrofit design process, the increase in airtightness of the refurbished dwellings showed the greatest improvements [1, 56, 62, 114, 115]. This attention to detail is prevalent in more specialised retrofit projects, but this is not generally reflected in the wider domestic retrofit building stock [116].

Despite the clear influence of airtightness on retrofit performance [56], it is often a secondary consideration. Lessons learned from the new build market suggest that undertaking measures, such as secondary sealing using mastics, to achieve a one-off airtightness test result is often prioritised over those measures required to achieve longer term airtightness [117]. Some specific airtightness retrofits do exist. For example, in ECO installing draught proofing strips around windows and doors is considered a retrofit measure, however, measures that rely on the addition of a seal (product, mastic or tape) may suffer from deterioration due to material ageing. Indeed, draught proofing retrofits in ECO are anticipated to have a lifetime of only 10 years compared to 36 years for SWI and 42 years for CWI and LI [57].

Moreover, there is very little performance data on airtightness-only retrofits, and where this does occur, the effect achieved is often complementary to other measures being installed. Consequently, the impact related to the airtightness reduction cannot always be verified. Where airtightness measures are found to work, the observations often refer to the change in infiltration rate achieved, rather than quantifying the reduction in space heating demand.

Beyond the specific products designed to improve airtightness, often the greatest improvements in airtightness can be achieved by addressing unusual air leakage pathways. Commonly, this occurs around penetrations for utilities.

Extreme examples of this exist in the housing stock. For example, Figure 2-13 shows a hole in a cavity wall directly linking the inside of the house to the outside via an unsealed meter box, yet there are no products that can resolve this problem and no reward or incentive in policy for addressing these issues. Such issues may go unresolved without cultural changes or consequences for those undertaking the work. This is something that a whole-house approach to retrofit would address.

Figure 2-13 Air leakage pathway around an electricity meter causes excessive heat loss post-retrofit, since rectifying air leakage is not an ECO measure [118]

Improving the airtightness of a dwelling carries an enhanced risk of unintended consequences if purpose-provided ventilation (trickle vents, air bricks etc.) is not already providing adequate fresh air. Thus, prior to any airtightness retrofit, an evaluation of ventilation and an assessment of infiltration may be required to ensure background air exchange is not reduced to too low a level, if for instance purpose-provided ventilation is not adequate. Indeed, PAS 2035 requires additional ventilation to be provided where retrofits have the potential to reduce the dwellings airtightness to ≤5 ac/h at 50Pa to mitigate moisture and indoor air quality risks [25].

Homes that have particular characteristics are likely to have greater air infiltration than others, for example, unfilled cavity walls, suspended timber floors and plasterboard rather than wet plastered walls. A study of steel frame homes identified consistently high infiltration rates due to failure in the construction, which was repeated across multiple homes. Specifically, a bypass linking the party wall and intermediate floor void to the loft space [119].

It also found that homes built by different teams on the same housing estates reflected the idiosyncrasies of those teams of builders, which affected air tightness in particular, and predictable, ways. This resulted in some homes being more airtight than others. The report also found that the airtightness of these homes fitted with EWI was no different to that of uninsulated homes on the same estate. Thus, it cannot be assumed that installing insulation will necessarily also improve the airtightness of a dwelling. It is issues such as this that are particularly suited to a whole-house approach.

Considering the prior discussion, there are likely to be many homes and house types that may benefit from airtightness retrofits, to bring them in line with existing new build standards. However, airtightness retrofits would need to be undertaken in conjunction with airtightness testing to ensure that sufficient purpose-provided fresh air ventilation is achieved, so that any risks to indoor air quality or condensation are not introduced. Undertaking such testing on a mass scale for retrofit may be feasible, given that an airtightness testing industry already exists to provide regulatory checks for new builds with established standards [120].

If airtightness retrofits become mainstream, care must be taken to ensure sufficient ventilation is provided throughout the house, since aggregate airtightness levels do not guarantee that all rooms are sufficiently well ventilated, i.e. some may be overventilated, while others are under ventilated.

Airtightness improvements: implications for DEEP

A home’s airtightness directly affects its energy efficiency. Furthermore, high levels of infiltration can undermine other retrofits installed in homes. The benefit of undertaking airtightness retrofits on a national scale is uncertain since there is limited understanding of the airtightness levels in the UK housing stock, though certain building characteristics and house types are particularly prone to excessive levels of infiltration. Where airtightness levels have been reduced as part of retrofits, their contribution is difficult to gauge as it is often aggregated within the overall benefit. DEEP will use case studies to investigate the effectiveness of airtightness-only retrofits in reducing space heating demand. In these case studies, longitudinal monitoring will be used to gauge any consequential impact on indoor air quality where possible. The project will also undertake airtightness testing on different building archetypes to begin to understand general levels and common causes of infiltration in the UK housing stock. The contribution of airtightness to other retrofit types will be investigated via case studies and modelling.

2.6 Ground floor insulation

There are two main types of ground floor; suspended (usually timber) and solid, though homes may have a combination of the two. Additionally, there are some historic homes with little or no conventional solid floor foundations where the finish rests on a substrate of simply compacted earth. The amount of heat a dwelling loses via the ground floor varies according to the floor type, building shape, local ground conditions, the level of efficiency of other building elements and, perhaps most significantly for suspended floors, infiltration through unsealed floors.

New homes must insulate ground floors to meet a limiting U-value of 0.25 W/m²K [79]. However, the U-value of ground floors in existing dwellings is not well understood, though retrofits have measured U-value improvements of between 65% and 95% [118, 121, 122].

Currently Building Regulations require that retrofitted homes must achieve a U-value of 0.7 W/m²K if the floor is being upgraded [6].

Heat loss from floors is more complex than via other elements, as heat is not lost directly to the external environment, meaning that conventional U-value calculations and measurements must take into account the mitigating effect of the ground, which will typically be at higher temperatures than ambient air in winter [118, 121].

Ventilation under suspended timber ground floors introduces a further complication, since higher and often unpredictable air change rates through the subfloor void can increase heat loss [123]. This means that subfloors that are not well ventilated may be warmer, reducing the potential savings from suspended ground floor retrofits. Consequently, a large variation in measured heat loss savings resulting from ground floor retrofits has been observed, ranging from 10% to 60% [118, 123-125].

However, given that there may be approximately 19.5 million uninsulated ground floors and up to 10 million of these are thought to be suspended timber constructions in the UK [122, 126], this represents a potentially large retrofit market. Despite this, ground floor insulation currently makes up less than 0.4% of measures installed in ECO [15]. While full retrofits may be relatively rare, floor coverings (carpets etc.) have also been shown to reduce the heat transfer coefficient in homes by around 2%. More data is needed to understand if improving the thermal performance of carpets can be a solution to overcoming the disturbance issues with full ground floor retrofits [127].

Suspended ground floor retrofits commonly involve the application of an insulant (usually mineral wool, foam boards or foam spray) below the floorboards, between and often under the floor joists. The wider benefits of insulating suspended timber floors are that infiltration from the floor void into the home can be substantially reduced, which could account for almost half of the heat loss reduction of a retrofit [118]. Insulated floors may be especially important to reduce the risk of Radon entering homes through the floor, while any retrofit that reduces general infiltration elsewhere in the home may risk increasing Radon levels in homes where radon is an existing concern [128]. Notwithstanding these considerations, adequate ventilation can alleviate the risks associated with Radon [129].

Solid floor retrofits are less common and either require insulation to be installed on top of the existing slab, or for the slab to be dug up and re-laid after insulation is installed. Both options are disruptive and if insulation is added on top of the slab, this can lead to problems with doorway heights, thresholds, ceiling heights and step heights on stairs. Perhaps, for these reasons, solid floor retrofit is not a common option, and has never been installed via ECO [15]. Very little research has been undertaken for this retrofit option. Given that the remaining potential for more common retrofits is reducing, the benefits and risks of ground floor insulation require further research.

Ground Floor Insulation: implications for DEEP

Fewer ground floor retrofits have been installed under policy than any other fabric improvements, so the benefits of insulating ground floors are less certain than for other elements, especially as ground floor heat flows are more complex. However, there is significant remaining potential for ground floor retrofits in the UK housing stock. There is also some evidence to suggest that they could provide similar levels of reduction in heat loss as achieved through wall retrofits. DEEP will provide data on a range of ground floor retrofit case studies to explore the potential performance and associated risks. The research will also investigate how ground floor insulation interacts with other retrofits. A range of different ground floor types will be surveyed to identify possible issues with existing insulation or barriers to future retrofits.

2.7 Multiple measures and deep retrofits

The previous sections have detailed the success and limitations observed for single-measure fabric retrofits. However, it is also possible to install multiple measures in homes in a single retrofit. This may simply be combining LI and CWI or undertaking a *deep* retrofit, which is where all or most of the fabric elements are improved. This may happen simultaneously or sequentially and generally also includes service upgrades [4]. However, multiple measure retrofits are not common in ECO [130].

Retrofitting multiple measures into homes, whether at the same time or over a period of some years, as would be expected, further reduces the heat demand of a house [43, 45, 56, 131, 132]. For example, NEED measured gas savings for homes that hadinstalled onlyLI or CWI to be 7.3% or 2.2% respectively (9.5% cumulatively).Yet, when LI and CWI were installed together, presumably as part of the same retrofit, they appeared to save only 8.5%, . This may be expected due to the law of diminishing returns for each additional energy saving measure introduced. However, NEED also found, that the combination of LI and SWI in a single retrofit resulted in a median energy saving of 17.3%, which is higher than combination of 12.4% and 2.2% savings measured for SWI and LI respectively when installed as single measures [133]. This suggests that, when combining measures, savings can sometimes appear to be greater than the sum of their individual parts. This may be somewhat surprising given the general expectation of the law of diminishing returns This may be indicative of additional retrofit activities taking place when multiple measures are installed that are not notifiable measures (e.g. air tightness improvements). Furthermore, alternative NEED analysis suggested that installing CWI and LI in the same year (and presumably the same retrofit) saved 10.9%, whereas homes which had LI and CWI retrofits installed several years apart were saving on average only 8.4% [134].

NEED has analysed the most common multiple measure retrofit installs over the past few years to explore the impact of these and their results are described in Figure 2-14, highlighting that it is not clear if there are benefits to installing multiple measures at the same time.

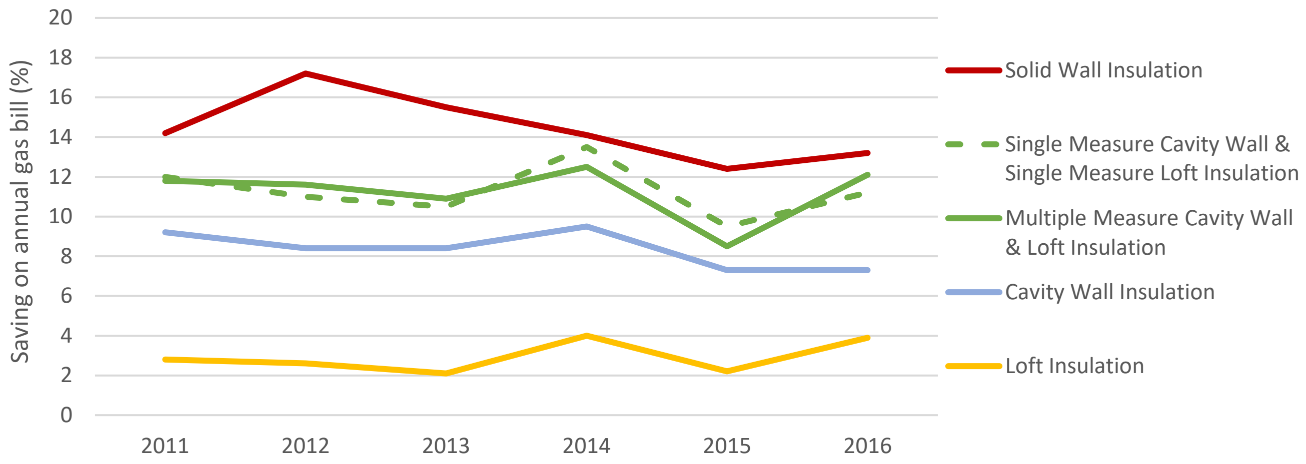

Figure 2-14 NEED measured savings for common single measure and multiple measure retrofits; comparing the difference in savings between installing cavity wall insulation and loft insulation at the same time (green) versus installing them separately (dashed green)

Consequently, the evidence suggests that there may be an advantage in installing multiple measures at the same time, perhaps because the operational performance of any retrofit measure is dependent on the other measures in place [132]. Furthermore, the effectiveness of multiple retrofit measures has been observed to depend upon their interactive effects [135]. Therefore, the installation of multiple measures may encourage consideration of the interfaces and interaction that is likely to occur between measures, as a whole-house approach is adopted.

The situation is not completely clear: Adan and Fuerst [84] calculated, also using NEED data, that savings from multiple retrofit measures did not match the cumulative total of the average of the savings from each of the single measures. While each additional measure is predicted to provide proportionally smaller improvements owing to the law of diminishing returns, when several measures are installed at the same time, it may be more likely that something like a whole-house approach is adopted. This may result in discontinuities in insulation being avoided or improvements in airtightness being made. However, it is not clear if combining measures will lead to cumulatively higher or lower savings than the sum of the individual measures.

In addition where more measures are being installed into a home, the opportunities for problems to occur increases, which in turn may contribute to the retrofit performance gap [131, 136]. For instance:

- *Workmanship* problems resulting in uncertain quality of installation;
- *Prediction gaps* which may overestimate savings;
- *Pre-bound effects* where occupants receiving retrofits use less energy than expected before the retrofit;
- *Comfort taking* by occupants who use the same energy post-retrofit but achieve greater thermal comfort; and
- *Heating efficiency penalty:* where more efficient heating systems installed alongside retrofits reduce the cost of delivering heat and reduce the perceived savings of retrofits.

These performance issues are common in the industry; one study found that out of 45 *deep* retrofits, which aimed to achieve an 80% CO_2 reduction in some instances, only three met their predicted savings, though in many of these the pre retrofit data was calculated rather than measured, which makes these results less certain [23]. Additionally, Swan et. al., performed a deep retrofit under controlled conditions and each element was measured to perform as expected, yet overall, the predicted savings were still not achieved [31]. Thus, installing multiple measures doesn't guarantee the performance gap will be minimised, and the data suggest that there is still uncertainty around how combinations of measures interact.

Installing multiple measure retrofits in a single phase of work can minimise disruption and capitalise on cost savings associated with materials and labour. However, since the up-front cost is high, this approach is less commonplace than single measure retrofits, so net savings may be less for households. Guidance requires installers to consider how other existing measures interact with the retrofit, though it doesn't explicitly require future proofing for anticipated retrofits [25]. Consequently, policy is not specifically making it simpler for homes to be upgraded in the future, so the issue of disruption may persist.

Little research has been done to equate the net energy, CO_2 emission and cost savings of piecemeal retrofits installed as soon as can be afforded by the householder, versus avoiding retrofits until the householder can afford to install the measures all in one go. However, from a national policy perspective, savings would be maximised by front loading multiple measure retrofits rather than waiting years or decades for homes to have piecemeal retrofits [132, 137]. Additionally, it has been observed that after having a single retrofit, regardless of its performance, householders will not embark on a new retrofit for some time, thus *locking in* a partial retrofit [51]. This is despite the fact that further retrofits are technically possible. The net effect is that the potential carbon savings of a deep retrofit are never fully attained [20].

The most comprehensive form of multiple measure retrofit is a *deep* retrofit whereby all or most of the heat loss elements are improved to greatly reduce energy losses. Several approaches to deep retrofit have been developed following the common principles of minimising heat loss via conduction and air leakage and ensuring good thermal comfort, for example Passivhaus EnerPHit [138, 139] and Energiesprong [140], with observed success [141].

The Retrofit for the Future programme undertook an extensive series of deep retrofits across a variety of dwelling types with the aim of reducing CO_2 emissions by 80% [142]. High savings were observed in this project, although these were lower than predicted [4]. Other case studies have also shown similar levels of performance resulting from deep retrofit [41, 45, 56, 61, 62].

Research suggests that the cost of *deep* retrofit is currently prohibitive without subsidies or unless other refurbishment work is taking place [143]. Consequently, payback is difficult to achieve under current funding mechanisms, which are more suited to retrofits targeting energy savings of only 10-30% [144]. Fawcett [145] suggests that the decisions of deep retrofit homeowners are not made as rational economic actors. Instead, motivations were observed to be holistic and included environmental concern, desire for improved comfort and living standards, reducing waste and saving on energy costs. Thus, demand for deep retrofits may change as homeowners become more aware of the comfort improvements that may be achieved, as well as environmental issues [144].

2.7.1 The whole-house approach

Central to the success of any retrofit, whether carried out in a piecemeal or packaged sequential manner, is the adoption of a whole-house approach [21, 26]. Thus, installers should consider the building as a single system whereby modifications made to one element will have an impact on the performance of another, regardless of whether single or multiple measures are being installed, or if a deep retrofit is being undertaken [110]. This approach has been promoted by experts [21] and is now embedded into retrofit standards [25].

Additionally, the interaction between systems and their impact on the property needs to be fully assessed [132]. This is to ensure that the *in situ* performance corresponds with the predictions and to fully consider risk and unintended consequences, particularly with regard to moisture [56, 103].

The whole-house approach as outlined in PAS 2035 [25] has been developed to avoid poor performance and unintended consequences and will become mandatory for future ECO retrofits. However, little research exists on evaluating the success of taking a whole-house approach to retrofits compared to the more common situation of installing combinations of single retrofits over time.

Multiple measures and deep retrofits: implications for DEEP

Multiple measure retrofits have greater potential for energy saving than single measures, and *deep* retrofits particularly may yield the greatest savings. However, there is uncertainty around how combinations of individual retrofits interact and perform to reduce fuel bills. For example, it is not clear how the law of diminishing returns impacts on performance gap issues. Furthermore, there is not yet any guidance in policy on best practice for future proofing retrofits, though the whole-house approach should be adopted for all single and multiple measure retrofits, whether *deep* or not. DEEP will use house surveys to investigate how multiple measures interact. Case study retrofits will also be undertaken of multiple measures in a phased way to replicate current practice. This will isolate the individual performance and cumulative savings achieved by each measure, as well as enabling the opportunities for mitigating and reducing risk to be observed. Modelling will predict the benefits and risks of improved performance and provide evidence for policy on how to best to incorporate and support a whole-house approach.

2.8 Summary of retrofit performance and risk

ECO has improved the thermal performance of millions of homes. Table 2-1 provides a summary of reported performance of common retrofit measures. Where only data on space heating demand was available this was assumed to represent 80% of the heating bill [146].

Table 2-1 Summary of range in performance of retrofits

	Observed reduction in heating energy	Factors affecting performance and unintended consequences
Loft Insulation	3.9 % - 17 %	Difficult to reach eaves, disruption from storage and maintaining services.
Windows and doors	5.6 % - 15.3 %	Failure to adequately resize openings, thermal bridging at frame and wall.
Cavity wall insulation	7.3 % - 15.5 %	Mortar snots and cavity debris, moisture penetration, problems with pre-existing partial fill insulation.
Solid wall insulation	13.2 % - 68 %	Thermal bridging and discontinuities in insulation layer, infiltration bypassing insulation, complex detailing, incomplete wall coverage.
Suspended timber ground floor insulation	8.8 % - 25 %	Existing infiltration paths, thermal bridging at ground floor perimeter, ground floor conditions.

Multiple measures	12.1 % - 20 %	Different combinations of measures installed, interaction of measures, design team approach.
Whole-house retrofits	35 % to 56 %	Different combinations of measures installed.

This review has not set out to quantify the performance of different retrofits. However, in the process of undertaking the literature review, several papers and reports identified the observed saving achieved by different retrofits. Thus, the summary of performance data is not intended to be authoritative, but is instead intended to be illustrative, since the uncertainty and robustness of each of the papers reviewed is not consistent. Some of the data is based on individual BPE case studies and others on annual gas readings and it may not be appropriate to aggregate the results from projects with different data collection methods as has been done here. In addition to the limitations around performance issues for each retrofit, there are various other confounding variables that need to be considered. These include but are not limited to: additional improvements not reported in the papers, dwelling size, form and orientation, baseline condition of the home, infiltration rate, efficiency of the heating system, uncertainty and accuracy in the measurement method and occupant behaviour (heating hours, set points and comfort taking).

There are often additional benefits to occupants of retrofits not captured in the performance data, specifically enhancements to thermal comfort, reduction in overheating risks, and health and wellbeing [147-149]. It has been noted that improvements in the street scene, as well as a householder's sense of pride in their home and neighbourhood may spur occupants to undertake future retrofit improvements [53].

This section has described the various benefits and risks from different retrofits in the context of UK policy and the whole-house approach. It has identified that performance varies tremendously, and that there are multiple instances where unintended consequences can occur, suggesting a need to move towards a whole-house and in some instances, even an *inter-house* approach. The following section will discuss the models that support retrofits and evaluate their inputs to understand if these can be improved.

3 Retrofit modelling

The Government's Standard Assessment Procedure (SAP) is primarily used to demonstrate regulatory compliance of new build homes. It is also used in a reduced data format (RdSAP) to generate Energy Performance Certificates (EPCs) for existing dwellings and to model retrofit performance. Deemed scores have been developed using RdSAP, on which ECO scores for different retrofits are based. Models which account for dynamic energy flows and the circumstances of specific retrofits may be used to make realistic performance predictions, aid design, and make risk assessments. Domestic retrofit modelling is also used by designers to predict improvements in building performance, evaluate risk and meet regulations. Dynamic models, thermal modelling and hygrothermal simulations can evaluate different types of risk, though these techniques are less commonly used. All these models to some extent rely on default values and conventions, which has an important impact on their accuracy, so validating model inputs is essential to better understand performance and risk.

3.1 Introduction to retrofit modelling

This section will discuss three types of models undertaken to inform and evaluate retrofits.

1) **Whole building modelling** which can be either:
    - Steady-state energy models to evaluate retrofit impact on energy consumption under standardised assumptions (often used in policy making and implementation); or
    - Dynamic simulation models (DSM) designed to investigate complex energy flows, by using at least hourly time steps for specific situations.
2) **Thermal modelling** to calculate thermal bridging and assess surface condensation and mould growth risk at junctions via critical temperature factor evaluation.
3) **Hygrothermal simulations** to evaluate moisture accumulation and mould growth risk via time series analysis of the water content in construction materials.

This review evaluates the literature on each of these retrofit models in turn, to identify where improvements to inputs, practice and interpretation can be made.

All modelling approaches considered in this review can be described as ‘physical law-driven’ models. The review will not attempt to critique the physical law equations and algorithms of the modelling techniques themselves, as significant work has been completed in the past that considers this [150-152]. Calculation methods are based upon well understood physical laws relating to heat transfer and thermodynamics.

To inform whole building models discrete **modelling inputs** are required and these are discussed at the end of the section. First the review introduces how retrofit models are currently used before the more detailed evaluation of the models is provided.

3.1.1 Relationship between models and in-use performance

Building energy models are used to estimate the impact of retrofits on in-use performance and are a vital tool in policy and industry practice. There is however often a difference between predicted and actual performance. This is commonly referred to as a ‘*performance gap*’ [153-155]. This is not always unexpected or a significant problem, however, some retrofit models are used to predict energy savings across the entire UK housing stock, and extrapolating small over-predictions in potential energy savings can become problematic [4, 40, 45, 156]. This is succinctly summarised in the famous aphorism:

> *“all models are wrong; the practical question is how wrong do they have to be to not be useful."* [157]

The *modelling performance gap* is relatively well established and has been observed widely in the non-domestic sector [158-161]. In the field of building performance simulation, how model outputs align with actual performance is commonly referred to as model accuracy [162-167]. Although the performance gap is evident in the domestic sector, domestic retrofit models can be refined to improve the accuracy of post-retrofit energy saving predictions [32, 33, 41, 45, 168]. The situation is similar for models that predict risks in retrofit. However, while improvements can be made, doing so relies on good quality measured inputs, which are not always available. Consequently, a trade-off between model accuracy and the practicality of using defaults must be made.

Steady-state models, and specifically SAP, are the most widely used and best understood whole building models. These steady-state models are commonly used in policy and can draw upon standardised input data. There is a further trade-off between complexity of calculation methods and the amount of time and resource required to complete a calculation, which can ultimately lead to reduced model accuracy. It is, however, possible to reduce performance gaps if default input data are improved and refined. Currently, there is room for improvement in retrofit modelling. Estimates predicted that by 2035, there could be a shortfall of 26% in the energy savings actually achieved through large scale retrofit when compared to what existing models predicted [126]. This shortfall is projected using data from the fifth carbon budget policy projections, adjusted with the in-use factors from the measured data in the National Energy Efficiency Database (NEED). The DEEP project will provide guidance on how to mitigate such a shortfall by investigating input variables that can lead to performance gaps, including: material physical properties, fabric performance, occupancy effects and weather inputs.

3.1.2 How are models used in retrofit policy?

All new homes are required to have an energy calculation using SAP to demonstrate compliance with Part L of the Building Regulations [6, 79]. In the past, SAP has been linked to various policy instruments including Stamp Duty exemption for zero carbon homes and the Green Deal [169]. Most retrofits that are delivered outside of retrofit policy do not need to undertake any modelling to comply with Part L of the UK Building Regulations, although some steady-state U-value calculations can be required and SAP can be used to demonstrate compliance when consequential improvements are considered [6]. However, retrofits delivered via government schemes have historically required modelling to estimate savings. In most cases, these schemes specify the use of RdSAP, which has been developed to model existing buildings quickly and relies on conventions, defaults and a limited amount of data collected about the building being retrofitted [169, 170].

RdSAP is used to predict annual savings achieved by a retrofit, which are used to calculate lifetime savings and the level of funding received. It has most recently been used in ECO, but schemes such as the Feed-in Tariff, the Renewable Heat Incentive and the Green Deal have also required RdSAP calculation outputs to inform financial payback [169].

Currently, PAS 2035 guidance, which ECO-funded projects must comply with, identifies thermal modelling as a critical part of the retrofit approach. It specifies that Retrofit Assessors, Designers and Co-ordinators should be familiar with full SAP, RdSAP or the Passive House Planning Package (PHPP) [25]. Additionally, PAS 2035 identifies the need for modelling of risk-critical features, such as thermal bridges, and the use of CIBSE *Technical Memorandum 59: design methodology for the assessment of overheating risk in homes* (TM59) [171] to assess overheating risk, though it is not clear how widespread their use is. This indicates that in addition to RdSAP or SAP, PHPP, dynamic simulation modelling (DSM), thermal modelling and hygrothermal simulations can all inform retrofits, and these are each discussed in more detail here.

3.2 Whole building modelling

There are two types of whole building energy modelling: 1) Steady-state and 2) Dynamic. These are discussed in this section. Throughout this review, Dynamic Simulation Modelling

(DSM) is referred to. It would be more accurate to describe this modelling technique as ‘Dynamic Thermal Simulation’, but DSM is now in common parlance and has been used here to avoid any confusion. It is important to reiterate here that the underlying physical laws of these models are well understood. The algorithms used in these models rely on established laws of physics and the long-term development history of building energy modelling has been well tracked and documented, back to the development of foundational algorithms [169, 172, 173]. Models can be divided into two broad categories: data-driven models and physical law-driven models [162]. This review considers the inputs and outputs associated with physical law-driven models only.

3.2.1 Steady-state whole building retrofit models

All steady-state models offer the advantage that they are computationally efficient, which means that, once all inputs have been added, the calculations are performed very quickly in comparison with DSM alternatives. Steady-state models can require relatively detailed inputs for building form and fabric, but only use aggregated daily inputs for more stochastic variables such as occupancy and weather, which are difficult and costly to compile [170, 174]. The most commonly used model for predicting the benefits of retrofits in existing buildings is RdSAP, which is primarily used for EPC compliance but has also been used in other government policies such as ECO and the Green Deal [25, 100, 169]. RdSAP relies on the use of default input data, so is not capable of accounting for the idiosyncrasies of specific buildings. It is worth considering that it was not originally intended to be used as a design tool, but rather to predict the indicative performance of existing buildings for EPC compliance.

RdSAP is itself an Appendix to full SAP (Appendix S) and therefore uses the same calculation algorithms as SAP. It is only the range of available inputs that are reduced in RdSAP, relying on standard tables of default values based upon building age and archetype, rather than empirical input data related to specific dwellings [169, 170].

SAP itself was developed from the BRE Domestic Energy Model (BREDEM) in the 1990s [169]. It is not necessary to provide a full history of the development of BREDEM and SAP but a brief history does provide some useful context for the DEEP research project. BREDEM was established as:

> *“…an engineering simulation tool for estimating individual building performance”* [169].

Although SAP is based upon the modelling procedures developed in BREDEM and uses the same algorithms, it was conceived as a national rating scheme to provide a normalised comparison with other buildings, rating their performance against the building stock [169].

Updates to BREDEM were introduced to reduce error and acknowledged the impact of key variables such as seasonal and monthly weather conditions and different heating zones [169]. Efforts have been made to validate BREDEM and SAP model outputs with some success, but these have been criticised for using limited sample sets in terms of numbers and archetype, and not being up to date [169, 175-177].

There is an opportunity in the DEEP project for more robust comparison of the latest version of SAP with detailed *in situ* measurements (SAP 2012 will be used in the first instance, with SAP 10 being used when it becomes available). A timeline charting the development of BREDEM, SAP and RdSAP is shown in Figure 3-1.

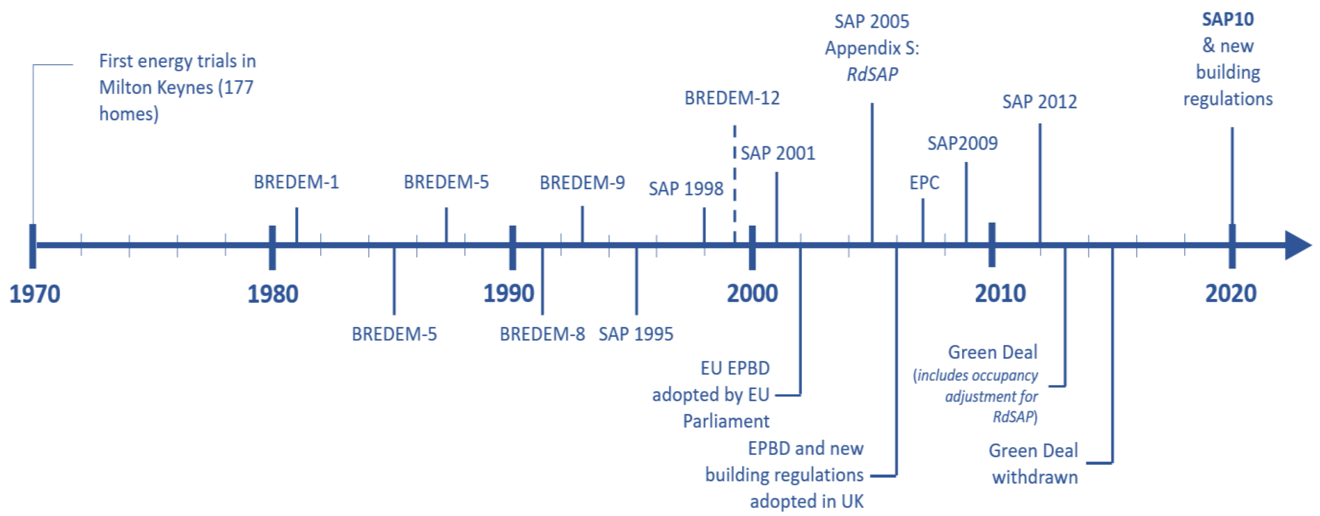

Figure 3-1 Timeline of BREDEM and SAP development (adapted from [169])

Building fabric inputs in RdSAP are based upon the age, size and type of construction of the dwelling, as well as standard occupancy profiles, heating and cooling set points and a central UK weather file [169, 170]. In full SAP, an average UK weather file is used to calculate the EPC and Environmental Impact (EI) rating and Dwelling Emissions Rate (DER).

Standard regional weather files are used to predict energy costs and, since SAP 2012, localised weather data for specific postcodes can be used in this aspect of the calculation [170]. Table 3-1 summarises the differences between SAP and RdSAP.

Table 3-1 Main differences between SAP and RdSAP (adapted from [178])

Input:	SAP (2012)	RdSAP (2012)
Weather data for compliance	UK average	UK average
Weather data for utility costs	Postcode-specific	UK average
Window area	Actual measured area	Estimated by age and floor area or option to enter areas in detail if unusually large or small
U-values	Calculated based upon construction type	Estimated based on construction type and age of dwelling
y-value	Default or calculated	Default 0.15 $W/m^2.K$
Infiltration	Default or calculated	Estimated based on construction type and age of dwelling
Ventilation	Standard schedule, calculated based on openings	Estimated based on age of dwelling

As SAP allows for a certain amount of inputs to be based on assumptions, there can often be a gap between predicted and actual building performance [169]. An alternative steady-state model is available, PHPP, which overcomes some of these issues and doesn’t rely on the same breadth of default inputs. PHPP was developed to demonstrate compliance with the Passivhaus Standard. Because of this, PHPP provides a more accurate appraisal of the efficiency of a specific building and is also cited as an appropriate retrofit design tool in PAS 2035 [25], though it requires a greater knowledge of input data. A simple comparison of the input data for these two steady-state calculation methods is given in Table 3-2.

There is an important difference between the intended purposes of outputs produced using the SAP and PHPP calculation tools: SAP outputs are intended to quantify carbon emissions and energy costs, whereas PHPP outputs quantify energy consumption for space heating and primary energy demand [22]. Essentially, SAP and PHPP calculate annual heat demand based upon very similar physical laws and algorithms. Although the calculation methods are fundamentally similar in terms of building physics, a greater extent of detailed empirical inputs are required for the PHPP method.

There is some evidence that the additional level of detail required for PHPP leads to a reduced gap in fabric performance, with examples of completed Passive House dwellings achieving within 10% of the designed HTC values [154, 179]. However, in many situations the inputs are calculated in the same way as SAP. Therefore, some of the reduction in their performance gap may be because homes built with extra scrutiny are built more carefully, so the U-values in the model may be more likely to be achieved in practice. However, a much larger sample size of both SAP and PHPP-based projects would be required to quantify this.

Table 3-2 Main differences between SAP and PHPP (adapted from [180])

Input:	SAP (2012)	PHPP (v9)
Dimensions	Internal measurements	External measurements
Internal floor area for calculations	Gross internal area	Treated floor area typically 10% less than gross internal floor area
Non-repeating thermal bridging	Calculated values (but default values can be used if necessary)	All thermal bridges must be either calculated or removed from the detailed design
Window U-values	Allows whole window U-value regardless of window dimensions and construction	Each window U-value must be calculated individually
Solar gains	Based on actual window sizes, shading measured in less detail	Each window is separately modelled for solar gain and shading
Internal gains	Standard assumptions and can be 100% higher than PHPP	Assumes best practice in choice of lighting and appliances and efficient occupants
Ventilation and infiltration	Based on air permeability rates	Based on air change rates
Internal temperature	Living room 21°C, other zones vary with efficiency of building fabric (18°C or 19°C)	Fixed at 20°C (can be altered in justified cases when agreed with certifier)

Overheating risk assessment	Mean daily summer temperature calculation and simplified risk level categorisation	Calculates percentage of annual hours that exceed 25°C which must be below 10%
External temperature (compliance)	Average UK data	Location (region) and altitude specific
External temperature (energy consumption/ cost)	Regional or postcode specific data (defined by full or partial postcode)	Location (region) and altitude specific (no cost calculations are included in PHPP)

There is a retrofit-specific standard for Passive House, EnerPHit, which sets more relaxed performance targets than the Passive House standard for new dwellings [22]. However, in contrast to SAP and RdSAP, there is no reduced data version of PHPP and the same calculation method and range of inputs is used for both new build and retrofit projects [181]. Due to the robust understanding of heat exchange that underpins steady-state models, they are useful for predicting heat demand and associated energy costs. As the SAP outputs have been developed to provide a comparison across the UK stock, it is a useful tool to predict heating energy consumption across relatively large samples [169]. However, it is the inputs, fixed to provide this normalised comparison, that can lead to performance gaps for specific dwellings as the idiosyncrasies of the individual buildings are not captured.

This is summarised in Figure 3-2 which compares SAP predictions with measured consumption. While there is relatively good fit of prediction there is a very large range and significant outliers meaning, practically, that SAP cannot accurately predict actual energy use for an individual building but may be useful in estimating average energy use in a population.

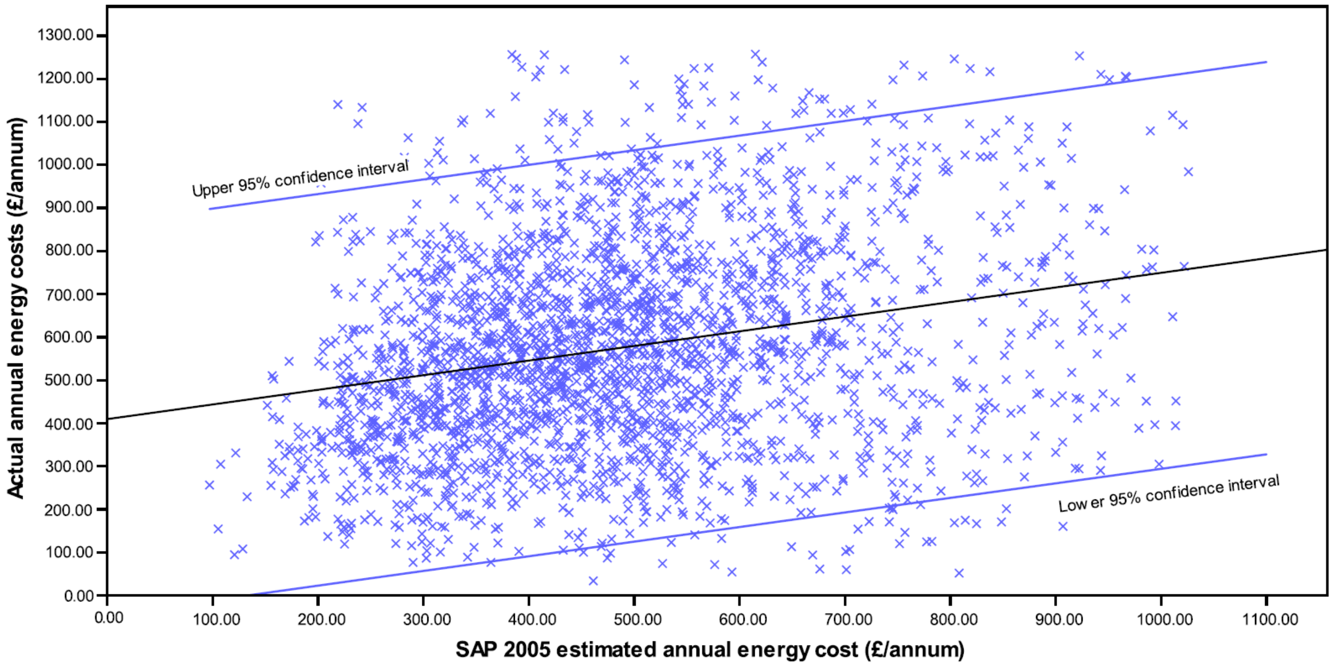

Figure 3-2 Comparison of SAP estimates and actual energy costs (from [169])

Models that allow for the majority of input variables to be adjusted can inherently be more detailed, but this also increases the margin for error [182]. In the context of this review, RdSAP represents the model with the most limited range of inputs. SAP allows for some bespoke inputs to be added and PHPP encourages either measurement or calculation of all key inputs. Beyond steady-state models, some DSM models allow for the vast majority of inputs to be altered at an hourly resolution [183] and these are discussed in the next section.

3.2.2 Dynamic whole building retrofit models

The previous section identified the steady-state models that are commonly used, describing their applications, some of their benefits and some limitations. DSM can offer greater flexibility and precision, and when used correctly, can offer more realistic predictions for retrofit performance [32, 33, 41, 45], especially when calibrated with measured data [162-164, 184].

More detailed DSM methods have been described as complex and resource intensive to produce [25] and there may be a risk that building modellers do not sufficiently understand the fundamental workings of the DSM application they use [182]. This has been suggested as another potential inaccuracy that leads to gaps between modelled and measured performance. This particular piece of research did, however, draw criticism from academics in the field of building simulation [185] and there are numerous examples of how refined models can more accurately predict realistic energy savings following retrofit [32, 33, 41, 45]. Ultimately, as identified by de Wilde [186], a co-ordinated effort and change of industry practice is required to address the range of issues that contribute to the performance gap. Pertinent to DEEP, de Wilde notes that further work is required to validate energy model outputs and to improve the quality of model input data [186].

The use of calibrated models is an established approach that aims to overcome some model inaccuracies, particularly in retrofit projects. As noted above, DSM software applications allow for the majority of variables to be adjusted, so are best suited to this approach, although calibration of steady-state models is possible.

If realistic input data are available, DSM can be particularly useful for whole-house retrofit, since they are capable of modelling the complexities of interacting retrofit measures and dynamic energy flows [37, 45, 154, 168, 187]. DSM methods can be more challenging, time consuming and computationally expensive to undertake than steady-state models, though the data analysis they perform is considerably more complex [25]. This could make it more likely that modellers do not completely understand how the models work. Consequently, more care is needed when interpreting the results of dynamic models [182], though in the field of building simulation practice, the majority of tasks that users are required to complete using DSM are well understood [185]. Having said this, DSM also provides useful compliance functions. For example, undertaking TM59 overheating analysis to comply with PAS 2035 [25, 171], indicates that it could be adopted more widely to provide compliance with energy performance in policy.

Several software applications can be used for DSM, including: Design Builder, which uses the open source building physics engine Energy Plus; Integrated Environmental Solutions Virtual Environment (IES VE); and TRANSYS [150]. Both CIBSE in the UK, and ASHRAE in the USA, independently validate the accuracy of these DSM applications, so their physics engines are not further critiqued here [151, 152]. However, there is scope to further improve the quality of DSM model input data and practice [186], and this is discussed in the following sections.

3.2.3 Calibration for DSM and steady-state whole building models

The need for calibrating models to improve their accuracy has been noted in the previous sections. There is no definitive range of parameters that must be measured when calibrating a model. Any measured or known data that can be input into the model may be used, although the more data included, the more accurate the model will be. Possible refined data inputs include:

- Building fabric in-use performance;
- Whole-house in-use performance (including heating and ventilation);
- Occupancy;
- Internal gains; and
- Weather conditions.

DSM is more commonly used to calibrate whole-house energy models and there are numerous published examples of this practice [33, 45, 153, 166, 168]. As noted earlier in this section, most validations of SAP are based on older versions of the software, although one recent study found that the accuracy could be improved by using measured U-values and airtightness results. This reduced the gap between the modelled and measured HTC reductions achieved by a retrofit from almost 20 W/K to just 3.6 W/K and from 14 W/K to 8 W/K, respectively, in one case study [45]. It is however important to note that this was a detailed study of two dwellings only and not a large sample set.

Thus, a model calibrated on measured fabric performance can be achieved relatively simply, since only a small number of parameters are required. However, calibrating against stochastic parameters, such as occupancy, weather and *in-use* performance is more challenging and require DSM and high quality data [162, 188, 189].

The additional cost and delay needed to calibrate models deters its use, except for research and where ‘investment grade’ decisions are made. DSM has been demonstrated to be highly effective where retrofit measures are multiple and interactive [163, 164, 188, 190], though it tends to be more often used in non-domestic projects.

Calibration techniques have been categorised by Reddy [184] and are defined as:

(a) manual, iterative and pragmatic interventions;
(b) informative graphical comparative displays;
(c) special tests/analytical procedures; and
(d) analytical and mathematical methods.

The most useful of these for evaluating retrofit models are those in category (a).

Although limitations can restrict the accuracy of iterative approaches, the process can be refined [189, 191, 192]. Also, despite manual approaches relying upon the modeller’s knowledge and experience [162, 167, 190], it is possible to structure iterative approaches [162, 163, 167]. An example of this is to plot consumption data against external dry-bulb temperature, creating a calibration signature that can be more easily compared to the modelled outputs [193].

The level of accuracy achieved by the calibration is determined by the quality and quantity of the data used to inform the process. Five levels of increasing accuracy for calibration are presented in Table 3-3. Quality of data is important for accuracy. For example, using a range of high resolution measured data (ideally at an hourly time step), and the actual weather data from the site, are vital when calibrating against in-use metered data [194, 195]. This raises the possibility of using smart meter data in the future to calibrate retrofit models. In an ideal situation, smart meter data could be used to create a *de facto* calibrated model for dwellings as they develop over time, essentially creating a digital twin that could be used in retrofit analysis.

Table 3-3 Calibration levels based on the building information available [167, 184]

Calibration levels:	Utility Bills	As-Built Data	Site Visit / Inspection	Detailed Audit	Short-Term Monitoring	Long-Term Monitoring
Level 1	X	X				
Level 2	X	X	X			
Level 3	X	X	X	X		
Level 4	X	X	X	X	X	
Level 5	X	X	X	X	X	X

A considerable amount of existing research has been aimed to devise robust methods that address uncertainty in model inputs [126, 162, 196-199]. Other work in the field of building simulation has also investigated the uses of probabilistic inputs and outputs [196, 200-203]. These techniques can aid in the calibration of models and, ultimately, improve their overall accuracy. In some cases, dynamic techniques have been developed for instances where reduced or limited data are available for domestic buildings [165]. The application and practicality of these techniques for domestic retrofit modelling will be explored as part of the DEEP project. The rest of this section considers the key model inputs required for retrofit modelling.

In terms of *in situ* measurements and laboratory testing, the main focus of DEEP will be on building fabric performance and how modelling can be used to produce more accurate predictions of post-retrofit performance, as well as mitigate risk and unintended consequences. Measured performance for the broad range of space heating, ventilation and cooling systems that are utilised in domestic properties is therefore beyond the scope of this work.

Many of the modelling methods that can be used in retrofit projects already include extensive databases of either manufacturer's data, or system performance calculated by building services professionals [170, 174, 204, 205]. It is, however, important to define how space heating, cooling and ventilation performance is applied in whole building models, and to consider if there are any implications for dwelling performance following either partial or whole-house retrofit.

Whole building modelling: implications for DEEP

ECO policy relies on RdSAP, a steady-state model used to predict retrofit success. However, the use of RdSAP generally results in reduced model accuracy and gaps between modelled and measured performance. Alternative calibrated steady-state and dynamic whole building models can predict retrofit energy performance with greater accuracy. DEEP will evaluate how RdSAP may be improved by comparing it to alternative static and dynamic models. It will also explore the sensitivity of predicted savings when different input variables are enhanced and make recommendations on default values. It will also investigate how useful and practical different levels of calibration may be for integration into retrofit models used in future policy.

3.2.4 Modelling overheating risks

Space heating accounts for the largest proportion of domestic energy use in the UK [206] and reducing this is the primary focus for energy reduction retrofits. Overheating in dwellings is, however, predicted to become more prevalent as the climate continues to change [207, 208]. This has implications for thermal comfort and the health and wellbeing of occupants [149]. In 2007, a study reported that 21% of bedrooms exceeded 26°C for more than 1% of night-time hours and 47% exceeded 24°C for more than 5% of night-time hours [209].

In 2009, another study found that 27% of living rooms exceeded 28°C for more than 1% of occupied hours and that approximately 20% of bedrooms exceeded 24°C during night-time hours for 30% of the monitoring period [210]. Reducing heat losses by constructing low-energy dwellings has been shown in some instances to unintentionally exacerbate the risk of overheating [211-213], although it is useful to note that the PAS 2035 guidance now recommends that retrofits evaluate overheating risk using the TM59 methodology [25].

Examples of retrofits extending the risk of overheating include summer bypass in MVHR units being under used, larger proportions of glazing being installed and inadequate ventilation being provided post-retrofit [214]. A study of a Passivhaus development in the UK [215] found that a larger percentage of dwellings were considered to overheat when using adaptive comfort criteria designed to rate conditions for vulnerable occupants, as identified in current CIBSE guidance TM52 and, subsequently, TM59 [171, 216]. Although much work has focused on overheating in new build dwellings, there are also examples of overheating in retrofitted dwellings [217, 218].

A meta-analysis of overheating studies found multiple examples of overheating in existing, retrofitted and new build dwellings, with kitchens and bedrooms being found to be at most risk of overheating in the retrofit examples [217]. Overheating was mainly identified in dwellings that had undergone cavity fill insulation retrofit, but also in solid wall dwellings that had been internally and externally insulated. Modelling studies have also shown that retrofitted properties are likely to overheat in future climate scenarios and may require active cooling strategies to mitigate this [218].

Recent research has used a simulation-based approach to parametrise performance of fabric insulation in the context of overheating [219]. This large-scale modelling exercise combined data mining techniques, which were validated against monitored data. This technique was used to evaluate the impact of key variables on overheating, including type of dwelling, orientation, location, insulation, thermal mass, glazing ratio, shading, internal heat gains, window opening, occupancy, infiltration and ventilation. Although fabric insulation can contribute to both increased and decreased overheating, this study noted that it only accounted for 5% of overall overheating when ranked against the other influencing factors noted above [219]. As this study uses examples from different climate zones, location is of course ranked as one of the highest influencing factors, along with ventilation strategy, thermal mass, infiltration and orientation which all have a greater impact than insulation. Shading is ranked below insulation in this study, but only fixed shading is modelled (overhangs and vertical fins) [219]. In fact, this study also shows that in poorly designed dwellings, increased levels of insulation tend to reduce overheating [219]. It is, however, important to note that this work was completed for eight different global locations and the results are aggregated. Further work is therefore required to evaluate how applicable these global results are to the UK.

Various measures are available that can help to avoid or mitigate overheating. These include: internal and external solar shading, increased natural ventilation, night-time purge ventilation, additional mechanical ventilation, and air conditioning [220, 221]. It has been established that external shading, in particular, is very effective in reducing solar gains and that retrofitted solar reflective paint and EWI can also help to mitigate overheating [222]. The effectiveness of these strategies can be modelled using DSM, but this is not a requirement in Building Regulations or ECO. However, it is important to also consider that the accuracy of overheating predictions made via DSM themselves may not be particularly reliable [223].

In current UK Building Regulations, there is a requirement to consider overheating using a relatively simplified method defined in SAP that aims to limit direct solar gains, rather than more sophisticated models that simulate more extreme temperatures at an hourly resolution [79, 224]. The SAP Appendix P method calculates the average internal temperature for the months of June, July and August and ranks overheating risk based upon the resulting mean (>23.5°C is categorised as ‘high risk’, 22 to 23.5°C is ‘medium risk’ and 20.5 to 22°C is a ‘slight risk’).

The PHPP calculation includes a significantly more sophisticated evaluation that estimates the percentage of annual hours that are above 25°C and this must not exceed 10% of the occupied hours. Expertise and increased understanding in the field of thermal comfort has led to the adaptive comfort model being favoured over the threshold exceedance methods in academic work.

The adaptive comfort method is defined for practice in the UK by CIBSE TM52 [216]. Subsequently, the need for a more sophisticated evaluation of overheating has been acknowledged at a policy level [225].

CIBSE has published guidance to simplify the modelling of overheating in dwellings in TM59 [171]. In TM59 two metrics are used to assess whether a dwelling will overheat, the first of which is taken from CIBSE TM52 [216]. The two assessment criteria are defined as follows:

i. For living rooms, kitchens and bedrooms: the number of hours during which the difference in temperature between inside and outside (ΔT) is greater than or equal to one degree (K) during the period May to September inclusive shall not be more than 3 percent of occupied hours (CIBSE TM52 Criterion 1: Hours of exceedance).

ii. For bedrooms only: to guarantee comfort during the sleeping hours the operative temperature in the bedroom from 10pm to 7am shall not exceed 26°C for more than 1% of annual hours (Note: 1% of the annual hours between 22:00 and 07:00 for bedrooms is 32 hours, so 33 or more hours above 26°C will be recorded as a fail).

Modelling overheating risk: implications for DEEP

The risk of homes overheating may increase as a result of retrofit and this is likely to be exacerbated in the future due to climate change. The effectiveness of SAP at evaluating overheating risk will be compared with the PHPP hourly method and DSM analysis (via TM59 and CIBSE’s adaptive comfort method). DEEP will evaluate these methods and explore how sensitive overheating risk is to different variables in retrofit models and will investigate the potential for RdSAP to be updated.

3.2.5 Building fabric in whole building models

Heat loss through the plane elements, thermal bridging and infiltration are the main heat loss pathways in a home and are key inputs to whole building models. This section discusses how these are used in models, including identifying uncertainty or possible improvements.

3.2.5.1 Modelling plane elements: ground floors, thermal bridges and thermal mass

Plane element fabric inputs (floor, roof, wall, windows and doors) have a great impact on model accuracy and are accounted for in models as U-values, which influence heat balance equations [170, 174, 183, 204, 226]. U-values are either entered manually or selected from libraries developed by ASHRAE, BRE or CIBSE depending on which model is used [170, 174, 183, 204, 226]. The suitability of default values in these libraries therefore underpins the accuracy of the model predictions.

While plane elements exposed to air are relatively simple to incorporate in models, ground floor heat loss is more complex, since it is influenced by seasonal ground temperatures and voids under suspended timber floors [118, 121]. Ground floor modelling is often treated very differently in steady-state and dynamic models. In SAP the ground below the building is incorporated within the U-value calculation and no specific ground temperatures are included in heat loss calculations. PHPP, on the other hand, includes an optional additional worksheet that accounts for building geometry and the effect of seasonal heat storage below the ground floor [174]. In some dynamic models, the ground temperature can be set for each month, whilst in others, it is taken from the weather file (which itself can be adjusted). Uncertainty over the accuracy of ground floor heat losses in models could cause uncertainty in the modelled savings predicted for ground floor retrofits.

DSM can account for non-repeating thermal bridging in some models, by allowing specific Psi values at junctions to be added [204] (‘Psi value’ describes the heat flow through a junction as a function of temperature difference and is quantified using W/m·K). Bridging can only be included in other DSM models using an overall y-value, which is used to adjust the elemental U-values, though there are less commonly used methods.

Appendix K in SAP 2012 includes an updated list of default Psi values and also allows bespoke Psi calculation values to be added, which are then aggregated and included in the overall heat transfer coefficient of the building fabric [170]. If no junction details are available, then a default y-value of 0.15 W/m^{2}·K is used to account for non-repeating thermal bridges. PHPP requires Psi value inputs to be modelled for each junction [170, 174]. How these different approaches affect the accuracy of models has not been conclusively quantified, neither has the impact of default y-values been evaluated definitively [227].

An additional complication relating to plane element heat loss is thermal mass, which can be accounted for in DSM by assigning construction layers to each element. This allows more complex heat storage to be considered in total energy consumption and surface temperatures to be considered in thermal comfort analysis [204, 226]. SAP models do not account for these differences through the constructions, although adjustments are included in the calculation to account for overall thermal mass [228].

3.2.5.2 Airtightness and infiltration

Infiltration rates in models have been demonstrated to have a large effect on model predictions [45, 182, 187, 229]. This is especially important in the context of RdSAP, which includes default air permeability rates that cannot be altered, thus contributing towards the prediction gap. Where existing infiltration rates account for a large amount of heat loss, this limits the impact that insulation could have on overall energy savings [170].

Additionally, where airtightness is measured onsite, it is important to understand if this is infiltration to the outside or to neighbours, otherwise the value inputted in models may be overestimated [45, 230]. As SAP uses air permeability inputs, background ventilation rates are approximated from the air pressurisation test results using the $n_{50}/20$ rule [231]. As air pressurisation tests use an elevated pressure of 50 Pa, the $n_{50}/20$ rule is used to estimate what the background ventilation is under perceived normal conditions. The $n_{50}/20$ rule uses a correction factor for local shelter and the SAP 2012 methodology adheres to this approach.

Local environmental conditions during the time of each air pressurisation test dictate the level of associated uncertainty, which is normally less than 10% [232]. However, the relevance of the $n_{50}/20$ rule has been brought into question, especially in relation to the UK housing stock [233]. Inaccurate infiltration rates have been shown to have a large influence on space heating demand, in both models and practice [45, 168, 187, 229]. Measured air change rates taken from pressurisation test results can however be used in alternative models, including PHPP and most DSM software.

It is of particular note that SAP air permeability inputs can be acquired using either a pressurisation or depressurisation test, whereas PHPP uses an average of these two tests to define a holistic air change rate at 50 Pascals [234].

Building fabric in whole building modelling: implications for DEEP

Default elemental U-values, y-values and Psi values and infiltration assumptions included in SAP, PHPP and DSM have a large influence on modelled performance and validating these is imperative to give confidence that this aspect of the whole building model is robust. It is not known how sensitive thermal bridging values are to changes when the fabric plane element is retrofitted. This will be investigated in DEEP, in addition to how infiltration is applied in models and the degree to which infiltration undermines predicted savings.

3.2.6 Weather files used in models

Building in colder locations is likely to lead to higher space heating bills, thus the weather data used in models will affect predictions of retrofit savings. Both steady state and DSM models have their own type of weather file. Static calculations most often use daily averages for different seasons or months, whereas DSM calculations most often use hourly building weather files [151, 170, 171, 174, 204]. The accuracy and appropriateness of weather data has been shown to lead to gaps between modelled and measured performance, especially when associated with localised micro-climates, e.g. urban heat islands [153, 235-237].

Weather conditions differ between regions and have even been shown to differ enough within regions to have a significant impact on building energy and thermal performance [236, 237]. For example, differences in elevation, aspect, eastings, northings, urbanisation and distance from the coast shows that moving the proposed site of buildings relatively short distances can sometimes have a considerable impact on the predicted energy performance [238].

Both SAP and RdSAP use average UK weather data to calculate the Environmental Impact (EI) ratings, and the Dwelling Emissions Rate (DER) [169, 170]. This allows for a comparison of dwelling performance, regardless of location. In order to provide a localised prediction of energy costs, average regional weather conditions from 21 different regions across the UK can be used in both methods [170]. A similar process is also contained in PHPP [174].

These can be refined further in SAP 2012, if the specific postcode is known, providing the option to use specific weather data for 3,014 different UK locations. Importantly, these locations are not used in RdSAP, (though they could be with a very minor change to the input) meaning retrofit evaluations are using less specific weather data that will provide less accurate predictions. In contrast to SAP, the PHPP calculation method allows the user to input location specific weather files [174]. For illustrative purposes, the difference in regional UK climatic conditions is presented in

Figure 3-3. It is clear from this figure that a significant difference in average daily air temperature is experienced across the UK throughout the year.

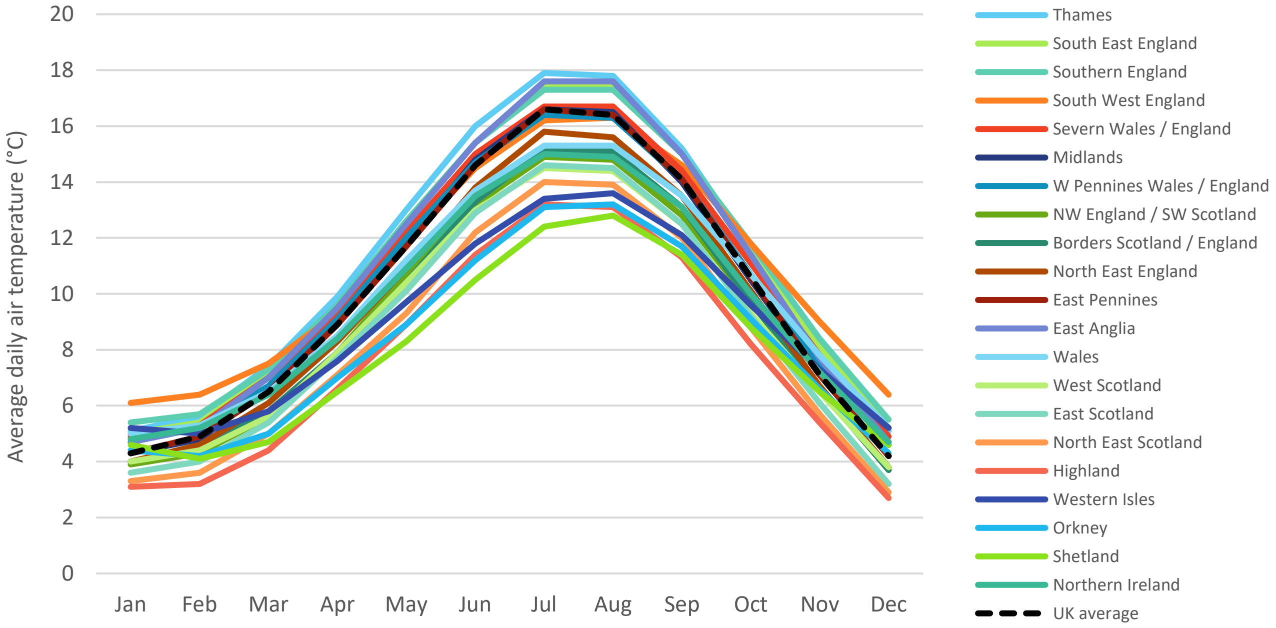

Figure 3-3 Daily average monthly air temperature for the 21 UK regions used in SAP and RdSAP [99]

3.2.6.1 Annual weather conditions

As they are steady-state calculation methods, both SAP and PHPP use daily average temperatures for each month of the year as part of their heat balance equations [170, 174]. In addition, the average wind speed and solar radiation on a horizontal plane used in SAP are mean values from data collected by the UK Met Office over a 19-year period (1987-2006) [170]. As this data is almost 15 years old, it may require updating to represent recent warming of the climate. This is particularly relevant, especially given that 2015, 2016, 2017 and 2018 have been the warmest years on record, and that the 2001-2010 decade was 0.21°C warmer than the previous 1991-2000 decade [239]. With respect to PHPP, the weather data used is taken from Meteonorm V6 [174].

Various sources of weather data are available globally. The Met Office provides a robust and extensive range of land and surface observation data for the UK, from the year 1853 to the present day, through its Met Office Integrated Data Archive System (MIDAS) [240]. In addition, MIDAS also provides daily and hourly weather measurements for parameters including wind (speed and direction), air temperatures, soil temperatures, sunshine duration and radiation measurements and rainfall [240]. This data can be used to compile suitable inputs for SAP and PHPP, though not RdSAP (at least in its current restricted data set form).

Whilst daily average values can be useful in estimating energy performance for monthly or annual calculations, they are not able to simulate the extreme conditions relevant to peak loads and thermal comfort, and in particular investigate overheating [225]. DSM uses building simulation weather data at an hourly time step and typically includes similar data for the parameters noted in Table 3-4, which compares steady-state and dynamic weather inputs.

Table 3-4 Weather data parameters for different modelling techniques

Weather parameter	Steady-state – daily mean	Dynamic – hourly
Dry bulb temperature	Degrees Celsius	Degrees Celsius
Wet bulb temperature	N/A	Degrees Celsius
Atmospheric pressure	N/A	Hectopascal
Global solar irradiation	Watts per square metre	Watts per square metre
Diffuse solar irradiation	N/A	Watts per square metre
Cloud cover	N/A	Oktas
Wind speed	Metres per second	Metres per second
Wind direction	N/A	Degrees clockwise from North

Other weather files are available for the UK through the Prometheus Project at the University of Exeter, which also uses Met Office data [236]. Providers such as ASHRAE, Whitebox Technologies and Energy Plus use data from the International Weather for Energy Calculation (IWEC) via the National Centres for Environmental Information in the USA (formerly the National Climatic Data Centre) [241-244]. Thus, there are many sources of weather data that can be used in retrofit modelling, though there has been little work previously to attempt to quantify the impact each source is likely to have on predictions.

In DSM, CIBSE’s Test Reference Year (TRY) files are often used, which represent a typical year, and are compiled using average months selected from a historical baseline period (1984-2013) [245]. While using average conditions is useful for predicting typical energy savings, another type of weather file is needed to predict overheating risk: the Design Summer Year (DSY) files. This is discussed in the next section. These file types are approved for non-domestic compliance modelling in the UK [224].

3.2.6.2 Summer weather conditions and overheating

Like the TRY files, the DSY files are based upon historic datasets (1984 to 2013) from which three different files are produced that can be used in DSM:

- DSY 1 – a moderately warm summer;

- DSY 2 – a short intense warm spell (heatwave); and
- DSY 3 – designed to represent a long, less intense warm spell [245].

Modelling of overheating has improved over recent years and DSY files are used in Building Regulations to predict overheating of non-domestic buildings. To meet Building Regulations, potential overheating for dwellings is assessed using SAP, although the calculation does not consider any extreme scenarios such as heatwave conditions or high internal gains coinciding with high temperatures [225]. For retrofits, no overheating assessment is performed in RdSAP, although PAS 2035 requires that overheating is evaluated via TM59 [25].

This could be seen as a little inconsistent as the guidance requires steady state models to be used in the energy calculations but then specifies the use of DSM to evaluate overheating using DSY files [171]. It may be more efficient to produce a single DSM model for all these purposes.

In addition to using the current DSY files, overheating can also be evaluated for future climate scenarios using CIBSE's morphed weather files [246]. Probabilistic files are available for low, medium and high emission scenarios for the 2020s, 2050s and 2080s [246]. Currently, TM59 specifies that the high emission scenario files for 2020 are used in overheating analysis as these best reflect current climate conditions [171]. This is the only formal requirement to use any of the future climate scenario weather files. Another example of variation to the standard approach is that, given the impact of urban heat islands on overheating, Central London has a specific DSY for use in overheating assessment [247]. Although bespoke weather data is not yet available, there is also growing evidence of the urban heat island phenomenon in other UK cities [248].

Weather files used in models: implications for DEEP

Weather affects the savings achieved by retrofits and has been shown to vary considerably within regions based on a range of factors. Despite this, steady state retrofit models do not take advantage of the wealth of weather data that exists. DSM models use hourly time step data, resulting in better predictions of retrofit performance and more realistic evaluation of overheating during extremely hot periods. Currently, the significance of how local weather data is used and its time resolution on the accuracy of domestic retrofits has not been well explored and there may be an opportunity to improve the accuracy of predictions by altering how weather is considered. The DEEP project will evaluate how steady-state and dynamic weather inputs affect model accuracy.

3.2.7 Occupancy and Internal Gains

Building occupants have a direct impact on energy performance, contributing to internal heat gains through the use of heating, lighting, appliances, cooking and controlling space heating and ventilation [43].

In domestic retrofit modelling, work has shown that occupant behaviour in dwellings differs to that which is assumed in RdSAP, identifying external temperature and space heating hours as being those factors that are responsible for the biggest difference between modelled and actual energy use [249]. Furthermore, the importance of occupancy patterns and occupant behaviour has been emphasised in recent years through the IEA Annex 66: Definition and Simulation of Occupant Behaviour in Buildings [250]. The preceding Annex 53: Total Energy

Use in Buildings, had already identified occupant behaviour as one of the key influences on building energy performance along with climate, building envelope, building services, indoor design criteria, and operation and maintenance [251].

Occupancy patterns and occupant behaviour are even more critical to energy and thermal performance in models that include occupancy-based controls [252, 253]. Thus, occupancy modelling can be highly complex, but for it to be useful to designers and engineers, there is a trade-off between practicality and accuracy [254]. Modelling approaches associated with occupancy can consider temporal, spatial and occupancy resolution [255]. The following sections explore this in more detail for retrofit modelling.

3.2.7.1 Occupancy modelling approaches

There are significant differences between how occupancy can be represented in static models and DSM. Guidance for SAP explicitly states that:

> *"The occupancy assumed for SAP calculations is not suitable for design purposes…"* [170].

Static models account for occupants at a daily resolution [170, 174]. The metabolic gains from occupancy are typically represented as a heat gain, using either Watts per square metre or Watts per person unit, depending on the calculation method used [170, 174, 224]. DSM calculations use deterministic profiles that control the density of occupants within a space using an hourly factor. How occupancy is captured in retrofit models is determined by particular software, for instance, steady state models such as SAP use fixed heat gain values to represent the presence of occupants whilst DSM software use dynamic heat gain inputs that follow hourly schedules [256]. However, comparisons of how limitations in software affect the accuracy of occupant influence in retrofit models is not well understood. Although SAP does not include hourly data, domestic occupancy profiles are included in the National Calculation Method (NCM). The NCM underpins the Standard Building Energy Model (SBEM) calculations that are used to demonstrate compliance with Part L of the UK Building Regulations and are used for Energy Performance Certificates for non-domestic buildings [257, 258].

Recent publications have summarised approaches to modelling occupancy [252, 254, 256, 259-261]. More complex methods aim to model the stochastic behaviour of occupants and are often used for scenarios where there are multiple opportunities for adaptive behaviour through interaction with specific control mechanisms (e.g. window opening). Examples of such methods are for instance Bernoulli processes, Markov chains and Survival analysis, which have all been used to mimic stochastic behaviours [254]. Co-simulation can also be used to couple different simulation tools and offers a robust means of integrating this level of complexity into DSM tools [261]. Co-simulation simply means combining modelling approaches, for example a complex, stochastic model of occupancy could be developed in Matlab and then coupled with Energy Plus (which cannot inherently include this type of stochastic model using its existing features). The extent to which these sophisticated approaches affect retrofit modelling is not known. Occupancy assumptions within the steady-state models used in retrofit are relatively unsophisticated and it would be very difficult, if not impossible, to enable a representative range of occupancy profiles to be incorporated [25]. Table 3-5 outlines how different models may consider occupancy.

Table 3-5 Types of occupancy model

Category:	Description:	Used for:

Building level	Number of occupants in a building at a given time	Static models, e.g. total gains per day: SAP/PHPP
Space level & occupied status	Presence of occupants at a particular time	Dynamic models, e.g. hourly time steps, W/m^2 input
Space level and number of occupants	Number of occupants in a space at a given time	Dynamic models, e.g. hourly time steps, W per person input
Occupant level	Detailed tracking of specific individuals	Advanced modelling techniques, e.g. co-simulation

3.2.7.2 Modelling internal gains from occupancy

Metabolic gains from occupancy, equipment and lighting are defined in Watts (W), as either an absolute number or are unitised per square metre [170, 174, 204, 224]. For all these approaches, the number or density of occupants is linked to the internal heat gains. In SAP and PHPP, the number of occupants is based upon the floor area of the dwelling, but there is a limited maximum number of occupants in larger dwellings, which is the equivalent of 3.2 people in total [170, 174].

The number of occupants included in SAP was reviewed in 2008 to account for variances in large homes. This review revised numbers for very large homes but also suggested that the updated values for SAP are aligned with the average household occupancy data recorded in the English House Condition Surveys [262]. The instantaneous heat emitted by an adult is assumed as being 100W in SAP and this broadly aligns with the generally accepted rate [174, 205, 263]. This value is however arbitrarily reduced to 60W to account for the fact that occupants will not be at home for some of the time and that some occupants (children for example) will emit less heat, and 50W when calculating heat demand in new dwellings [263]. The implications of this assumption on retrofit model outputs have not been fully explored.

Assumptions are made in SAP around the total energy consumed through lighting appliances which are based on various sources, including the Energy Follow-Up Survey (EFUS) [263]. The input values in SAP for lighting and equipment are calculated using an annual electricity consumption figure taken from EFUS, which is then divided into end uses based on the aggregation of other data sources [263].

It has been noted previously that SAP includes higher internal heat gains than those found in PHPP [169, 180, 264]. Thus, directly comparing internal heat gain values is not simple as they depend on other factors such as occupancy levels and total floor areas, and so there is a need to explore how changing internal gains affects the outcome of retrofit modelling.

Potential sources of data for internal heat gains include: SAP, PHPP, CIBSE Guide A: Environmental Design, CIBSE TM59, and EFUS 2011 [170, 171, 174, 205]. There is no fixed occupancy schedule as such in SAP. Instead, it assumes a heating season (September to April) of 68 weekend days with 16 hours of heating and 170 weekdays with 14 hours of heating (two 7 hour heating periods with 8 hours of no heating), but not at any set times as these have no relevance when calculating a daily heat balance [170].

Data sources such as the EFUS report can be used to define hourly occupancy schedules, which will be relevant at a daily scale but will also have inter-seasonal implications, such as reduced demand for lighting in the summer months, as is already accounted for in steady-state models.

Occupancy and internal heat gains: implications for DEEP

Occupants play a crucial role in the energy performance of buildings, though the way in which their impact is modelled varies and is subject to a range of limitations. This means that RdSAP may over or underestimate retrofit savings. This is problematic for policy makers who rely on EPCs, and for householders who may expect a particular level of performance improvement. DEEP will perform a sensitivity analysis comparing the impact of competing approaches to, and default assumptions for, occupant behaviour. This will provide recommendations, specifically around the way internal gains are allocated, and how the sensitivity of predicted savings to a range of occupant types may be captured in policy.

3.3 Elemental Modelling

The previous section has discussed whole building models used to calculate energy requirements of homes and predict energy savings that may be made by retrofits. This section considers elemental modelling that is used to determine the thermal and hygrothermal behaviour of individual building elements and the junctions between them using numerical modelling techniques. Elemental modelling will be used to predict changes in the thermal and hygrothermal behaviour of elements and assess risks associated to the retrofits. Firstly, the quantification of U-values is outlined. Secondly, the models used to quantify thermal bridging are discussed. Thirdly, the approaches used to evaluate hygrothermal behaviour are reviewed. Finally, a detailed discussion is presented on how material properties data are often used in these elemental models for the assessment of retrofits.

3.3.1 U-values

A U-value is the thermal transmittance of a plane element of a building, such as a wall, floor or roof. Expressed in $W/m^2 \cdot K$, direct *in situ* measurements of U-values can be used in models to predict retrofit performance. However, in most cases this data is not available and so a calculated U-value is used, derived via one of the following methods:

i. *Simplified methods* rely on calculations (including calculation tools) using the method in BS EN ISO 6946 [265]. Ground floors must include treatment at the perimeters of the floor and heat transfer into the ground, so should follow BS EN ISO 13370 [266]. Methods for windows and doors are outlined in BS EN ISO 10077 [267].

ii. *Numerical methods* use computer models capable of simulating multi-dimensional heat flow through a building element. This is particularly useful where a plane element features a complicated build-up with inhomogeneous layers and repeating thermal bridges. Numerical methods are relatively expensive since they require computer software compliant with BS EN ISO 10211-2007 [267], together with specialist expertise in operating the software and interpreting the results.

Both approaches require accurate characteristics of the building elements to be known including thicknesses of layers within a build-up and the size and spacing of any repeating thermal bridges (e.g. timber studs etc.). Accurate material properties are also important, for thermal conductivity of materials (λ-values) or thermal resistances of layers (R-value). Thus, a possible source of error in retrofit models is inaccurate input data when calculating U-values.

Simplified methods are used in SAP for new homes, however, for retrofits, RdSAP simplifies this further since the properties of the building fabric may not be known. It provides a set of U-values based on characteristics of the building and its age band, which are published in Appendix S of SAP in Tables S6 through to S12 [228]. Clearly, this introduces a large element of uncertainty over the fabric efficiency, potentially undermining the predicted retrofit savings for individual houses. These may need investigating further to improve retrofit modelling. For instance, insulated U-values have been observed to be generally higher (worse performing) than their associated default in RdSAP, meaning modelled savings may be underestimates [268-270].

Furthermore, the uninsulated U-values have recently been measured to be lower on average than previously understood [249], particularly for solid walls but also for cavity walls, further reducing potential savings.

In solid walls particularly, core drilling has identified small air cavities of 5 to 10mm between the sides of adjacent stretchers [269]. Therefore, uncertainty of the makeup of the inhomogeneous fabric is another source of error in retrofit models, specifically for solid walls, though the same may be found for cavity walls whose cavities are significantly obstructed by mortar snots, for example [271].

Additionally, a lack of material data specifically for various types of stone and other heritage materials is common [271]. Table 3-6 provides a list of the possible methods for obtaining U-values that modellers could select when undertaking assessments of the thermal performance, energy use, and carbon dioxide emissions of buildings.

Table 3-6 Sources of U-values

Source	Description
SAP 2012 Appendix S	In RdSAP, unless a U-value is known for a building element, a default value can be taken from Table S6 in SAP Appendix S, selected by element characteristics and age of the element.
CIBSE guide A	Tables 3.48 - 3.54 give U-values and other properties of typical constructions, listing properties against typical element build ups.
Manufacturer	Some manufacturers provide U-values for building elements using their products. In retrofit scenarios, an example of a typical retrofitted element will be given. Calculations must conform to the relevant standards.
Calculated	SAP 2012 requires that a calculated U-value be used for opaque building elements. Calculations must conform to the relevant standards. PHPP includes its own U-value calculator.

It has been suggested that adopting median values for assumed U-values in RdSAP, derived from in situ measured building elements, may lead to EPCs that are more representative of actual building performance [268]. This suggests that more data is needed on the performance of a greater variety of wall types to inform default U-values in retrofit modelling.

Field data, including brick density, moisture content and the presence of a small cavity between stretchers in brickwork, have been collected for a range of walls and used to inform hygrothermal simulations. This has had some success in resolving the discrepancy between calculated and in situ measured U-values [269]. Similarly, data on the moisture content of walls have been used again, with some success in hygrothermal simulation, to improve the accuracy of U-value calculations [272]. Thus, variation in the hygrothermal condition and material properties of walls also introduce uncertainty into retrofit models.

U Values: implications for DEEP

Retrofit models which predict thermal performance tend to use default U-values. These may not be appropriate since they may rely on assumptions around construction properties (wall thickness, type of brick or stone, age of property, etc). Field measurements can be used to improve the accuracy of models. However, it is highly unlikely this can be done in most situations. It may therefore be possible to have a wider range of defaults to represent a wider set of circumstances for modellers to choose from.

3.3.2 Thermal bridging

Thermal bridges occur at junctions between elements or where there are changes to the composition of the fabric and are caused by either *constructional* or *geometric effects* [273]. A change in the thickness of layers within a building element, and the full or partial penetration of an insulation layer with a material of different thermal conductivity are constructional effects [274].

A difference between internal and external surface area of the building envelope or the positioning of an insulation layer are examples of geometric effects [274]. This section explores how these are accounted for in models. This is particularly important since as the building fabric thermal performance improves as the dwellings are retrofitted, the influence of thermal bridging increases, as it will represent a greater proportion of overall heat loss [275].

3.3.2.1 Current use in models

Thermal bridges can be classified into two main categories:

i. **Repeating thermal bridges** are caused by features that occur at regularly spaced intervals within the building fabric [276]. Typical examples include studwork in framed construction and wall ties or mechanical fixings that penetrate an insulation layer. Repeating thermal bridges can have a significant effect on heat loss and consequently BS EN ISO 6946 [265] requires that they be taken into account in the calculation of plane element U-values.

ii. **Non-repeating thermal bridges** are intermittent and occur at junctions between plane elements, or at isolated points caused by anomalies in the thermal envelope [277] (ref). These discontinuities may be a result of the construction method used or because of individual design features. Typical examples include the junctions between the main elements of the external envelope (floors, walls and roofs), around windows, doors and rooflights, around loft hatches, where internal walls penetrate the thermal envelope, and where steelwork is used to support other elements of structure and it penetrates an insulation layer. Non-repeating thermal bridges should be assessed using numerical modelling software [252]. As mentioned, the value for non-repeating linear thermal bridging is a Ψ-value (psi-value) given in units of Watts per metre length for each Kelvin difference between the internal and external temperatures (W/m·K). The value for non-repeating point thermal bridging is the χ-value (chi-value) expressed in Watts per Kelvin temperature difference. Non-repeating point thermal bridges are ignored by SAP [278].

Numerical modelling of thermal bridging should be carried out in accordance with BS EN ISO 10211 using a numerical modelling software program that is validated using examples contained in the standard [273]. BR 497 provides guidance for the application of BS EN ISO 10211 and forms the basis of thermal bridging calculations in the UK [279].

The heat loss attributed to all non-repeating thermal bridges in a building (H_{TB}) can be calculated by multiplying the Ψ-value for each thermal bridge by the length over which the bridge applies and summing the resulting value for each thermal bridge to give the H_{TB} for the whole building. The H_{TB} is added to the sum of the heat loss attributed to the plane elements (sum of area multiplied by U-value for all elements) to calculate the heat transmission coefficient (H) of the building, which represents the total fabric heat loss in Watts per Kelvin temperature difference.

Carrying out numerical modelling of thermal bridging can be an onerous task requiring specialist knowledge of heat transfer, as well as the skills to use an appropriate software program [280]. A simpler route to assessing thermal bridging in a building is to use default Ψ-values. Default Ψ-values can be obtained from Table K1 of SAP 2012 [170]. Alternatively, improved Ψ-values can be used if Approved Design Details are used in the building design and construction. One source of Approved Design Details is the Accredited Construction Details for Part L of the Building Regulations [281]. A combination of calculated Ψ-values and Default/Approved Ψ-values can be used when calculating a building's H_{TB}. It should be noted that SAP 10 intends to remove the Approved ψ-values [282].

If the H_{TB} is not calculated for a building using calculated or Default Ψ-values, the H_{TB} can be calculated using the default y-value of 0.15 W/m^2K. The y-value is multiplied by the total surface heat loss area to give the building H_{TB}. For new build, if the Default values from SAP Table K1 or a y-value of 0.15 W/m^2K is used, then the notional dwelling values used elsewhere would need to be significantly improved to achieve Building Regulations compliance. It is proposed for SAP 10 to increase the Default y-value to 0.20 Wm^2K [282].

Numerical modelling of thermal bridging can also be used to assess the risk of surface condensation formation and mould growth, which can lead to health problems for occupants and damage to the surface finishes within a building. This is done by converting the predicted internal surface temperature adjacent to a thermal bridge into a temperature factor (f_{Rsi}) and comparing it with a critical temperature factor (f_{CRsi}) set for a use type. A critical temperature factor of 0.75 is set to avoid mould growth in UK domestic buildings and temperature factors must equal or exceed this value [283].

Table 3-7 shows a list of possible options for accounting for thermal bridging in models and how these differ.

Table 3-7 Sources of thermal bridging values

	Comments
Calculated	This is the preferred method of determining Ψ-values; calculations are carried out in accordance with BS EN ISO 10211 using guidance contained in BR 497.

Approved Construction Details	This method allows pre-modelled junction Ψ-values to be used, if the junction detail is adopted within the design.
BS EN ISO 14683:2017	This British Standard gives a simplified method of calculating Ψ-values without numerical simulation, it also provides a range of typical junction configurations along with Ψ-values.
SAP 2012, Appendix K	Specifies a default y-value and Appendix K Table K1 gives a list of generic Ψ-values that can be used to calculate a building's H_{TB}.
RdSAP Table S13	Table S13 in Appendix S of SAP 2012 can be used to determine a default y-value, based on building age band and type.

3.3.2.2 Issues with existing approaches

A number of shortcomings in the way thermal bridging is currently handled in SAP 2012 have been highlighted [227, 284]; SAP is the primary method of assessing the energy efficiency of dwellings in the UK. The convention for using a y-value of 0.15 W/m^2K for new builds is based on assumptions of typical junction lengths and Ψ-values for typical bridges. Inevitably this value is likely to be unrepresentative of a building's H_{TB}.

Accredited Construction Details for a limited range of construction types were originally created in 2002 and made publicly available [281], though these are now out of date. Their associated ψ-values are unsuitable for current constructions, particularly as plane element U-values are lower than in the detailed designs assessed in 2002.

RdSAP's approach is based on average thermal bridging values for dwellings by age band and does not account for differing construction types and variation in detailing. Although the default values are based on the state of knowledge at the time of development, their continued use will frustrate design decisions needed to achieve the sort of energy improvements that are required.

3.3.2.3 General solutions to issues

BRE Consultation Paper 06 [285] suggests more pessimistic y-values and default Ψ-values should be used in upcoming versions of SAP and RdSAP. This would encourage numerical modelling of thermal bridging or the use of pre-assessed details in building designs. Catalogues of patterns that offer solutions for set configurations of specific construction types are limited in coverage by their nature [280]. It has been suggested by the Zero Carbon Hub [286] that a publicly accessible database should be established to provide best practice patterns for the main building fabric junctions using current construction methods. If set up, this could be expanded to include retrofit solutions.

An alternative technique is to use for as-built construction is Quantitative Infrared Thermography to assess thermal bridges *in situ*. This technique has the potential to enable thermal bridging to be assessed where the internal layers of a wall are unknown, which can hamper numerical modelling of an existing building's fabric [287]. The technique is also capable of assessing complex thermal bridging where multiple thermal bridges interact and laboratory tests have shown that the technique is capable of giving results in good agreement with a hot box experiment [71]. This technique is potentially useful for retrofits where it is more difficult to determine Ψ-values due to the lack of enough information and the construction.

Thermal bridging: implications for DEEP

Thermal bridging is especially important for retrofit models, since as the thermal performance of fabric elements improves post retrofit, the relative proportion of heat loss via bridging increases. Retrofit models use default data for the level of bridging heat loss that may occur pre- and post-retrofit. However, little has been done to understand the appropriateness of these assumptions under different circumstances. DEEP will undertake modelling of thermal bridging to conduct a sensitivity analysis to evaluate the different approaches in capturing bridging. It will also use case study retrofits to measure the change in thermal bridging heat loss attributable to different fabric improvements and retrofit standards.

3.3.3 Hygrothermal Behaviour

Hygrothermal behaviour of building fabric is evaluated to ascertain the influence of moisture. Two approaches are generally used:

1) *Dynamic numerical simulation,* and
2) *Glaser method*.

These can be used to enable the evaluation of existing construction and the effect of interventions.

Dynamic numerical simulation evaluates building fabric over a specific period when exposed to simulated weather conditions. This is especially important for retrofits since this will investigate any unintended consequences that may manifest during the serviceable life. An example of this is shown in Figure 3-4 where moisture content is predicted to increase following an IWI retrofit and to a lesser extent increase following thin internal wall insulation (TIWI) retrofits.

Generally, one-dimensional simulations are undertaken over three years, however, if moisture content has not reached dynamic equilibrium during this period then simulations may be extended. Dynamic numerical simulation of the hygrothermal performance of building fabric offers a method of assessing moisture-related risks that account for both vapour and liquid transport mechanisms.

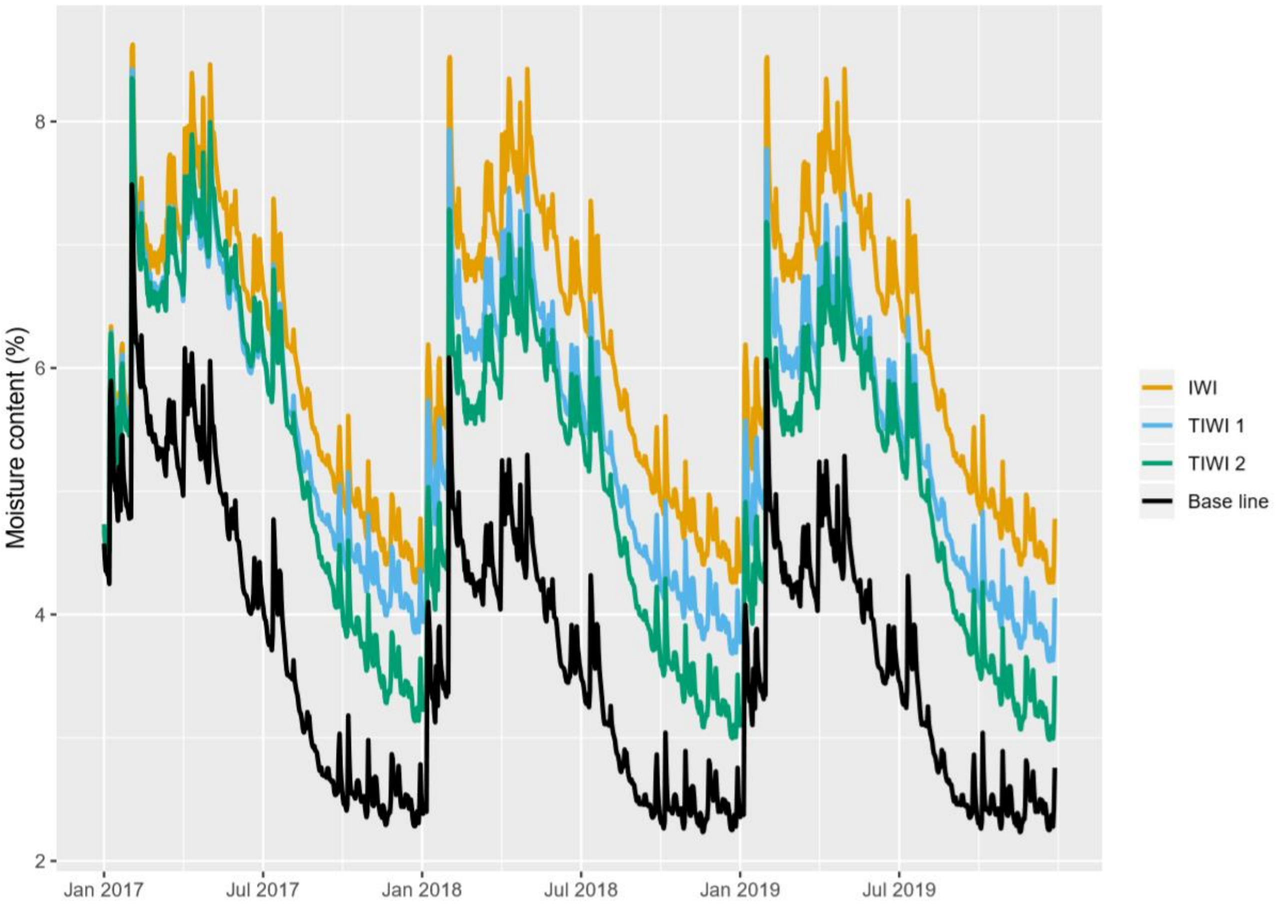

Figure 3-4 Moisture accumulation in a solid wall increases following the application of internal insulation (IWI) and two types of thin IWI (TIWI) [27]

BS EN ISO 15026 [288] lays out the methodology for assessing hygrothermal risks in building fabric using one-dimensional numerical modelling software. Hygrothermal simulation software allows for a variety of moisture transport mechanisms to be modelled over time and for variation in the internal and external conditions to be accounted for [288].

One-dimensional hygrothermal simulations should only be applied to plane elements of building fabric that do not feature any two-dimensional effects caused by discontinuities. Two-dimensional simulations can be used at junctions to understand hygrothermal behaviour where two fabric elements interact. However, these simulations are complex and rarely undertaken despite the risk that these situations present.

Some projects have adopted one-dimensional simulations to evaluate the impact of retrofits, and it has been identified that applying between 70mm and 150mm of foam IWI to solid walls can cause moisture accumulation in brick walls to increase compared to the uninsulated condition, especially in the inner leaf, causing increased time that timbers within these walls may be exposed to conditions where timber rot may occur post-retrofit [289, 290].

Installing breathable insulation retrofit options or insulation of lower thermal resistance, e.g. thin internal wall insulation (TIWI) have been predicted to reduce this moisture accumulation risk compared to non-breathable alternatives [289, 291]. Similar evaluations for other retrofit scenarios are less common in the literature; DEEP will provide hygrothermal simulations on a range of retrofit options and will therefore be a substantial contribution to knowledge in this area and additionally provide data which compares model results against measured effects in field trials.

The Glaser method identifies if there may be condensation risk by calculating a change in building temperature and vapour pressure through the building fabric (i.e. where the dew point and temperature profile intersect). The Glaser method outlined in BS EN ISO 13788 for condensation risk analysis of lightweight constructions assumes that moisture transfer within a building element occurs only as a result of water vapour diffusion through the fabric [292]. The simplicity of the Glaser method makes it inaccurate as it does not account for changes of material properties due to varying moisture content, moisture transport by means other than vapour diffusion and the dynamic changes over time of the internal and external boundary conditions [205].

In most retrofits, no evaluation of hygrothermal behaviour will take place as this is not a requirement in ECO. Building Regulations Part C [293] stipulates the need to protect buildings and people from the harmful effects of interstitial and surface condensation in new-build and material change of use scenarios. However, the Building Regulations are not explicit about material alteration, which will form the basis of most thermal upgrading schemes. These issues mean that many retrofits have been installed in homes without an understanding of their specific risk of moisture accumulation within the fabric.

3.3.3.1 Material properties data

Material properties are very important to the accuracy of any models or simulations of the performance of building elements. Simulations and calculations are reliant on accurate input data to achieve accurate outputs. There are a variety of sources for material property data that can be used when defining materials in numerical models and other calculations. Where possible, material-specific properties are preferred. These data should be acquired from testing that complies with the relevant standards, though generic data are sometimes needed.

Material manufacturers will often provide material properties data in their literature, though this is not always provided, nor will it use the same format consistently across the industry. However, the λ90/90 (conductivity over 90%, for 90% of the time) is commonly used. This lack of specific material performance data is identified as being a source of uncertainty in performance calculations and simulations [269, 270]. When sourcing materials data for hygrothermal simulations, default data provided in the software package is commonly used.

Because of this, there may be a disparity with the specific materials found in a particular UK retrofit, and the generic data in the software, representing a possible source of uncertainty in the model. Table 3-8 shows the possible options for determining the material properties of building elements in models.

Table 3-8 Sources of material properties

	Comments
Laboratory testing	Gives specific material properties but can be prohibitively expensive and may require destructive testing if applied to an existing structure.
BS EN ISO 10456	Hygrothermal properties of common building materials and products. However, these are relatively limited and often insufficient for including in dynamic numerical simulation.
BS EN 12524	Hygrothermal properties of building materials and products. Contains data for use in calculating U-values and hygrothermal

	assessment. However, these are relatively limited and often insufficient for including in dynamic numerical simulation.
BS EN 1745	Defines methods to determine material properties of masonry products and gives tabulated design values for various products.
BS EN ISO 6946	Primarily focussed on the method of calculating U-values. Also contains guidance for determining properties of air layers in construction.
CIBSE Guide A & BR443	These guides contain several tables that can be used to determine a suitable value to use for various materials.
Software databases	Hygrothermal simulation software sometimes includes a database of material hygrothermal properties, provided by the publisher that is based upon test results.

Different approaches to attaining the material properties include:

- Experimental derived values: Require additional testing and materials to use in experiments, requiring time and money.
- Manufacturer values: Not always available. The conditions that the materials are tested under are not necessarily reflective of in situ conditions, and different manufacturers may use different test methodologies.
- Database values: Does not cover every material that could be found in buildings. Values are generic, and do not account for variations between similar but different types.

Hygrothermal behaviour: implications for DEEP

Predicting water accumulation and risk of rot in construction fabric before and after retrofits have taken place is not common. But studies have shown, specifically with IWI, that risks can increase substantially where systems are not breathable and where discontinuities in insulation occur. The impact of using default materials data from databases on these predictions is not clear however, and little data on UK specific construction materials exist, e.g. assumed properties of density, porosity and water content, etc. This means there are unknown risks of moisture accumulation and timber rot being introduced into homes that have been retrofitted. DEEP will identify the relevant material properties for common UK construction materials to better inform hygrothermal simulations. DEEP will also investigate how sensitive model predictions are to different material properties. Furthermore, since there is little data currently available, DEEP will also undertake scenario analysis for a range of common retrofits and house construction types to quantify moisture accumulation risk currently being introduced into UK homes that are having retrofits.

4 Conclusion

Throughout the literature review, key issues related to retrofit performance and risk have been identified. Consideration has been made of current limitations in retrofit models and how these could be overcome. The data and knowledge base are extensive for popular retrofits, however, those less common or more complex retrofits suffer from significant gaps in understanding. Furthermore, some modelling conventions and input data are absent, leaving substantial modelling and knowledge gaps to be addressed.

4.1 Retrofit policy

The UK Government supports the retrofit of existing dwellings via policy, which has changed over time, affecting the type and scale of retrofits that take place. Current policy promotes single measures to be installed in homes in phases, rather than undertaking deep retrofits. It is not known if this approach is compatible with a whole-house approach, or how this affects performance and risk of retrofits in homes and the potential to achieve national carbon targets.

4.2 Retrofit performance and risks

The body of work relating to performance and risks associated with domestic retrofits is considerable, though gaps in understanding are substantial. It appears that knowledge on element performance does not translate into practice, something the whole-house approach attempts to address. Due to the lack of literature on whole-house retrofits, it is difficult to evaluate this approach and its potential impact. There is a lack of understanding around the performance and risks of less common retrofit measures, such as floor insulation and airtightness improvements. Few studies have investigated the performance differences and risks when retrofit is experienced through the piecemeal approach with retrofit applied sequentially over years, compared to a deep retrofit undertaken in one step. DEEP will use field trial retrofit case studies combined with energy efficiency surveys to provide performance data on less common retrofits for solid walled homes, quantify the impact of adopting a whole-house approach, and compare multiple measure versus deep retrofits.

4.3 Retrofit modelling

Predictions of retrofit performance are made using RdSAP and tend to be unrepresentative of actual performance for a variety of reasons. DSM models and other flexible steady-state models can improve predictions by incorporating more realistic inputs, and although these are rarely used in policy, they are encouraged in standards. Detailed DSM, thermal modelling and hygrothermal simulations are seldom undertaken for individual retrofits and little has been done to systematically validate their inputs or findings on a range of retrofit scenarios. DEEP will explore the trade-off between accuracy and practicality. DEEP will also explore how RdSAP, thermal bridging and hygrothermal simulation inputs may be enhanced to consider building-specific variations in fabric and ventilation performance, local weather and varying occupancy profiles. It will adopt a systematic approach to explore the sensitivity to changes in model input variables and inform how the use of models may be most effectively enhanced.

References

[1] Technology Strategy Board, Retrofit Revealed: The Retrofit for the Future projects – data analysis report, Department of Buinsess Energy and Industrial Strategy, London, HM government, (2013).
[2] UCL, Understanding Best Practice in Deploying External Solid-Wall Insulation in the UK, Department of Buinsess Energy and Industrial Strategy, London, HM government, (2017).
[3] P. Webber, A. Gouldson, N. Kerr, The impacts of household retrofit and domestic energy efficiency schemes: A large scale, ex post evaluation, Energy Policy, 84 (2015) 35-43.
[4] R. Gupta, M. Gregg, Do deep low carbon domestic retrofits actually work?, Energy and Buildings, 129 (2016) 330-343.
[5] OFGEM, Final Determination Report ECO2, Office of Gas and Electricity Markets, HM Government, London, (2019).
[6] HM Government, UK Building Regulations. Part L1B: Conservation of Fuel and Power in Existing Dwellings in, RIBA Publishing Ltd, London, 2014.
[7] MHCLG, English Housing Survey Headline Report, 2018-19 Ministry of Housing Communities and Local Government, HM Government, London, (2020).
[8] OFGEM, Energy Company Obligation Final Report, (2015).
[9] OFGEM, ECO public reports and data, Approved ECO3 measures by category, Office of Gas and Electricity Markets, Online, Accessed, 07/02/2020, https://www.ofgem.gov.uk/environmental-programmes/eco/contacts-guidance-and-resources/eco-public-reports-and-data/measures, (2019).
[10] R. Gupta, L. Barnfield, T. Hipwood, Impacts of community-led energy retrofitting of owner-occupied dwellings, Building Research & Information, 42 (4) (2014) 446-461.
[11] DECC, Low Carbon Communities Challenge, Evaluation Report, A Synthesis Report by DECC, drawing upon independent evaluation research, Department of Energy and Climate Change, HM Government, London, (2012).
[12] DECC, Evaluation of the Carbon Emissions Reduction Target and Community Energy Saving Programme: Executive Summary, Department for Business, Energy & Industrial Strategy, Ipsos Mori, CAG Consultants, UCL, Energy Saving Trust, HM Government, London, (2014).
[13] BEIS, Household Energy Efficiency Statistics, headline release April 2020, Department for Business, Energy & Industrial Strategy, HM Government, London, (2020).
[14] OFGEM, The final report of the Carbon Emissions Reduction Target (CERT) 2008-2012, in, 2013.
[15] BEIS, Household Energy Efficiency Statistics, headline release January 2020 Department for Business, Energy & Industrial Strategy, HM Government, London, (2020).
[16] CCC, Net Zero; The UK's Contribution to stopping Global Warming, Committee on Climate Change, London, (2019).
[17] IET, Nottingham Trent University, Scaling Up Retrofit 2050, Why a nationwide programme to upgrade the existing housing stock is the only way for the UK to achieve its carbon saving goals., The Institute of Engineering and Technology and Nottingham Trent University, London, (2018).
[18] Catapult Connected Places, Homes fit for the Future; Retrofit towards a sector-wide roadmap 2020, Housing Innovation Programme, London, (2019).
[19] BEIS, Houshold Energy Efficiency Headline Release: Great Briain Data to May 2019, Department for Business, Energy & Industrial Strategy, HM Government, London, (2019).
[20] D. Ürge-Vorsatz, S. Tirado Herrero, Building synergies between climate change mitigation and energy poverty alleviation, Energy Policy, 49 (2012) 83-90.
[21] P. Bonfield, Each Home Counts: An Independent Review of Consumer Advice, Protection, Standards and Enforcement for Energy Efficiency and Renewable Energy, Department for Business, Energy and Industrial Strategy (BEIS) and the Department for Communities and Local Government (DCLG), London, HM Government, (2016).
[22] J. Traynor, EnerPHit: A step by step guide to low energy retrofit, RIBA Publishing, London, 2019.
[23] R. Gupta, M. Gregg, S. Passmore, G. Stevens, Intent and outcomes from the Retrofit for the Future programme: key lessons, Building Research & Information, 43 (4) (2015) 435-451.
[24] BRE, Solid wall heat losses and the potential for energy saving, Consequences for consideration to maximise SWI benefits: A route-map for change, in: D.o.E.a.C. Change (Ed.), BRE, London, 2016.
[25] HM Government, PAS 2035:2019 Retrofitting dwellings for improved energy efficiency - Specification and guidance, in, BSI Standards Limited 2019, London, 2019.

[26] P. Hansford, Solid Wall Insulation: Unlocking Demand and Driving Up Standards. A report to the Green Construction Board and Government by the Chief Construction Adviser, HM Governemnt, London, (2015).
[27] D. Glew, J. Parker, F. Fylan, F. Thomas, M. Fletcher, D. Miles-Shenton, D. Farmer, A. Hardy, M. Brooke-Peat, C. Gorse, Measuring Energy Performance Improvements in Dwellings Using Thin Internal Wall Insulation Department for Business, Energy and Industrial Strategy (BEIS), London, HM Government, (2021).
[28] A. Hardy, D. Glew, C. Gorse, M. Fletcher, Validating solid wall insulation retrofits with in-use data, Energy and Buildings, 165 (2018) 200-205.
[29] N. Campbell, T. McGrath, S. Nanukuttan, S. Brown, Monitoring the hygrothermal and ventilation performance of retrofitted clay brick solid wall houses with internal insulation: Two UK case studies, Case Studies in Construction Materials, 7 (2017) 163-179.
[30] L. Rodrigues, J. White, M. Gillott, E. Braham, A. Ishaque, Theoretical and experimental thermal performance assessment of an innovative external wall insulation system for social housing retrofit, Energy and Buildings, 162 (2018) 77-90.
[31] W. Swan, R. Fitton, C. Gorse, D. Farmer, M. Benjaber, The staged retrofit of a solid wall property under controlled conditions, Energy and Buildings, 156 (2017) 250-257.
[32] L. Jankovic, Lessons learnt from design, off-site construction and performance analysis of deep energy retrofit of residential buildings, Energy and Buildings, 186 (2019) 319-338.
[33] M.R. Hall, S.P. Casey, D.L. Loveday, M. Gillott, Analysis of UK domestic building retrofit scenarios based on the E.ON Retrofit Research House using energetic hygrothermics simulation – Energy efficiency, indoor air quality, occupant comfort, and mould growth potential, Building and Environment, 70 (2013) 48-59.
[34] F. Moran, T. Blight, S. Natarajan, A. Shea, The use of Passive House Planning Package to reduce energy use and CO2 emissions in historic dwellings, Energy and Buildings, 75 (2014) 216-227.
[35] Q. Wang, S. Holmberg, A methodology to assess energy-demand savings and cost effectiveness of retrofitting in existing Swedish residential buildings, Sustainable Cities and Society, 14 (1) (2015) 254-266.
[36] R. Gupta, L. Barnfield, Unravelling the unintended consequences of home energy improvements, International Journal of Energy Sector Management, 8 (4) (2014) 506-526.
[37] D. Johnston, D. Farmer, M. Brooke-Peat, D. Miles-Shenton, Bridging the domestic building fabric performance gap, Building Research and Information, 44 (2) (2016) 147-159.
[38] N. May, N. Griffiths, Planning responsible retrofit of traditional buildings, Sustainable Traditional Buildings Alliance, London, (2015).
[39] V. Tink, S. Porritt, D. Allinson, D. Loveday, Measuring and mitigating overheating risk in solid wall dwellings retrofitted with internal wall insulation, Building and Environment, 141 (2018) 247-261.
[40] H. Elsharkawy, P. Rutherford, Energy-efficient retrofit of social housing in the UK: Lessons learned from a Community Energy Saving Programme (CESP) in Nottingham, Energy and Buildings, 172 (2018) 295-306.
[41] P. Jones, X. Li, E. Perisoglou, J. Patterson, Five energy retrofit houses in South Wales, Energy and Buildings, 154 (2017) 335-342.
[42] BEIS, Household Energy Efficiency Statistics, detailed report 2018 Department for Business, Energy & Industrial Strategy, HM Government, London, (2019).
[43] J. Currie, J. Williamson, J. Stinson, Historic Scotland Technical Paper 19: Monitoring thermal upgrades to ten traditional properties, Technical Papers, Historic Scotland, Edinburgh, (2013).
[44] D. Miles-Shenton, C. Gorse, F. Thomas, External walls partially filled with insulation, and the potential to “top-up” the residual cavity. , Leeds Beckett University, Leeds, (2015).
[45] J. Parker, D. Farmer, D. Johnston, M. Fletcher, F. Thomas, C. Gorse, S. Stenlund, Measuring and modelling retrofit fabric performance in solid wall conjoined dwellings, Energy and Buildings, 185 (2019) 49-65.
[46] EST, Roof and Loft, Home Insulation, Energy Saving Trust, Online, Accessed, 10/2/2020, https://energysavingtrust.org.uk/home-insulation/roof-and-loft, (2020).
[47] G. Killip, A. Owen, Seven Myths of Building Retrofit, in: The International Refurbishment Symposium, Institution of Engineering and Technology, London, 2017, pp. 67 - 73.
[48] OFGEM, The final report of the Carbon Emissions Reduction Target (CERT) 2008-2012 Office of Gas and Electricity Markets, HM Government, London, (2013).

[49] Kingspan, Mineral Fibre Loft Insulation, Compaction, Settlement, Missing Mineral Fibre and Heat Loss: A White Paper, Kingspan Internaltional Limited, Herefordshire, (2006).
[50] D. Glew, M. Smith, D. Miles-Shenton, C. Gorse, Assessing the quality of retrofits in solid wall dwellings, International Journal of Building Pathology and Adaptation, 35 (5) (2017) 501-518.
[51] A.J. Summerfield, A. Pathan, R.J. Lowe, T. Oreszczyn, Changes in energy demand from low-energy homes, Building Research & Information, 38 (1) (2010) 42-49.
[52] P. Brown, W. Swan, S. Chahal, Retrofitting social housing: reflections by tenants on adopting and living with retrofit technology, Energy Efficiency, 7 (4) (2014) 641-653.
[53] F. Fylan, D. Glew, M. Smith, D. Johnston, M. Brooke-Peat, D. Miles-Shenton, M. Fletcher, P. Aloise-Young, C. Gorse, Reflections on retrofits: Overcoming barriers to energy efficiency among the fuel poor in the United Kingdom, Energy Research & Social Science, 21 (2016) 190-198.
[54] BEIS, National Energy Efficiency Data-Framework (NEED): impact of measures data tables 2019 - Headline impact of measures 2016, Department for Business, Energy & Industrial Strategy, HM Government, Online, (2020).
[55] Kingspan, Mineral Fibre Loft Insulation, Cold Bridging, Ventilation & Heat Loss at the Eaves, A White Paper, Kingspan International Limited, Herefordshire, (2006).
[56] C. Gorse, D. Glew, D. Johnston, F. Fylan, D. Miles-Shenton, M. Brooke-Peat, D. Farmer, A. Stafford, J. Parker, M. Fletcher, F. Thomas, Core cities Green Deal monitoring project, Department of Buinsess Energy and Industrial Strategy, London, HM government, (2017).
[57] OFGEM, Energy Company Obligation (ECO3): Measures table, Office of Gas and Electricity Markets, HM Governemnt, London, (2020).
[58] C. Ahern, P. Griffiths, M. O'Flaherty, State of the Irish housing stock—Modelling the heat losses of Ireland's existing detached rural housing stock & estimating the benefit of thermal retrofit measures on this stock, Energy Policy, 55 (2013) 139-151.
[59] S.N. Murray, B. Rocher, D.T.J. O'Sullivan, Static Simulation: A sufficient modelling technique for retrofit analysis, Energy and Buildings, 47 (2012) 113-121.
[60] C. Ahern, B. Norton, B. Enright, The statistical relevance and effect of assuming pessimistic default overall thermal transmittance coefficients on dwelling energy performance certification quality in Ireland, Energy and Buildings, 127 (2016) 268-278.
[61] D. Farmer, C. Gorse, W. Swan, R. Fitton, M. Brooke-Peat, D. Miles-Shenton, D. Johnston, Measuring thermal performance in steady-state conditions at each stage of a full fabric retrofit to a solid wall dwelling, Energy and Buildings, 156 (2017) 404-414.
[62] D. Miles-Shenton, J. Wingfield, R. Sutton, M. Bell, Temple Avenue Project Part 2: Energy efficient renovation of an existing dwelling: Evaluation of design & construction and measurement of fabric performance Leeds Metropolitan University, Leeds, (2011).
[63] M. Arıcı, H. Karabay, M. Kan, Flow and heat transfer in double, triple and quadruple pane windows, Energy and Buildings, 86 (2015) 394-402.
[64] S. Grynning, A. Gustavsen, B. Time, B.P. Jelle, Windows in the buildings of tomorrow: Energy losers or energy gainers?, Energy and Buildings, 61 (2013) 185-192.
[65] Oreszczyn T, Mumovic D, Ridley I, Davies M, The reduction in air infiltration due to window replacement in UK dwellings: Results of a field study and telephone survey, International Journal of Ventilation, 4 (1) (2005) 71-78.
[66] M.C. Gillott, D.L. Loveday, J. White, C.J. Wood, K. Chmutina, K. Vadodaria, Improving the airtightness in an existing UK dwelling: The challenges, the measures and their effectiveness, Building and Environment, 95 (2016) 227-239.
[67] M. Bell, R. Lowe, Energy efficient modernisation of housing: a UK case study, Energy and Buildings, 32 (3) (2000) 267-280.
[68] E. Cuce, Role of airtightness in energy loss from windows: Experimental results from in situ tests, Energy and Buildings, 139 (2017) 449-455.
[69] R.M.S.F. Almeida, N.M.M. Ramos, P.F. Pereira, A contribution for the quantification of the influence of windows on the airtightness of Southern European buildings, Energy and Buildings, 139 (2017) 174-185.
[70] N. Van Den Bossche, W. Huyghe, J. Moens, A. Janssens, M. Depaepe, Airtightness of the window–wall interface in cavity brick walls, Energy and Buildings, 45 (2012) 32-42.
[71] M. O'Grady, A.A. Lechowska, A.M. Harte, Application of infrared thermography technique to the thermal assessment of multiple thermal bridges and windows, Energy and Buildings, 168 (2018) 347-362.

[72] C. Misiopecki, M. Bouquin, A. Gustavsen, B.P. Jelle, Thermal modeling and investigation of the most energy-efficient window position, Energy and Buildings, 158 (2018) 1079-1086.
[73] W. Maref, N. Van Den Bossche, M. Armstrong, M.A. Lacasse, H. Elmahdy, R. Glazer, Condensation risk assessment on box windows: the effect of the window—wall interface, Journal of building physics (Print), (1) (2012) 35.
[74] S. Ilomets, K. Kuusk, L. Paap, E. Arumägi, T. Kalamees, Impact of linear thermal bridges on thermal transmittance of renovated apartment buildings, Journal of Civil Engineering and Management, 23 (2016) 1-9.
[75] F. Sierra, B. Gething, J. Bai, T. Maksoud, Impact of the position of the window in the reveal of a cavity wall on the heat loss and the internal surface temperature of the head of an opening with a steel lintel, Energy and Buildings, 142 (2017) 23-30.
[76] MHCLG, Accredited Construction Details, Part L Conservation of Fuel and Power, MCI WD Windows and Doors, Version 1, Ministry of Housing Communities and Local Government, HM Government, London, (2006).
[77] Roberts D, Bell M, Lowe R, Stamford Brook, Interim Report Number 2 – Design Process Stamford Brook, , Evaluating The Impact Of An Enhanced Energy Performance Standard On Load-Bearing Masonry Domestic Construction, Leeds Metropolitan University, Leeds, (2004).
[78] Miles-Shenton D, Wingfield J, Sutton R, B. M, Final Report to Joseph Rowntree Housing Trust, Temple Avenue Project Part 2, Energy efficient renovation of an existing dwelling: Evaluation of design & construction and measurement of fabric performance Leeds Beckett University, Leeds, (2011).
[79] HM Government, UK Building Regulations. Part L1A: Conservation of Fuel and Power in New Dwellings in, RIBA Publishing Ltd, London, 2014.
[80] SWEET, Retrofit for the Future: analysis of cost data For the Technology Strategy Board Final Report, Sweet Group, (2014).
[81] Palmer J, Livingstone M, Adams A, What does it cost to retrofit homes; Updating the Cost Assumptions for BEIS's Energy Efficiency Modelling, Department for Business, Energy & Industrial Strategy, HM Government, London, (2017).
[82] HAPM, Component Life Manual, Housing Association Property Mutual (HAPM) 1st Edition, CRC Press, London, (1992).
[83] BEIS, Collection National Energy Efficiency Data-Framework (NEED) Statistical releases, department for Business, Energy & Industrial Strategy, HM Government, https://www.gov.uk/government/collections/national-energy-efficiency-data-need-framework, acessed April 2020, (2020).
[84] H. Adan, F. Fuerst, Do energy efficiency measures really reduce household energy consumption? A difference-in-difference analysis, Energy Efficiency, 9 (5) (2016) 1207-1219.
[85] A. Byrne, G. Byrne, G. O'Donnell, A. Robinson, Case studies of cavity and external wall insulation retrofitted under the Irish Home Energy Saving Scheme: Technical analysis and occupant perspectives, Energy and Buildings, 130 (2016) 420-433.
[86] F. Stazi, F. Tittarelli, G. Politi, C. Di Perna, P. Munafò, Assessment of the actual hygrothermal performance of glass mineral wool insulation applied 25 years ago in masonry cavity walls, Energy and Buildings, 68 (2014) 292-304.
[87] T.V. Rasmussen, A. Nicolajsen, Assessment of the performance of organic and mineral-based insulation products used in exterior walls and attics in dwellings, Building and Environment, 42 (2) (2007) 829-839.
[88] J. Toman, A. Vimmrová, R. Černý, Long-term on-site assessment of hygrothermal performance of interior thermal insulation system without water vapour barrier, Energy and Buildings, 41 (1) (2009) 51-55.
[89] CIGA, Cavity wall insulation complaints – a review of CIGA complaints handling, Cavity Insurance Guarentee Agency, (2015).
[90] C. Iwaszkiewicz, Study on hard to fill cavity walls in domestic dwellings in Great Britain. , Inbuilt & Davis Langdon, Department for Energy and Climate Change, CESA EE0211, Herts UK, (2010).
[91] J. Lecompte, Energy - Insulation: The influence of natural convection on the thermal quality of insulated cavity construction, results of experimental research and computer simulation, Building Research and Practice, 6 (1990) 349-354.
[92] H. Hens, A. Janssens, W. Depraetere, J. Carmeliet, J. Lecompte, Brick Cavity Walls: A Performance Analysis Based on Measurements and Simulations, Journal of Building Physics, 31 (2) (2007) 95-124.

[93] J. Langmans, M. Indekeu, S. Roels, The impact of workmanship on the thermal performance of cavity walls with rigid insulation boards: where are we today?, Energy Procedia, 132 (2017) 255-260.
[94] C. Gorse, D. Miles-Shenton, D. Farmer, M. Fletcher, D. Glew, A. Stafford, J.M. Parker, The gap between calculated and real performance: Experience from the field and the measures required to address the difference. Dynamic Analysis Simulation and Testing applied to the Energy and Environmental Performance of Buildings. , in: International Energy Agency: Energy in Buildings and Communities Programme - Annex 58, Dynastee, Ghent, Belgium, 2014.
[95] D. Johnston, D. Miles-Shenton, M. Bell, J. Wingfield, Airtightness of Buildings - Towards Higher Performance. Final Report - Domestic Sector Airtightness, Department for Communities and Local Government, Project Reference Number CI 61/6/16(BD2429), London, (2011).
[96] T. Oreszczyn, D. Mumovic, M. Davies, I. Ridley, M. Bell, M. Smith, D. Miles-Shenton, Condensation Risk - Impacts of Improvements to Part L & Robust Details on Part C. , in: Building Operational Performance Framework, London, 2011.
[97] R. Lowe, J. Wingfield, M. Bell, J.M. Bell, Evidence for heat losses via party wall cavities in masonry construction, Evidence for heat losses via party wall cavities in masonry construction. Building Service Engineering Research and Technology,, 28 (2) (2007) 161-181.
[98] J. Wingfield, M. Bell, D. Miles-Shenton, R. Lowe, T. South, Evaluating the impact of an enhanced energy performance standard on load-bearing masonry domestic construction: Stamford Brook Field Trial. Co-heating Tests and Investigation of Party Wall Thermal Bypass. Partners in Innovation Project: CI 39/3/663, Department for Communities and Local Government, London, HM Government, (2007).
[99] J. Palmer, N. Terry, D. Johnston, D. Miles-Shenton, C. Gorse, P. Pope, Cavity Party Walls: Measuring U-values Department for Business, Energy & Industrial Strategy, HM Government, London, (2018).
[100] HM Government, UK Building Regulations. Part L1A: Conservation of Fuel and Power in New Dwellings in, RIBA Publishing Ltd, London, 2013.
[101] Farmer D, Miles-Shenton D, Brooke-Peat M, Knauf Insulation / City West – Party Wall Investigation 1, Technical Note, Leeds Beckett University, Leeds, (2013).
[102] H. Harrison, Mullin, S., Reeves, B., Stevens, A., Non Traditional House: Identifying non traditional houses in the UK 1918-75, BRE Report 469, in: BRE Report 469, BRE, Watford, 2004.
[103] BRE, Solid wall heat losses and the potential for energy saving. Consequences for consideration to maximise SWI benefits: A route-map for change, Building Research Establishment, Department of Business Energy and Industrial Strategy, London, (2016).
[104] J. Patterson, Arbed 1 Scheme: Evaluation of the Warm Wales Programme, Cardiff University, Cardiff, UK, (2012).
[105] J. Palmer, N. Terry, Solid Wall Insulation: Best Practice and Innovation, Cambridge Architectural Research, Department for Business and Industrial Strategy, London, HM Government, (2017).
[106] P. Baker, External Insulation of Masonry Walls and Wood Framed Walls National Renewable Energy Laboratory (NREL), Golden, CO. (USA) (No. DOE/GO-102013-3571), (2013).
[107] E. Brandt, T. Bunch-Nielsen, G. Christensen, Interior insulation of solid brick walls in cold climates in: 5th International Conference on Building Physics (ICBP), Kyoto University, Kyoto, Japan, 2012, pp. 299-302.
[108] C. King, C. Weeks, Designing out unintended consequences when applying solid wall insulation, IHS BRE Press, 2016.
[109] Browne. D, The SPAB Research Report 3. The SPAB Hygrothermal Modelling: Interim Report, Society for the Protection Ancient Buildings, London, (2012).
[110] D. Glew, M.B. Smith, D. Miles-Shenton, C. Gorse, Assessing the quality of retrofits in solid wall dwellings, International Journal of Building Pathology and Adaptation, 35 (5) (2017) 501-518.
[111] WHO, WHO guidelines for indoor air quality: dampness and mould, Workd Health Organsiation, Druckpartner Moser, Germany, (2009).
[112] Stephen, BRE Report 359, Airtightness in UK dwellings: BRE's test results and their significance, Building Research Establiashment, Watford, (1998).
[113] ATTMA, Lodgement statistics, Air Tightness Testing and Measurement Association, Northampton, UK, Online, Accessed 5th February 2020, (2018).
[114] M. Gillott, D. Loveday, K. Vadodaria, Briefing Note 1: Airtightness improvements and ventilation systems in domestic refurbishment in: D. Loveday, K. Vadodaria (Eds.) Project CALEBRE: Consumer Appealing Low Energy technologies for Building REtrofitting: A summary of the project and its findings, Loughborough University, Loughborough, UK, 2013, pp. 4-8.

[115] TSB, Retrofit Revealed: The Retrofit for the Future projects – data analysis report, Technology Strategy Board, Swindon, (2013).
[116] GGF, The Good Practice Guide for the Installation of Replacement Windows and Doors, Gall and Glazing Federation, Online Accessed 10th February 2020, https://garrardwindows.co.uk/pdfs/W&D_Good_Practice_Guide-4ec42d0c5aa21.pdf, (2011).
[117] J. Love, J. Wingfield, A.Z.P. Smith, P. Biddulph, T. Oreszczyn, R. Lowe, C.A. Elwell, 'Hitting the target and missing the point': Analysis of air permeability data for new UK dwellings and what it reveals about the testing procedure, Energy and Buildings, 155 (2017) 88-97.
[118] D. Glew, D. Johnston, D. Miles-Shenton, F. Thomas, Retrofitting suspended timber ground-floors; comparing aggregated and disaggregated evaluation methods, Building Research and Information, (2019).
[119] Glew. D, Miles-Shenton. D, Thermography and air tightness report for Wakefield District Housing, Final Report Leeds Beckett University, Leeds, (Unpublished report).
[120] ATTMA, ATTMA Technical Standard L1. Measuring the Air Permeability of Building envelopes (Dwellings), in, Air Tightness Testing and Measurement Association, Northampton, 2010.
[121] S. Pelsmakers, B. Croxford, C.A. Elwell, Suspended timber ground floors: measured heat loss compared with models, Building Research and Information, 47 (2) (2019) 127-140.
[122] S. Pelsmakers, C.A. Elwell, Suspended timber ground floors: Heat loss reduction potential of insulation interventions, Energy and Buildings, 153 (2017) 549-563.
[123] D. Harris, S. Dudek, Heatlosses from suspended timber floors. Laboratory experiments measuring heat losses through flooring utilizing a variety of insulation and ventilation rates to determine appropriate strategies for retrofitting insulation. , Building Research & Information, 25 (1997) 226-233.
[124] EST, Good Practice Guide 171: Domestic energy efficiency primer, an introduction to energy efficiency in existing homes, Energy Savings Trust, London, (2003).
[125] NEF, Insulating your home: Insulating your floor, National Energy Foundation, Online, Accessed January 10th 2020, http://www.nef.org.uk/knowledgehub/view/insulating-your-home (Undated).
[126] A. Gillich, E.M. Saber, E. Mohareb, Limits and uncertainty for energy efficiency in the UK housing stock, Energy Policy, 133 (2019).
[127] Fitton. R, Marshall. A, Benjaber. M, Swan. W, Investigating the Impact of Renewing Floor Coverings on the Energy Performance of Dwellings with Suspended Timber Floors, Tested under Controlled Conditions, in: SDBE (Ed.) International Conference for Sustainable Design of the Built Environment London, 2018.
[128] L. Pampuri, P. Caputo, C. Valsangiacomo, Effects of buildings' refurbishment on indoor air quality. Results of a wide survey on radon concentrations before and after energy retrofit interventions, Sustainable Cities and Society, 42 (2018) 100-106.
[129] B. Collignan, E. Le Ponner, C. Mandin, Relationships between indoor radon concentrations, thermal retrofit and dwelling characteristics, Journal of Environmental Radioactivity, 165 (2016) 124-130.
[130] V.j.A. Haines, V.A. Mitchell, R.A.L. Mallaband, Using a Practice-Orientated Approach to Inform the Design of Energy Efficiency Measures for Older Homes, in: Proceedings of ERSCP-EMSU Conference, 25-28 October 2010, Delft, 2010, pp. 1-17.
[131] S.H. Hong, T. Oreszczyn, I. Ridley, The impact of energy efficient refurbishment on the space heating fuel consumption in English dwellings, Energy and Buildings, 38 (10) (2006) 1171-1181.
[132] P. Banfill, S. Simpson, D. Loveday, K. Vadodaria, Briefing Note 3: Impact of the order of domestic retrofit on long-term energy and carbon savings, in: D. Loveday, K. Vadodaria (Eds.) Project CALEBRE: Consumer Appealing Low Energy technologies for Building REtrofitting: A summary of the project and its findings, Loughborough University, Loughborough, UK, 2013, pp. 11-15.
[133] BEIS, National energy efficiency data-framework - summary of analysis using the national energy efficiency data framework (NEED), Department for Business, Energy & Industrial Strategy, HM Government, London, (2018).
[134] BEIS, National Energy Efficiency Data Framework Summary of analysis using the National Energy Efficiency Data-Framework (NEED), Department for Business, Energy & Industrial Strategy, HM Government, London, (2016).
[135] S.E. Chidiac, E.J.C. Catania, E. Morofsky, S. Foo, Effectiveness of single and multiple energy retrofit measures on the energy consumption of office buildings, Energy, 36 (8) (2011) 5037-5052.
[136] M. Sunikka-Blank, R. Galvin, Introducing the prebound effect: the gap between performance and actual energy consumption, Building Research & Information, 40 (3) (2012) 260-273.

[137] S. Simpson, P. Banfill, The importance of the order of installation of retrofit measures in optimising long term energy and CO2 reductions, , Retrofit 2012 Conference, 24th to 26th January 2012, Salford, (2012).
[138] Passive House Institute, Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard, in, Passive House Institute, Darmstadt, Germany, 2015, pp. 13.
[139] Passivhaus Institute, Passivhaus Planning Package , Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard, , Passive House Institute, 2016, Darmstadt, Germany, Online, Accessed: 6th March 2020, https://passiv.de/downloads/03_building_criteria_en.pdf, (2016).
[140] Energiesprong, Researching and developing technical solutions for Energiesprong retrofits in the UK, Energiespong Institute, Transition Zero - a European Union Horizon 2020 Project, Online, Accessed 6th March 2020 https://assets.website-files.com/59944999990f53000134107e/5c1ba33102ca997b97716063_0.%20NEF%20ES%20TECH%20Guidance%20-%20Index.pdf, (2020).
[141] C. Jimenez-Bescos, R. Prewett, Monitoring IAQ and thermal comfort in a conservation area low energy retrofit, Energy Procedia, 147 (2018) 195-201.
[142] Innovate UK, Retrofit Revealed The Retrofit for the Future projects – data analysis report, in: I. UK (Ed.), Innovate UK, Swindon, 2016.
[143] K.N. Streicher, S. Mennel, J. Chambers, D. Parra, M.K. Patel, Cost-effectiveness of large-scale deep energy retrofit packages for residential buildings under different economic assessment approaches, Energy and Buildings, (215) (2020) 109870.
[144] P. Jones, S. Lannon, J. Patterson, Retrofitting existing housing: How far, how much?, Building Research and Information, 41 (5) (2013) 532-550.
[145] T. Fawcett, G. Killip, Anatomy of low carbon retrofits: evidence from owner-occupied Superhomes, Building Research & Information, 42 (4) (2014) 434-445.
[146] DECC, Estimates of heat use in the United Kingdom in 2013, Department for Energy & Climate Change, London, HM Government, (2014).
[147] A. Mavrogianni, M. Davies, M. Batty, S.E. Belcher, S.I. Bohnenstengel, D. Carruthers, Z. Chalabi, B. Croxford, C. Demanuele, S. Evans, R. Giridharan, J.N. Hacker, I. Hamilton, C. Hogg, J. Hunt, M. Kolokotroni, C. Martin, J. Milner, I. Rajapaksha, I. Ridley, J.P. Steadman, J. Stocker, P. Wilkinson, Z. Ye, The comfort, energy and health implications of London's urban heat island, Building Services Engineering Research and Technology, 32 (1) (2011) 35-52.
[148] Á. Broderick, M. Byrne, S. Armstrong, J. Sheahan, A.M. Coggins, A pre and post evaluation of indoor air quality, ventilation, and thermal comfort in retrofitted co-operative social housing, Building and Environment, 122 (2017) 126-133.
[149] S. Vardoulakis, C. Dimitroulopoulou, J. Thornes, K.M. Lai, J. Taylor, I. Myers, C. Heaviside, A. Mavrogianni, C. Shrubsole, Z. Chalabi, M. Davies, P. Wilkinson, Impact of climate change on the domestic indoor environment and associated health risks in the UK, Environment International, 85 (2015) 299-313.
[150] P. Strachan, K. Svehla, I. Heusler, M. Kersken, Whole model empirical validation on a full-scale building, Journal of Building Performance Simulation, 9 (4) (2016) 331-350.
[151] CIBSE, TM33: Tests for Software Accreditation & Verification, in, CIBSE, London, 2006.
[152] ASHRAE, Standard 140-2007: Standard method of test for the evaluation of building energy analysis computer programs, in, ASHRAE, Atlanta, 2007.
[153] E. Cuerda, O. Guerra-Santin, J.J. Sendra, F.J. Neila, Understanding the performance gap in energy retrofitting: Measured input data for adjusting building simulation models, Energy and Buildings, 209 (2020).
[154] D. Johnston, D. Miles-Shenton, D. Farmer, Quantifying the domestic building fabric 'performance gap', Building Services Engineering Research and Technology, 36 (5) (2015) 614-627.
[155] P.X.W. Zou, X. Xu, J. Sanjayan, J. Wang, Review of 10 years research on building energy performance gap: Life-cycle and stakeholder perspectives, Energy and Buildings, 178 (2018) 165-181.
[156] E. Mantesi, C.J. Hopfe, M.J. Cook, J. Glass, P. Strachan, The modelling gap: Quantifying the discrepancy in the representation of thermal mass in building simulation, Building and Environment, 131 (2018) 74-98.
[157] G. Box, N. Draper, Empirical Model-Building and Response Surfaces, John Wiley & Sons, New York, 1987.
[158] R. Cohen, The performance gap in non-domestic buildings: evidence collected from the Technology Strategy Board's Building Performance Evaluation Programme, in, London, 2013.

[159] The Carbon Trust, Closing the gap: lessons learned on realising the potential of low carbon building design, in, London, 2011.
[160] A.C. Menezes, A. Cripps, D. Bouchlaghem, R. Buswell, Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap, Applied Energy, 97 (2012) 355-364.
[161] E. Burman, D. Rigamonti, J. Kimpain, D. Mumovic, Performance gap and thermal modelling: a comparison of simulation results and actual energy performance for an academy in North West England, in: IBPSA England First Building Simulation and Optimization Conference, IBPSA, Loughborough, UK, 2012, pp. 35-42.
[162] D. Coakley, P. Raftery, M. Keane, A review of methods to match building energy simulation models to measured data, Renewable and Sustainable Energy Reviews, 37 (2014) 123-141.
[163] P. Raftery, M. Keane, J. O'Donnell, Calibrating whole building energy models: An evidence-based methodology, Energy and Buildings, 43 (9) (2011) 2356-2364.
[164] Y. Heo, R. Choudhary, G.A. Augenbroe, Calibration of building energy models for retrofit analysis under uncertainty, Energy and Buildings, 47 (2012) 550-560.
[165] A. Badiei, D. Allinson, K.J. Lomas, Automated dynamic thermal simulation of houses and housing stocks using readily available reduced data, Energy and Buildings, 203 (2019).
[166] Y. Ji, A. Lee, W. Swan, Building dynamic thermal model calibration using the Energy House facility at Salford, Energy and Buildings, 191 (2019) 224-234.
[167] E. Fabrizio, V. Monetti, Methodologies and advancements in the calibration of building energy models, Energies, 8 (4) (2015) 2548-2574.
[168] Y. Ji, A. Lee, W. Swan, Retrofit modelling of existing dwellings in the UK: the Salford Energy House case study, International Journal of Building Pathology and Adaptation, 37 (3) (2019) 344-360.
[169] S. Kelly, D. Crawford-Brown, M.G. Pollitt, Building performance evaluation and certification in the UK: Is SAP fit for purpose?, Renewable and Sustainable Energy Reviews, 16 (9) (2012) 6861-6878.
[170] HM Government, The Government's Standard Assessment Procedure for Energy Rating of Dwellings, 2012 Edition., in: DECC (Ed.), Building Research Establishment Ltd, Watford, 2014.
[171] C. Bonfigli, M. Chorafa, S. Diamond, C. Eliades, A. Mylona, B. Taylor, D. Virk, TM59: Design methodology for the assessment of overheating risk in homes., in: K. Butcher (Ed.), CIBSE, London, 2017.
[172] J. Haberl, S. Cho, Literature review of uncertainty of analysis methods, in, Texas Engineering Station, Texas A&M University, Texas, 2004.
[173] K. Tupper, E. Franconi, C. Chan, C. Fluhrer, M. Jenkins, S. Hodgin, Building energy modelling innovation, Building energy modelling innovation summit, Rocky Mountain Institute, Boulder, (2011).
[174] Passivhaus Institute, Passivhaus Planning Package, Passivhaus Institute 9, Dramstadt, Online, Accessed: 6th March 2020, https://passivehouse.com/04_phpp/04_phpp.htm#PH9., (2015).
[175] G. Henderson, L.D. Shorrock, BREDEM - the BRE domestic energy model: testing the predictions of a two-zone version, Building Services Engineering Research and Technology, 2 (7) (1986) 87-91.
[176] C.M. Dickson, J.E. Dunster, S.Z. Lafferty, L.D. Shorrock, BREDEM: Testing monthly and seasonal versions against measurement and against detailed simulation models, Building Services Engineering Research and Technology, 3 (17) (1996) 135-140.
[177] L. Shorrock, Validation of BREDEM, (2011).
[178] F. Sierra, L. Mahdjoubi, B. Gething, A. Alzaatreh, R. Fitton, A. Marshall, Comparison of prediction tools to determine their reliability on calculating operational heating consumption by monitoring no-fines concrete dwellings, Energy and Buildings, 176 (2018) 78-94.
[179] D. Johnston, M. Siddall, O. Ottinger, S. Peper, W. Feist, Are the energy savings of the passive house standard reliable? A review of the as-built thermal and space heating performance of passive house dwellings from 1990 to 2018, Energy Efficiency, (2020).
[180] R. Mitchell, S. Natarajan, Normalising domestic space heating demand using post hoc models, Building Services Engineering Research and Technology, 40 (3) (2019) 340-359.
[181] S. Lewis, PHPP Illustrated: A designer's companion to the Passivhaus Planning Package, RIBA Publishing, London, 2017.
[182] S. Imam, D.A. Coley, I. Walker, The building performance gap: Are modellers literate?, Building Services Engineering Research and Technology, 38 (3) (2017) 351-375.
[183] Department of Energy, EnergyPlus 9.2.0, (2020).
[184] T. Reddy, Literature review on calibration of building energy simulation programs: uses, problems, procedures, uncertainty and tools, ASHRAE Transactions, (211) (2006) 226-240.

[185] P. de Wilde, ‘The building performance gap: Are modellers literate?’, Building Services Engineering Research and Technology, 38 (6) (2017) 757-759.
[186] P. de Wilde, The gap between predicted and measured energy performance of buildings: A framework for investigation, Automation in Construction, 41 (2014) 40-49.
[187] A. Marshall, R. Fitton, W. Swan, D. Farmer, D. Johnston, M. Benjaber, Y. Ji, Domestic building fabric performance: Closing the gap between the in situ measured and modelled performance, Energy and Buildings, 150 (2017) 307-317.
[188] T. Reddy, I. Maor, C. Panjapornpon, Calibrating detailed building energy simulation programs with measured data – Part II: Application to three case study office buildings, HVAC&R Research, 13 (2) (2007) 243-265.
[189] P. Raftery, M. Keane, A. Costa, Calibrating whole building energy models: Detailed case study using hourly measured data, Energy and Buildings, 43 (12) (2011) 3666-3679.
[190] T. Reddy, I. Maor, C. Panjapornpon, Calibrating detailed building energy simulation programs with measured data – Part I: General methodology, HVAC&R Research, 13 (2) (2007) 221-241.
[191] J. Yoon, E.J. Lee, D.E. Claridge, Calibration procedure for energy performance simulation of a commercial building, Journal of Solar Energy Engineering, Transactions of the ASME, 125 (3) (2003) 251-257.
[192] Y.S. Kim, M. Heidarinejad, M. Dahlhausen, J. Srebric, Building energy model calibration with schedules derived from electricity use data, Applied Energy, 190 (2017) 997-1007.
[193] A.E. Kandil, J.A. Love, Signature analysis calibration of a school energy model using hourly data, Journal of Building Performance Simulation, 7 (5) (2014) 326-345.
[194] J.A. Shonder, P.J. Hughes, J.W. Thornton, Using calibrated engineering models to predict energy savings in large-scale geothermal heat pump projects, in: ASHRAE Transactions, 1998, pp. 944-954.
[195] V.I. Soebarto, Calibration of hourly energy simulations using hourly monitored data and monthly utility records for two case study buildings, International Building Performance Simulation Conference, IBPSA, Prague, (1997).
[196] P. De Wilde, W. Tian, Towards probabilistic performance metrics for climate change impact studies, Energy and Buildings, 43 (11) (2011) 3013-3018.
[197] A. Srivastav, A. Tewari, B. Dong, Baseline building energy modeling and localized uncertainty quantification using Gaussian mixture models, Energy and Buildings, 65 (2013) 438-447.
[198] G. Kumbaroglu, R. Madlener, Evaluation of economically optimal retrofit investment options for energy savings in buildings, Energy and Buildings, 49 (2012) 327-334.
[199] W. Tian, Y. Heo, P. de Wilde, Z. Li, D. Yan, C.S. Park, X. Feng, G. Augenbroe, A review of uncertainty analysis in building energy assessment, Renewable and Sustainable Energy Reviews, 93 (2018) 285-301.
[200] P. De Wilde, Y. Sun, G. Augenbroe, Quantifying the performance gap-An initial probabilistic attempt, in: European Group for Intelligent Computing in Engineering, EG-ICE 2013 - 20th International Workshop: Intelligent Computing in Engineering, 2013.
[201] M. Gul, D.P. Jenkins, S. Patidar, P.F.G. Banfill, G. Menzies, G. Gibson, Tailoring a future overheating risk tool for existing building design practice in domestic and non-domestic sectors, Building Services Engineering Research and Technology, 33 (1) (2012) 105-117.
[202] D.P. Jenkins, M. Gul, S. Patidar, P.F.G. Banfill, G. Gibson, G. Menzies, Designing a methodology for integrating industry practice into a probabilistic overheating tool for future building performance, Energy and Buildings, 54 (2012) 73-80.
[203] T. Kershaw, M. Eames, D. Coley, Assessing the risk of climate change for buildings: A comparison between multi-year and probabilistic reference year simulations, Building and Environment, 46 (6) (2011) 1303-1308.
[204] DesignBuilder Software Ltd, DesignBuilder Version 6.1, in, DesignBuilder Software Ltd, Stroud, UK, 2016.
[205] CIBSE, Guide A: Environmental Design, in, London, 2015.
[206] L. Pérez-Lombard, J. Ortiz, C. Pout, A review on buildings energy consumption information, Energy and Buildings, 40 (3) (2008) 394-398.
[207] M.F. Jentsch, G.J. Levermore, J.B. Parkinson, M.E. Eames, Limitations of the CIBSE design summer year approach for delivering representative near-extreme summer weather conditions, Building Services Engineering Research and Technology, 35 (2) (2014) 155-169.
[208] G.A. Meehl, C. Tebaldi, More intense, more frequent, and longer lasting heat waves in the 21st century, Science, 305 (5686) (2004) 994-997.

[209] A. Beizaee, K.J. Lomas, S.K. Firth, National survey of summertime temperatures and overheating risk in English homes, Building and Environment, 65 (2013) 1-17.
[210] K.J. Lomas, T. Kane, Summertime temperatures and thermal comfort in UK homes, Building Research and Information, 41 (3) (2013) 259-280.
[211] R. Gupta, M. Kapsali, Empirical assessment of indoor air quality and overheating in low-carbon social housing dwellings in England, UK, Advances in Building Energy Research, (2015).
[212] A. Mavrogianni, M. Davies, Z. Chalabi, P. Wilkinson, M. Kolokotroni, J. Milner, Space heating demand and heatwave vulnerability: London domestic stock, Building Research and Information, 37 (5-6) (2009) 583-597.
[213] A. Dengel, M. Swainston, Overheating in new homes: A review of the evidence, in, NHBC Foundation, Milton Keynes, 2012.
[214] ZCH, Monitoring Overheating: Housing Association Case Studies, Zero Carbon Hub, Milton Keynes, (2015).
[215] S.M. Tabatabaei Sameni, M. Gaterell, A. Montazami, A. Ahmed, Overheating investigation in UK social housing flats built to the Passivhaus standard, Building and Environment, 92 (2015) 222-235.
[216] CIBSE, TM52: The limits of thermal comfort: avoiding overheating in European buildings. , in, London, 2013.
[217] R. Gupta, M. Gregg, R. Irving, Meta-analysis of summertime indoor temperatures in new-build, retrofitted, and existing UK dwellings, Science and Technology for the Built Environment, 25 (9) (2019) 1212-1225.
[218] R. Gupta, M. Gregg, K. Williams, Cooling the UK housing stock post-2050s, Building Services Engineering Research and Technology, 36 (2) (2015) 196-220.
[219] D. Fosas, D.A. Coley, S. Natarajan, M. Herrera, M. Fosas de Pando, A. Ramallo-Gonzalez, Mitigation versus adaptation: Does insulating dwellings increase overheating risk?, Building and Environment, 143 (2018) 740-759.
[220] K. Butcher, TM55: Design for Future Climate: Case Studies, in, London, 2014.
[221] S.M. Porritt, P.C. Cropper, L. Shao, C.I. Goodier, Heat wave adaptations for UK dwellings and development of a retrofit toolkit, International Journal of Disaster Resilience in the Built Environment, 4 (3) (2013) 269-286.
[222] S.M. Porritt, P.C. Cropper, L. Shao, C.I. Goodier, Ranking of interventions to reduce dwelling overheating during heat waves, Energy and Buildings, 55 (2012) 16-27.
[223] B.M. Roberts, D. Allinson, S. Diamond, B. Abel, C.D. Bhaumik, N. Khatami, K.J. Lomas, Predictions of summertime overheating: Comparison of dynamic thermal models and measurements in synthetically occupied test houses, Building Services Engineering Research and Technology, 40 (4) (2019) 512-552.
[224] HM Government, National Calculation Methodology (NCM) modelling guide (for building other than dwellings in England and Wales), in, BRE Ltd, London, 2013.
[225] Zero Carbon Hub, Assessing Oveheating Risk: Evidence Review, in, London, 2015.
[226] IES, Virtual Environment, in, 2015.
[227] Brooke-Peat. M, Assessing the Impact of Thermal Bridging on Building Fabric Performance, Doctor of Philosophy Thesis, Leeds Beckett University, Leeds, UK, (2019).
[228] HM Government, Standard Assessment Procedure: Guidance on how buildings will be SAP energy assessed under the Green Deal and on recent changes to incentivise low carbon developments., in: DECC (Ed.), HMSO, London, 2013.
[229] B. Jones, P. Das, Z. Chalabi, M. Davies, I. Hamilton, R. Lowe, J. Milner, I. Ridley, C. Shrubsole, P. Wilkinson, The effect of party wall permeability on estimations of infiltration from air leakage, International Journal of Ventilation, 12 (1) (2013) 17-29.
[230] S. Ahmed, Assessment of urban heat islands and impact of climate change on socioeconomic over Suez Governorate using remote sensing and GIS techniques, Egyptian Journal of Remote Sensing and Space Science, 21 (1) (2018) 15-25.
[231] M.H. Sherman, Estimation of infiltration from leakage and climate indicators, Energy and Buildings, 10 (1) (1987) 81-86.
[232] BSI, BS EN ISO 9972:2015. Thermal performance of buildings – determination of air permeability of buildings – fan pressurization method, British Standards Institution, London, (2015).
[233] D. Johnston, A. Stafford, Estimating the background ventilation rates in new-build UK dwellings - Is n50/20 appropriate?, Indoor and Built Environment, 26 (4) (2017) 502-513.

[234] R. McLeod, M. Jaggs, B. Cheeseman, A. Tilford, K. Mead, Passivhaus Primer: Airtightness Guide, Building Research Establishment, Watford, (2014).
[235] C. Demanuele, A. Mavrogianni, M. Davies, M. Kolokotroni, I. Rajapaksha, Using localised weather files to assess overheating in naturally ventilated offices within London's urban heat island, Building Services Engineering Research and Technology, 33 (4) (2012) 351-369.
[236] M. Eames, T. Kershaw, D. Coley, On the creation of future probabilistic design weather years from UKCP09, Building Services Engineering Research and Technology, 32 (2) (2011) 127-142.
[237] T. Kershaw, M. Eames, D. Coley, Comparison of multi-year and reference year building simulations, Building Services Engineering Research and Technology, 31 (4) (2010) 357-369.
[238] M. Eames, T. Kershaw, D. Coley, The appropriate spatial resolution of future weather files for building simulation, Journal of Building Performance Simulation, 5 (6) (2012) 347-358.
[239] Climatic Research Unit, Global temperature record, University of East Anglia, Norwich, Online, Accessed, 16th January 2020, https://crudata.uea.ac.uk/cru/data/temperature/, (2020).
[240] Met Office, Met Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Data (1853-current), in, NCAS British Atmospheric Data Centre, 2012.
[241] ASHRAE, ASHRAE Weather data centre, in, ASHRAE, Atlanta, 2017.
[242] White Box Technologies, White Box Technologies: Weather data for energy calculations, in, White Box Technologies Inc., Moraga, 2020.
[243] Department of Energy, Energy Plus Weather Data, in, National Renewable Energy Laboratory, 2020.
[244] National Oceanic and Atmospheric Administration, National Centers for Environmental Information, in, National Oceanic and Atmospheric Administration, Asheville, 2020.
[245] D. Virk, M. Eames, CIBSE weather files 2016 release: Technical briefing and testing, in, CIBSE, London, 2016.
[246] CIBSE, CIBSE Weather Data Sets, in, CIBSE, London, 2016.
[247] CIBSE, TM49: Design Summer Years for London. , Chartered Institute of Building Services Engineers, London, (2014).
[248] G.J. Levermore, J.B. Parkinson, P.J. Laycock, S. Lindley, The urban heat island in manchester 1996-2011, Building Services Engineering Research and Technology, 36 (3) (2015) 343-356.
[249] BRE, Solid wall heat losses and the potential for energy saving, Closing the gap. Pre, post-insulation field trial, Building Research Establiashment, Watford, (2016).
[250] D. Yan, T. Hong, Definition and Simulation of Occupant Behaviour in Buildings, in, International Energy Agency, Paris, 2014.
[251] H. Yoshino, S. Chen, Total energy use in buildings: Analysis and evaluation methods (Annex 53): Project summary report, in, International Energy Agency, St Albans, 2016.
[252] C. Wang, D. Yan, Y. Jiang, A novel approach for building occupancy simulation, Building Simulation, 4 (2) (2011) 149-167.
[253] C. Liao, Y. Lin, P. Barooah, Agent-based and graphical modelling of building occupancy, Journal of Building Performance Simulation, 5 (1) (2012) 5-25.
[254] D. Yan, W. O’Brien, T. Hong, X. Feng, H. Burak Gunay, F. Tahmasebi, A. Mahdavi, Occupant behavior modeling for building performance simulation: Current state and future challenges, Energy and Buildings, 107 (2015) 264-278.
[255] R. Melfi, B. Rosenblum, B. Nordman, K. Christensen, Measuring building occupancy using existing network infrastructure, in: 2011 International Green Computing Conference and Workshops, IGCC 2011, 2011.
[256] T. Hong, S.C. Taylor-Lange, S. D’Oca, D. Yan, S.P. Corgnati, Advances in research and applications of energy-related occupant behavior in buildings, Energy and Buildings, 116 (2016) 694-702.
[257] HM Government, UK Building Regulations. Part L2A: Conservation of Fuel and Power in Buildings Other than Dwellings in, RIBA Publishing Ltd, London, 2014.
[258] HM Government, UK Building Regulations. Part L2B: Conservation of fuel and power in existing buildings other than dwellings in, RIBA Publishing Ltd, London, 2014.
[259] X. Feng, D. Yan, T. Hong, Simulation of occupancy in buildings, Energy and Buildings, 87 (2015) 348-359.
[260] J. Yang, M. Santamouris, S.E. Lee, Review of occupancy sensing systems and occupancy modeling methodologies for the application in institutional buildings, Energy and Buildings, 121 (2016) 344-349.

[261] T. Hong, H. Sun, Y. Chen, S.C. Taylor-Lange, D. Yan, An occupant behavior modeling tool for co-simulation, Energy and Buildings, 117 (2016) 272-281.
[262] J. Henderson, A review of the relationship between floor area and occupancy in SAP in, BRE, Watford, 2008.
[263] J. Henderson, A review of auxiliary energy use and the internal heat gain assumptions in SAP, in, BRE, Watford, 2009.
[264] L. Reason, A. Clarke, Projecting energy use and CO2 emissions from low energy buildings: A comparison of the Passivhaus Planning Package (PHPP) and SAP, in, AECB, Llandysul, 2008.
[265] BSI, Building components and building elements. Thermal resistance and thermal transmittance. Calculation methods BS EN ISO 6946:2017 Bristish Standards Institute, (2017).
[266] BSI, BS EN ISO 13370:2017, Thermal performance of buildings. Heat transfer via the ground. Calculation methods, Bristish Standards Institute, (2017).
[267] ISO, ISO 10077-1:2017 Thermal performance of windows, doors and shutters — Calculation of thermal transmittance — Part 1: General, International Standards Organisation, (2017).
[268] P. Davidson, Consultation Paper: CONSP:16 Review of default U-values for existing buildings in SAP, Ver. 1.0, in, BRE, Watford, 2016.
[269] J. Hulme, S. Doran, In situ measurements of wall U-values in English housing, in, BRE, Watford, 2014.
[270] F. Smith, P. Biddulph, I.G. Hamilton, R. Lowe, A. Mavrogianni, E. Oikonomou, R. Raslan, S. Stamp, A. Stone, A.J. Summerfield, D. Veitch, V. Gor, T. Oreszczyn, Solid-wall U-values: heat flux, Building Research & Information, (2015) 238-252.
[271] C. Rye, C. Scott, The SPAB Research Report 1. U-Value Report, in, Society for the Protection of Ancient Buildings, 2012.
[272] C. Flood, L. Scott, W. Gleeson, Application of Transient Hygrothermal Modelling to Assess Thermal Transmittance: A Case Study in Dublin, Ireland, in: CIB World Building Congress 2016, Tampere, Finland, 2016.
[273] BSI, BS EN ISO 10211: Thermal Bridges in Building Construction – Heat Flows and Surface Temperatures – Detailed Calculations, in: B.S. Institute (Ed.), British Standards Institution, Milton Keynes, 2007.
[274] S. Real, Gomes, M., Rodrigues, A. and Bogas, J. , Contribution of Structural Lightweight Aggregate Concrete to the Reduction of Thermal Bridging Effect in Buildings, Construction and Building Materials, (121) (2016).
[275] B. Berggren, M. Wall, Calculation of Thermal Bridges in (Nordic) Building Envelopes – Risk of Performance Failure Due to Inconsistent Use of Methodology, Energy and Buildings, 65 (2013) 331-339.
[276] D. Comiskey, Detailing to Minimise Heat Loss at Junctions of Building Elements, University of Central Lancashire, Preston, 2010.
[277] N. Norris, M. Lawton, P. Roppel, Concept of Linear and Point Transmittance and its Value in Dealing with Thermal Bridges in Building Enclosures, National Institute of Building Sciences, Washington DC, Atlanta USA, 2012.
[278] BRE, SAP 2012. The Government's Standard Assessment Procedure for Energy Rating of Dwellings 2012, in, Building Research Establishment, UK, 2017.
[279] BRE, BR 497 Conventions for calculating linear thermal transmittance and temperature factors (BR 497 2nd edition), Building Research Establiashment, Watford, (2016).
[280] K. Martin, A. Erkoreka, I. Flores, M. Odriozola, J.M. Sala, Problems in the calculation of thermal bridges in dynamic conditions, Energy and Buildings, 43 (2) (2011) 529-535.
[281] BSI, Accredited Construction Details for Part L, Bristish Standards Institute, Department for Communities and Local Government, Planning Portal, HM Governemnt, (09/03) (2015).
[282] BEIS, SAP 10.0: The Government’s Standard Assessment Procedure for Energy Rating of Dwellings, Department for Business, Energy and Industrial Strategy, Building Research Establishment, Watford, (2018).
[283] T.I. Ward, IP 1/06: Assessing the effects of thermal bridging at junctions and around openings, in, Building Research Establishment, Watford, 2006.
[284] P. Davidson, Consultation Paper: CONSP:06, TREATMENT OF THERMAL BRIDGES, in, Building Research Establishment, Watford, 2016.
[285] BRE, Consultation Paper: CONSP:06 Treatent of Termal Bridges Issue 1.0, SAP Supporting Document, Building Research Establsihment, (2016).

[286] ZCH, Closing the gap between design and as built performance, End of term report, in, Zero Carbon Hub, 2014.
[287] M. O'Grady, A. Lechowska, J.A. Schnotale, A.M. Harte, Assessment of Thermal Bridging Heat Loss by Means of the Infrared Thermography Technique: Sustainable Buildings in Cold Climates, in: Cold Climate HVAC, 2018, pp. 625-635.
[288] BSI, BS EN 15026: 2007 Hygrothermal performance of building components and building elements. Assessment of moisture transfer by numerical simulation, British Standards Institution, London, (2007).
[289] D. Glew, J. Parker, F. Fylan, F. Thomas, M. Fletcher, D. Miles-Shenton, D. Farmer, A. Hardy, M. Brooke-Peat, C. Gorse, Measuring Energy Performance Improvements in Dwellings Using Thin Internal Wall Insulation in: E.I.S. Department for Business (Ed.), HM Government, London, 2020.
[290] C. Gorse, D. Glew, D. Johnston, F. Fylan, D. Miles-Shenton, M. Brooke-Peat, D. Farmer, A. Stafford, J. Parker, M. Fletcher, F. Thomas, Core cities Green Deal monitoring project, in: BEIS (Ed.), London, 2017.
[291] Browne D, The SPAB Research Report 3. The SPAB Hygrothermal Modelling: Interim Report, in: SPAB (Ed.), Society for the Protection Ancient Buildings 2012.
[292] BSI, BS EN ISO 13788:2012 Hygrothermal performance of building components and building elements. Internal surface temperature to avoid critical surface humidity and interstitial condensation. Calculation methods, Bristish Standards Institute, (2012).
[293] HM Government, Building Regulations for England and Wales, Part C - Site preparation and resistance to contaminants and moisture (2004 Edition incorporating 2010 and 2013 amendments), (2010).

This publication is available from: https://www.gov.uk/government/publications/demonstration-of-energy-efficiency-potential-deep