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Deterioration of retrofit insulation performance (DRIP): Phase 1

Final report

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Abstract

This report presents the findings from Phase 1 of the Deterioration of Retrofit Insulation Performance (DRIP) project. The DRIP project aims to quantify the impact of retrofit degradation over time. Phase 1 establishes the current state of knowledge on retrofit degradation and presents analysis of existing datasets and expert stakeholder engagement.

Review of published academic literature found unequal representation of insulation products in existing research studies. Where research had taken place, this was predominantly in laboratory or modelled environments, with a lack of in situ measurement or testing of samples taken from the field. Studies exploring the effect of ageing in a laboratory setting often applied unrealistic accelerated ageing methods, with little evidence from long-term monitoring.

Published studies on the effects of ageing seldom had energy as their primary focus, with topics such as moisture accumulation and structural stability more common. Research also rarely differentiated between underperformance relative to design targets (commonly referred to as the performance gap) and a continuing decline in performance during service life. More generally, there is a lack of research from the UK context.

Grey literature (produced by the insulation industry and associated trade and insurance organisations) claims long product lifetimes with no reduction in performance. The source of these claims is unclear, although they are repeated in international material testing standards. The assertion of constant performance applies only where products are undisturbed and in ideal condition, however, which is not a true representation of their use.

Following a review of existing datasets in the public domain, the National Energy Efficiency Data-Framework (NEED) was identified as the most likely to provide insight into retrofit deterioration.

As the construction industry encompasses a broad range of stakeholders that are likely to have insight into retrofit deterioration but who do not routinely publish their findings, two activities were undertaken to supplement literature review and capture this unpublished expertise.

Firstly, 20 experts in retrofit insulation attended a workshop to explore what causes insulation to deteriorate and how it affects performance. While it was reported that poor installation is the primary cause of retrofit underperformance, the participants explored how and why insulation performance can deteriorate over time. These discussions were used to identify 13 different classifications of insulation deterioration.

Following the workshop, an expert panel of 26 surveyors were recruited for a Delphi study in which three rounds of questionnaires were used to gain consensus on what should be included in a national building survey of insulation deterioration. Initial classifications of retrofit deterioration were refined during this process until a consensus was reached on what should be measured, how it should be measured, how the deterioration should be graded, and risk factors that surveyors should be aware of. From participants' estimates of the incidence of insulation deterioration, an approach to sampling for a national survey was suggested.

Phase 1 findings were collectively applied to develop recommendations for a proposed DRIP Phase 2.

Executive Summary

There is a wealth of research exploring retrofit performance immediately following construction or installation. However, there is more limited data on how retrofit insulation performance changes over a longer time period. Thermal performance is assumed to be constant over the service life of the insulation. The aim of this project was to establish the existing evidence on the impact of retrofit degradation over time, and what it means for insulation performance. This report summarises current understanding, classifying key mechanisms for degradation and makes recommendations for how to address identified knowledge gaps.

1. Academic research has limitations but suggests insulation performance can degrade over time under certain conditions

Laboratory and simulation results show that many insulation materials can see a decrease in thermal resistance over time. Foamed plastic products, such as polystyrene and polyurethane, appear to degrade over time due to loss of blowing agents, with some studies finding decreases in thermal resistance of over 20%.

Water accumulation is also a factor in the degradation of all insulation products, increasing the thermal conductivity of the material and degrading the insulation's thermal performance. For example, some studies found increases in thermal conductivity over 10% in mineral wools exposed to moisture over several years. Vapour permeable insulation systems pose the least risk of moisture related degradation in IWI applications, as they allow moisture to dry out.

Shortcomings of insulation system design or during the construction process can lead to future deterioration or failure of insulation systems in use. Accounting for future climate conditions is also an important issue.

However, the usefulness of existing academic research is limited by the following issues:

- *Unequal representation of insulation products:* Less evidence on cavity wall and loft insulation which are most prevalent in the UK. There are few UK based studies, and many do not consider domestic buildings.
- *Lack of in situ or field measurement:* Discrepancies between idealised laboratory or simulation conditions and real world conditions limit reliability, and miss out on capturing in-situ material condition.
- *Research focus rarely considers energy/carbon implications:* Focus on material properties rather than resulting building energy consumption or associated carbon emission makes impact quantification difficult.
- *Differentiation between underperformance and degradation:* Research does not explore how poor design and installation impact deterioration and thus long-term performance.
- *Unrepresentative assessment of aging:* Many studies use testing methods to simulate aging which may not be representative of actual mechanisms of degradation.

2. Industry literature suggests insulation performance does not degrade over time

This study also explored manufacturer and industry literature not in peer-reviewed academic journals. Manufacturer trade association literature suggests that product performance does not

significantly decline over time. Where testing has taken place, this typically involves materials in good condition from non-domestic buildings, which may not be representative of the insulation condition of all domestic housing. Manufacturer product literature typically states performance under idealised conditions, with typical stated product lifetimes shown in Table A.

Table A: Manufacturer stated product lifetimes

Product type	Service life (years)
Cellulose fibre	50
Fibreboard	50 / Building lifetime
Foam glass	Unlimited
Stone wool	Building lifetime / unlimited
Vacuum insulated panels (VIPs)	40
Polyurethane (PU)	50
Expanded polystyrene (EPS)	35 - 50
Extruded polystyrene (XPS)	Building lifetime

Source: Kono et al (2016) [67]

Insulation Guarantee Agencies offer guarantees on installations of wall insulation for 25 years, although it is unclear where the guarantee for materials comes from and why only the 25 year period and not the service lifetimes shown above. There is an apparent disagreement between academic and grey literature concerning product lifetimes and ageing effects.

International standards provide useful insight into product deterioration and methods, but they are lacking a real-world usefulness, considering only idealised laboratory performance.

3. Few existing datasets can provide much insight on long term performance

Following a review of existing datasets in the public domain, the National Energy Efficiency Data-Framework (NEED) was identified as the most likely public dataset to provide useful insight into retrofit deterioration. Analysis published alongside the NEED data shows while the gas savings from solid wall and cavity wall insulation are sustained in the 5 years after installation, the savings from loft insulation are around a tenth lower in the fifth year after installation, than in the first year[1]. Further analysis of the full NEED dataset may provide some additional insight on shorter term degradation. There may also be other datasets not in the public domain which may provide insight on insulation degradation, however none were forthcoming in the course of this project.

[1] https://www.gov.uk/government/statistics/national-energy-efficiency-data-framework-need-report-summary-of-analysis-2023

4. Stakeholder engagement used to classify mechanisms of damage and inform approach to address evidence gaps

Two stakeholder engagement activities were run to draw on expert insights on mechanisms of damage to insulation and inform recommendations for addressing identified evidence gaps.

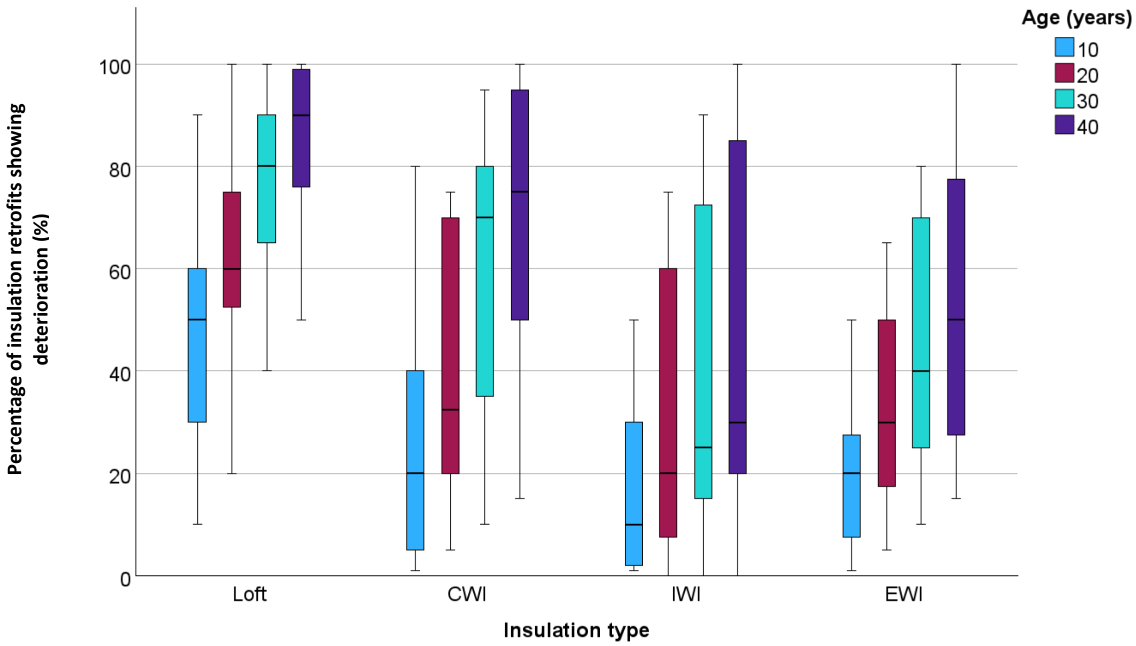
The first of these brought together experts in retrofit insulation to explore what causes insulation to deteriorate and how it affects performance. A summary of classified causes for why insulation performance can deteriorate over time is summarised in Table B.

Table B: Summary of Classification of Insulation Degradation

Insulation Type	Classifications of Deterioration
Loft	The loft insulation has been moved, e.g. to allow access to services.
	The loft insulation blocks ventilation at the eaves leading to condensation which damages the insulation.
	The insulation has been damaged e.g. by weather, vermin, or compressed by storage.
Cavity Wall (CWI)	The insulation material has deteriorated over time (e.g. crumbled)
	The insulation has been poorly installed, which means it has deteriorated (e.g., slumping).
	The insulation has been contaminated by water, debris, or vermin.
Internal Wall Insulation (IWI)	The product, design, or specification is inappropriate for the building.
	Lack of building maintenance has enabled insulation deterioration.
	Insulation has been damaged post installation e.g. DIY, flood, etc.
External Wall Insulation (EWI)	The product, design, or specification is inappropriate for the building.
	Lack of maintenance of fixings or sealants has caused deterioration.
	Cut arounds for penetrations have never been sealed leading to deterioration of the insulation.
	Insulation has been damaged post installation e.g. DIY, flood, etc.

A second stakeholder engagement exercise involved bringing together an expert panel of surveyors to gain consensus on what should be measured, how it should be measured, how the deterioration should be graded, and risk factors that surveyors should be aware of. From participants' estimates of the incidence of insulation deterioration, an approach to sampling for a potential national survey was developed. Figure A below shows the range of expert estimates for incidence of insulation deterioration.

Figure A: Expert estimates of the percentage of insulation retrofits showing deterioration.



5. Recommendations for future research to address this question

Based on degradation prevalence rates determined through expert elicitation, the researchers recommend the following minimum sample sizes for data collection:

- 180-190 homes with loft & cavity wall insulation.
- 130-140 homes with loft & internal wall insulation.
- 170-180 homes with loft & external wall insulation.

All insulation materials should be considered within scope, however priority should be given to materials at risk of settlement and/or compression. Typically, this relates to 'loose' materials such as mineral wool, blown fibre and poly-bead products.

Taken together, the observations from the literature give rise to the following recommendations for follow-on future research:

- Should have an emphasis on in situ observations and samples from the field, to accurately account for deterioration and enable lab-based performance analysis of real world naturally aged insulation products.
- Should consider a variety of insulation degradation mechanisms, including poor quality install, accidental disturbance, and material breakdown. Specifically, data should be captured to represent suboptimal conditions.
- Should also assess a range of housing archetypes and geographical spread present in the UK, to determine whether "one size fits all" estimations of performance decline are appropriate.

Contents

Introduction

This report presents the findings from the Deterioration of Retrofit Insulation Performance (DRIP) Phase 1 project. This project is looking to quantify the impact of degradation of insulation retrofits over time. This phase is primarily concerned with establishing the existing understanding of the subject and providing recommendations on whether to pursue for a future phase to address any identified knowledge gaps.

Project overview

Domestic dwellings account for around 16% of total UK carbon emissions [1], with the majority of this energy consumption associated with space heating. Reducing the energy consumption of domestic dwellings is a central component of the UK Heat and Buildings strategy [2]. Insulating the building fabric reduces the energy required to heat a home and provide thermal comfort for the occupants.

Significant improvement to the efficiency of new build housing has been made through increased minimum standards for energy conservation, as required by the building regulations [3]. It is estimated, however, that over 80% of existing homes in the UK will still be in use in 2050, many of which were constructed prior to building regulations that required high quality thermal insulation. In response, there has been significant national effort to retrospectively insulate the existing building stock though programmes such as the Energy Company Obligation (ECO).

National retrofit programmes have made a significant contribution towards reducing domestic heating energy demand [4]; however, there is uncertainty around how long these benefits can be expected to last. Current narratives around retrofit make several assumptions:

- The retrofit is done correctly and to a high standard.
- The materials will remain in good condition throughout the duration of their service life.
- The energy saving will be consistent throughout the product life span.

Evidence suggests that these assumptions are not robust, and that estimations of energy saving from retrofit may be overestimated [5]. One element of this underperformance is a decline in insulation performance over time.

This may be influenced by imperfect initial installations, external issues affecting the retrofit during its lifetime (e.g., moisture penetration or interaction with occupants), as well as a natural reduction in performance that may be expected even where the insulation is not impacted by external factors i.e., through normal wear and tear.

Uncertainty around retrofit performance has a material impact on the usefulness of future UK energy demand projections and thus the resource and infrastructure required to meet this future demand. Uncertainty in long-term performance of individual retrofit measures also has real-world implications for retrofit and investment decisions by impacting the payback period, and may require revisiting energy saving advice given to homeowners.

It is, therefore, essential to gather evidence on the long-term energy performance of retrofit. Such evidence must establish the extent that retrofit efficacy changes throughout the installed life, to update energy saving assumptions underpinning modelled energy savings as well understand implication for retrofit decisions and advice to homeowners.

This project aims to quantify the impact of retrofit degradation over time. This phase of the project aims to establish the current state of knowledge on retrofit degradation and provide novel analysis of any existing datasets. This will be used to make recommendations on the requirement and scope for a further phase of work, which will focus on gathering new data to address any identified gaps in knowledge.

This phase will address the following research questions:

1. What is the current level of knowledge on longevity and degradation of insulation retrofits over time?
2. How can poor quality retrofit be classified and evaluated?
3. What insight into retrofit degradation can be provided by utilising existing datasets?
4. What is an appropriate method for evaluating retrofit degradation and how may this be applied to a representative sample of UK dwellings?

Figure 1 shows the work packages developed to answer these questions, with research work packages expanded upon in Table 1:

Figure 1: DRIP Phase 1 work packages

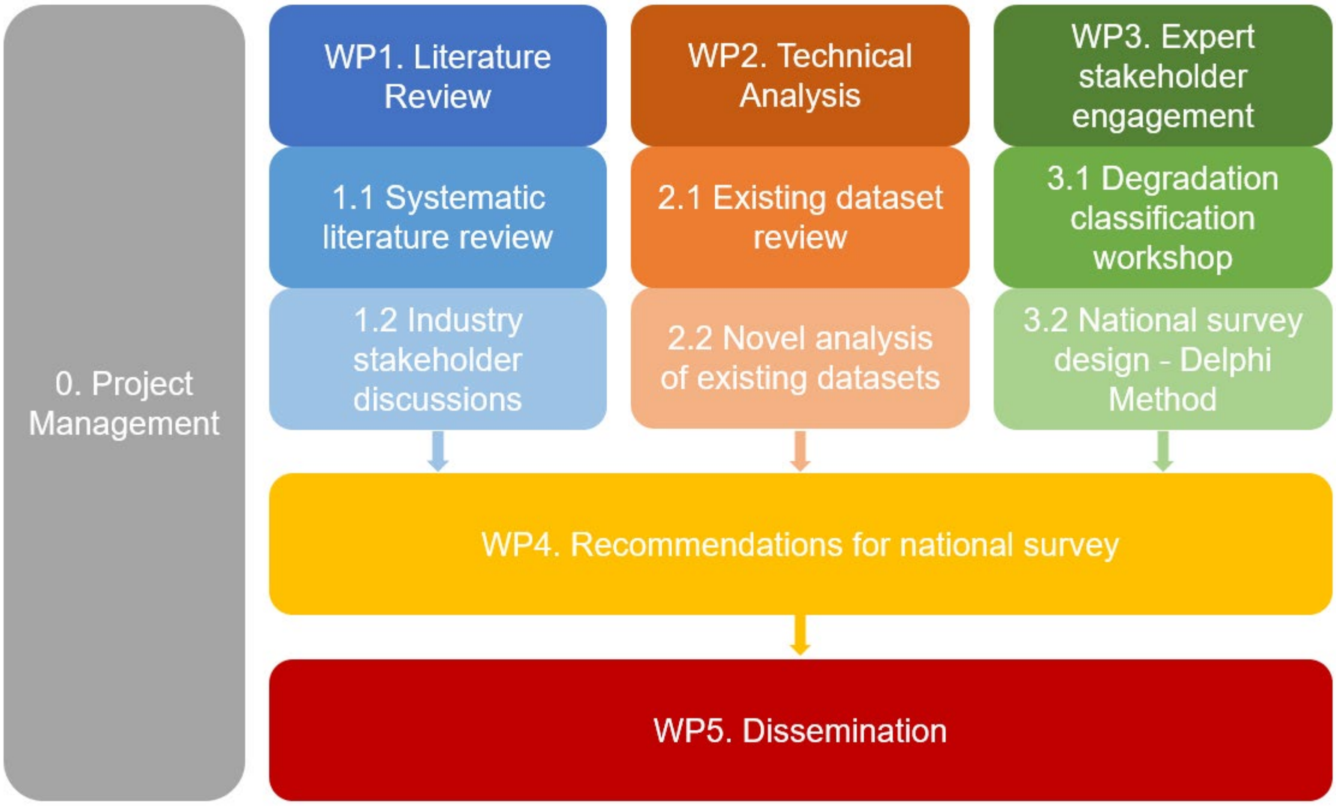


Table 1: DRIP Phase 1 research work packages

WP	Research activities	Outputs
1	• Systematic review of published academic literature. • Review of published 'grey' literature, including reports produced by government, industry, and trade/regulatory associations. • Engagement with industry stakeholders to access relevant unpublished reports and analysis.	• Synthesis of current knowledge on retrofit deterioration, with gaps in knowledge identified for Phase 2 scoping recommendation.
2	• Review of existing datasets that may be applied to DRIP research aim. • Analysis of identified datasets.	• Novel insight on retrofit deterioration using existing datasets.
3	• Workshop with key retrofit stakeholders. • Delphi study with key retrofit stakeholders.	• Classifications for retrofit underperformance. • Recommendation for methods for measuring performance degradation in Phase 2.

		• Recommendation for representative building sample that should be included in any Phase 2 survey programme.

Project scope

Buildings are complex systems, with many factors that influence their lifetime performance including (but not limited to) their construction materials, built form, age, usage, occupancy, and local context. Given this complexity, it is necessary to focus the scope of the present project.

This research is focussed on residential dwellings, with emphasis on data from the UK context. Where related research from non-UK regions or non-domestic contexts is found that is of significant relevance, this is included. All dwelling types are in scope, regardless of building typology. Where the specific local context of a building is directly related to a change in retrofit performance, for example prevailing weather, this will be highlighted during discussion.

Regarding retrofit method, this research considers only the most common retrofits installed in the UK, namely:

- Cavity wall insulation
- Loft insulation
- Solid wall insulation (both internal and external)

No exclusions are applied for the insulation material, with all insulation products that are appropriate for use in the above retrofit types considered within scope.

The focus of the present project is to evaluate change in energy and thermal performance of retrofit over time. Existing evidence for other impacts of retrofit change over time, such as structural change or occupant health, sit outside of the core purpose of this project and any identified literature that has these topics as the sole focus will be excluded from literature review. Where research considers the associated issues of deterioration alongside the change in energy/thermal performance this will be discussed, but the findings presented within this report should not be regarded as exhaustive on these related topics.

When considering the deterioration of retrofit performance, this is defined as a change in performance post-installation due to:

- Poor quality installation leading to accelerated performance decline
- Accidental damage (both human and natural causes)
- Material deterioration

It is important at this stage to note that deterioration during the lifetime of the retrofit is different to underperformance at the time of completion, which is typically referred to as the building fabric “performance gap”. There is a substantial body of evidence for the fabric performance gap [6, 7], whereby retrofit does not achieve intended savings due to poor quality workmanship, inappropriate design and material underperformance.

Whilst these issues may influence the rate at which retrofit performance deteriorates the performance gap refers to the gap between the predicted energy consumption of the design versus the actual energy consumption of the building. This project is looking at changes that take place after installation/construction i.e. during the lifetime of the insulation measure.

The research work packages will be used to develop a set of recommendations for a possible future phase of research to address identified research gaps.

Literature review

A review of both peer-reviewed academic literature and 'grey' literature produced by government, business, and industry stakeholders is an essential first step to establish existing knowledge of retrofit deterioration. This review synthesises the state of the art for research methods and helps to identify salient knowledge gaps that should be addressed in a future phase of research.

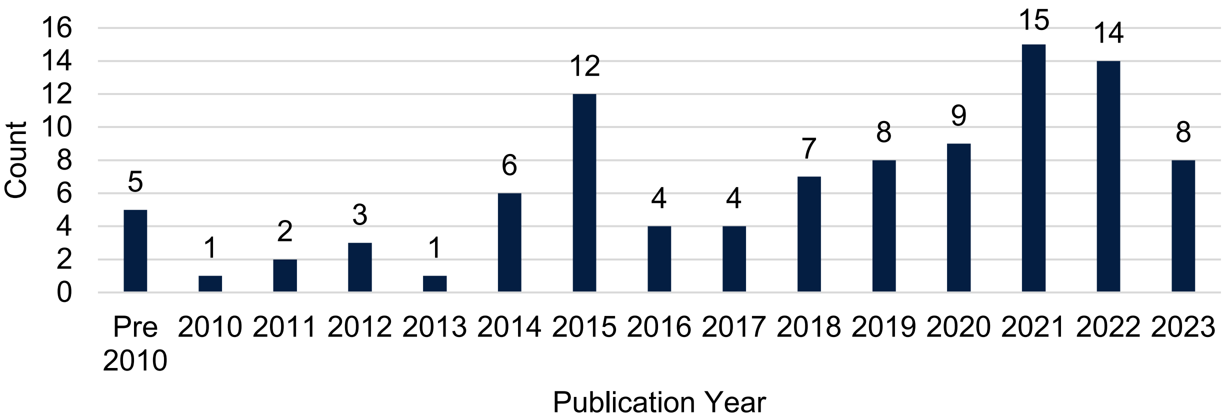
Academic literature review

A systematic review of academic literature was undertaken using defined search terms and searches of databases of peer reviewed literature. Relevant texts were identified to produce the following literature review. Further details of the literature search can be found in Appendix 1, with summarised observations from the academic literature presented in this section.

Academic literature characteristics

Before discussing the findings from literature review, it is relevant to show the contextual characteristics of the reviewed literature. Firstly, as shown by Figure 2, although there appears to be a developing interest in the subject with a growing trend of publications between 2016 and 2021, the absolute number of publications produced each year is modest given the scale of the topic, particularly when compared to the volume of literature available for associated building performance evaluation research. For comparison, the Scopus database returns 83 papers published in 2023 exploring the performance gap in buildings.

Figure 2: Academic literature, by publication date.



As shown by Figure 3 and Figure 4, it is significant to note that very little research captured during systematic review was UK-based, and this is particularly true where the research considers in situ measurements. When considering research method, the majority of the research uncovered during systematic review is based on simulation and laboratory study, as shown by Figure 5.

Figure 3: Academic literature, by publication region.

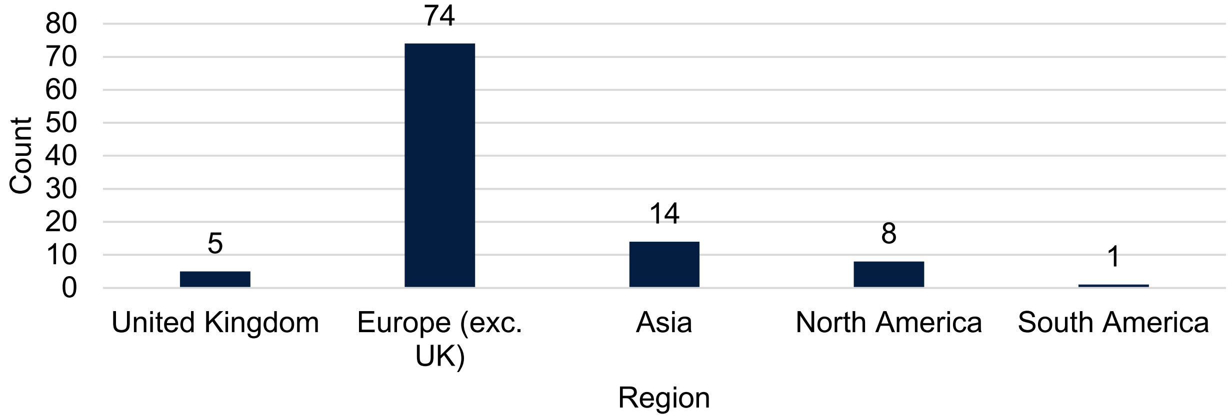


Figure 4: Academic literature applying in situ measurement, by region.

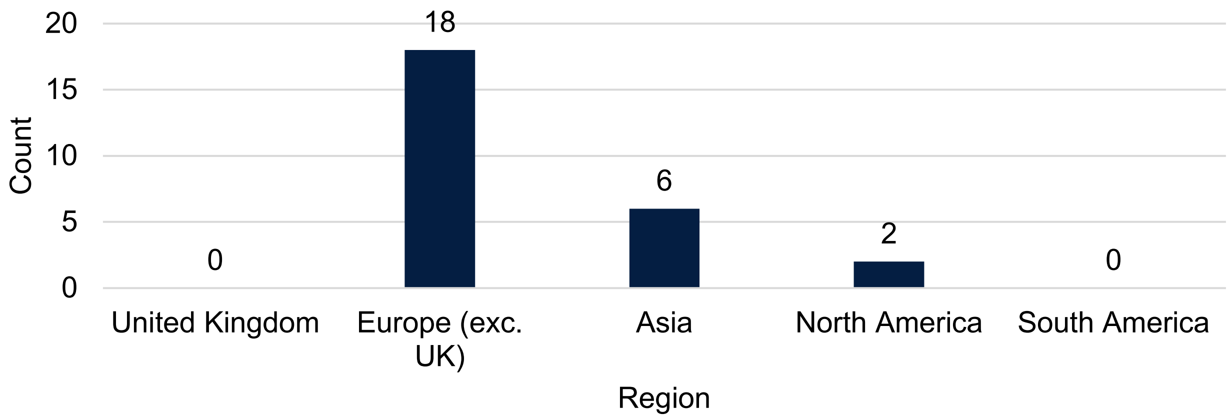
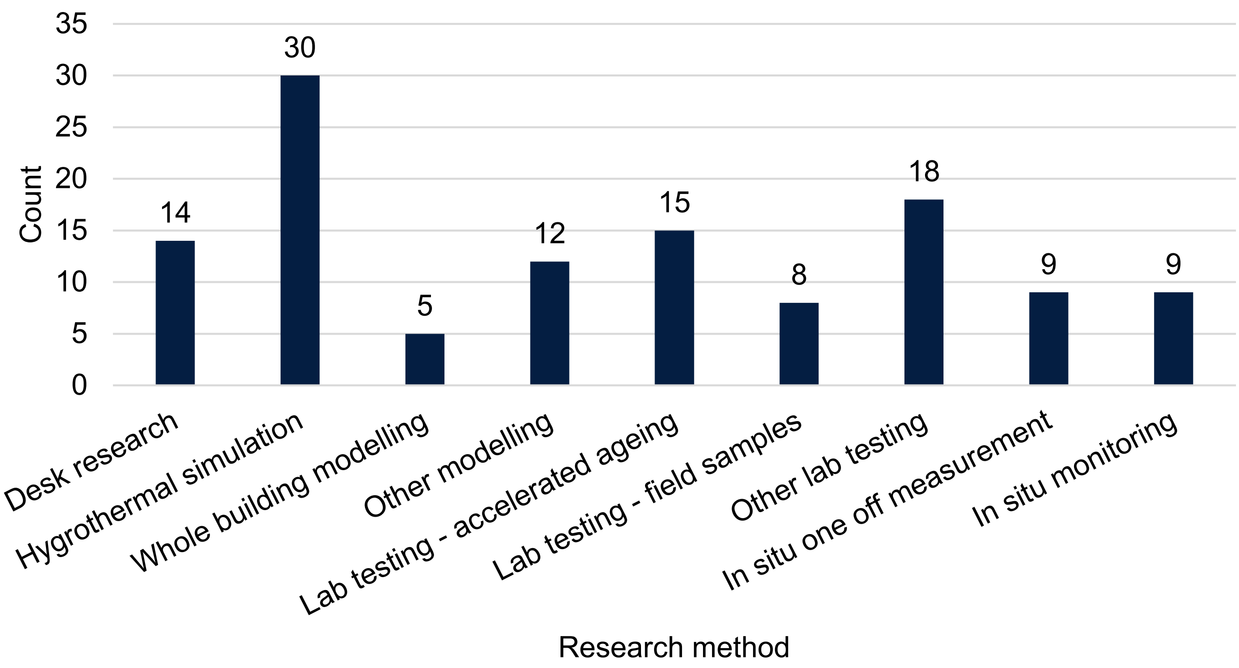


Figure 5: Academic literature, by research method.



Data collection methods

Simulation

There are multiple studies using simulation software to investigate lifetime performance, however it is often unclear how material deterioration is incorporated into model design. Studies tend to focus on hygrothermal effects (e.g., moisture accumulation) to infer risk of structural failure rather than energy effects of reduced insulation performance.

Where whole house models are used, it is possible to simulate energy saving over multiple decades under different weather and climate scenarios, although it is unclear how deterioration of materials is incorporated into energy consumption projections. Life cycle assessments for insulation materials are additionally challenging, ultimately producing lifetime energy and carbon costs with high uncertainty or producing comparisons that neglect consideration of durability completely [8, 9].

Laboratory testing

Laboratory tests described in literature fall into two broad categories:

1. Analysis of samples extracted from existing buildings.
2. Accelerated ageing.

Each method has merit, however the published results are not sufficient to fully address the aims of the DRIP research project. Where samples have been extracted from buildings and analysed, they have generally been in good condition and taken from non-domestic environments, where they will have been largely undisturbed during their lifetime. There is also a lack of research comparing the longevity of well-installed materials with poorly installed ones. Similarly, there is little research exploring the effect of damage, moisture ingress, compression, and chemical deterioration. This leads to a bias in reporting, with findings from material sample studies lacking external validity as they do not represent realistic insulation conditions for UK housing.

Accelerated ageing tests attempt to mimic damage, with forced weather effects and compression. The limitation of existing studies is that they are typically on the more extreme end of the spectrum, for example submersion or heating to 100°C [10-12]. This again may not be representative of the UK housing stock insulation condition. Some tests may also misrepresent full insulation system performance decline [13] where materials are sliced, obscuring bulk heat transfer properties and exaggerating surface/edge effects.

More generally, the current body of literature for testing of both real-world samples and accelerated ageing is limited in scope for both materials and conditions. More research is needed for useful application to any deterioration prediction model.

In situ field testing

There is a wealth of evidence evaluating building performance immediately following retrofit up to approximately 1 year post retrofit [14]. These studies provide useful insight into qualitative (thermography, visual survey, borescope survey, material forensics) and quantitative (coheating [15], heat flux [16], moisture measurement) methods to evaluate insulation performance and condition.

There is a lack of field study research extending beyond this time frame to provide longitudinal data for energy consumption post-retrofit [14]. This is likely due to the nature of research funding, which often suffers from short-term budgetary limitations. There may, therefore, be significant value in revisiting homes that have been previously tested in earlier studies (for which good data exists) to measure performance deterioration.

A summary of specific methods observed in the literature is shown in Table 2.

Table 2: Research methods observed in the literature.

Type	Method	Description
Simulation	Hygrothermal simulation	Physical law-driven model to evaluate moisture transfer in materials.
	Whole building simulation	Physical law-driven digital representation of a dwelling with weather, energy use and ventilation simulated over an extended duration.
	Energy modelling	Data-driven model to predict future energy consumption from prior trends.
Laboratory Testing	Accelerated ageing	New insulation materials exposed to extreme heat, moisture, and disturbance to rapidly induce stress/deterioration.
	Passive / Natural ageing	Ageing of materials under natural conditions over a long duration.
	Gravimetric measurement	Sequential weight measurement of an insulation sample to evaluate moisture and composition.
	Heat flow measurement	“Hot Box” test cell that induces a temperature gradient across a sample to measure rate of heat flow.
	Climatic chamber	Artificially controlled environment to test energy performance under different thermal/weather conditions. Can be used for whole buildings or individual samples.

Type	Method	Description
	Capillary absorption	Measurement of the moisture absorption rate of a material.
Field Testing	Thermography	Use of thermal (infra-red) camera to identify areas of heat transfer.
	Coheating	Method to measure the whole house heat loss coefficient of buildings.
	Heat flux measurement	Method to measure individual heat loss (U-Value) of single construction elements.
	Longitudinal monitoring	Long-term monitoring of energy, temperature, and humidity to identify change over time.
	Surveying	Visual assessment of building condition.

Insulation degradation - Laboratory tests

Laboratory tests to determine the extent of degradation of insulation products allow for a controlled setting, where the experimental parameters can be determined by the researchers. A range of test methods have been employed within the literature.

Polystyrene is a common insulation material found in buildings, found as both Expanded Polystyrene (EPS) and Extruded Polystyrene (XPS). A review of testing of polystyrene insulation found that when the water content by volume increases above 10%, in both expanded polystyrene and extruded polystyrene products, the thermal conductivity begins to increase rapidly with increased water content [17] meaning the performance of the material as insulation declines.

In a separate study a number of samples of both EPS and polyurethane (PU) insulation within a test wall were exposed to South Korean external and ambient internal conditions over a period of 5000 days (over 10 years) to evaluate passive ageing under natural conditions. Heat flow meter measurements were carried out on the samples during the ageing period [18]. The thermal resistance of all samples reduced over time as the samples aged due to loss of the blowing agent. In all cases, each insulation material fell below the South Korean national standard requirement for insulation performance. EPS experienced a thermal resistance decrease of 20.6 – 42.7%, PU foam decreased by 23.7 – 30.6%.

The dimensional stability of EPS has also been tested within the literature, as EPS is often used as a structural component of external thermal insulation composite systems (ETICS) and as such, changes in size and shape can result in cracking and failure of a system. The dimensional stability of graphite infused (grey) EPS and plain (white) EPS were compared in response to exposure to intense sunlight [19] – samples were exposed to natural sunlight and artificial sunlight on a test stand. Under natural sunlight, the samples did not reach the stated melting point of the EPS materials and remained stable. Under more intense artificial sunlight, softening of the EPS material occurred, leading to surface deformation, and warping of the EPS boards, with the grey EPS boards being more strongly affected. Another experiment exposed grey EPS to elevated temperatures over time [20]. After exposure to 70°C for 6 weeks, the thermal conductivity of the samples increased marginally. When exposed to temperatures of 110°C for 1-hour, thermal conductivity increased by 8-10%. In addition, shrinkage of the samples occurred, which could lead to structural failure in an ETICS installation.

Accelerated ageing tests on mineral wool found that exposure to moisture and liquid water degrades the binding additives, along the fibres that make up the material, resulting in degraded compression resistance and increased moisture retention. This resulted in worsened thermal performance [21]. Testing to simulate longer term exposure (100 years) of in-use climate cycles found that the insulation products' performance declined and would be unlikely to last 100 years in use [22].

Long term, natural ageing of glass wool and mineral wool insulation products has also been undertaken. In tests undertaken on a timber frame test wall, exposed to the external environment and ambient internal conditions over a period of 7 years, the results found that the thermal performance of the insulation degraded by 6 - 19%, largely due to moisture accumulation [23].

Vacuum insulated panels (VIP) are a high-performance insulation product, consisting of a porous insulation core encapsulated in a foil material under partial vacuum, which has the effect of lowering the thermal conductivity of the whole product. However, the foil encapsulation is also a weakness of VIPs. Heat flux measurements undertaken on VIPs found that the overall system thermal conductivity is worsened by thermal bridging at the joints between the VIPs. Damage to the foil encapsulation, resulting in subsequent vacuum loss, resulted in a measured increase in thermal conductivity from 0.0034 W/mK when intact to 0.0228 W/mK [24].

Ageing of VIPs can also lead to a moisture ingress into the product. In one study, VIP samples were aged passively and under accelerated ageing conditions [25], with sample weight increases taken to indicate water penetration. Sample weight increased the most under extreme climate conditions (70°C temperature, 90% relative humidity) causing the foil encapsulation of some of the samples to fail. In extreme ambient conditions, which were more representative of in situ conditions, the lowest increase in mass occurred (up to 0.6%). Although the authors of this study did not measure changes in thermal conductivity, any increase in water content within the insulation material would also result in an increase in the thermal conductivity of the insulation panels. Similar results were also obtained by other authors when ageing VIP samples under controlled environmental conditions [26].

Aerogel is another high-performance insulation product; its low thermal conductivity allows thinner applications of aerogel products to achieve the same target thermal resistances. A blanket form of aerogel insulation is one practical application of this material. The effect of moisture content on the thermal performance of aerogel blankets has been measured [27] after exposure to high levels of humidity for up to 24 hours, the moisture content in the samples increased and reached 6.5% by weight. This also resulted in a significant increase in the dry thermal conductivity of the samples, rising from 0.018 W/mK to 0.029 W/mK. Although the dry thermal conductivity of the samples increased significantly (almost two-fold), U-value calculations indicated that the increase in moisture content would only result in the thermal transmittance through a full wall construction increasing from 0.70 to 0.86 W/m^2K, principally due to the thinness of aerogel layer relative to the brick and plaster forming the whole wall construction.

Aerogel insulation can also be found in granular form. Samples of aerogel granules exposed to accelerated moisture ageing were sealed in a chamber and then exposed to cycles of elevated temperature and relative humidity [28]. After accelerated ageing equivalent to 10-20 years of in situ exposure, the thermal conductivity of the aerogel samples had increased by 5-10%.

In addition to man-made insulation products, there are also a number of natural insulation products, which have increased in popularity in recent years. Natural insulation materials encompass a wide variety of sources, including plant fibres, animal hair and beyond. Degradation of the fibres in natural insulation products, due to moisture loads, has been highlighted as a particular concern. For instance, a hemp mortar based ETICS was subjected to accelerated ageing protocols to investigate deterioration during exposure to the elements. It was found that the plant fibres within the mortar had degraded, resulting in an increase in the water vapour permeability and a minor increase in the thermal conductivity [29].

Passive ageing studies have also been undertaken on natural insulation products. For instance, a study related to the passive ageing of wood fibre insulation installed within a timber-framed test wall was carried out over a 7-year period. The walls were exposed to the external environment on one side and ambient internal conditions on the inside. The wood fibre was found to have increased in thermal conductivity by 90% due to moisture accumulation in the insulation itself. Glass fibre and mineral wool insulation were also tested in the same experiment, and these products increased in thermal conductivity by 6 - 19% [23]. In another experiment, wood fibre was fitted to a test wall between two climate chambers, representing a cold climate and an internal climate (a ‘hot box’ test chamber). The results found that the wood fibre insulation had the greatest moisture accumulation and mould was also detected at the boundary between the insulation and the wall [30].

Whole ETICS products, including insulation, external finishes and adhesives have also been tested, to examine how the systems as a whole respond to ageing. Several ETICS samples, each with a different insulating material, were put through accelerated ageing cycles, including wetting, heating - cooling and freeze - thaw [31]. Following accelerated ageing, the thermal transmittance of the Polyurethane sample had increased by 5% and the EPS sample by 2%. The short-term water absorption of the external finish of all samples also increased following accelerated ageing. This could lead to worsening thermal performance and shortening of system service life.

The laboratory testing of insulation products and systems in the academic literature indicates that all insulation can be expected to degrade in thermal performance over time. Foamed plastic products, such as polystyrene and polyurethane, also appear to degrade over time due to loss of blowing agents.

Water accumulation is a factor in the degradation of all insulation products, increasing the thermal conductivity of the base material and thus degrading thermal performance. Water also degrades the structural integrity of products, such as mineral and glass wools, breaking down binders. Natural materials are also susceptible to moisture accumulation, degrading their thermal performance as well as posing a risk of biological deterioration.

Insulation degradation – In situ

In situ installations of insulation also feature in the literature, where insulation has been installed in buildings that are in use and not for the purpose of scientific evaluation.

A review of Polystyrene insulation found that XPS tended to have a constant water content by volume of around 1% until ten years, where the range of water content would then increase. In contrast, EPS would have a much higher initial water content, up to 10% from year 1 onwards [17]. This indicates that in situ XPS polystyrene insulation resists moisture accumulation better than EPS polystyrene insulation. However, it should be noted that the sample within the review includes insulation that had suffered from a failure and is not necessarily reflective of insulation that is in good condition.

In a separate study, samples of mineral wool insulation batts were removed from a number of case study buildings in Italy; the insulation had been installed within cavity external walls for 25 years before sampling [32]. Although the samples were found to be in good condition, the thermal conductivity of the mineral wool insulation was found to have increased by 10 – 12% and the in-situ measurement of the case study walls resulted in an increase in U-value of between 8 – 10%.

In contrast, a 10-year-old sample of mineral wool insulation batt was taken from the roof of an industrial building, where a failed steam vapour barrier had allowed moisture to accumulate within the insulation. Laboratory analysis found that the binder materials had degraded over time due to exposure to high levels of moisture, resulting in reduced compressive strength and resistance to moisture accumulation [21]. The impact of the degradation on the thermal conductivity was not measured.

With respect to VIPs, the fragility of the encapsulation of the material is a risk in situ, with an estimated 5% failure rate, primarily attributed to damage during the construction process [33]. Monitoring of temperature and humidity within a wall retrofitted with an external thermal insulation cladding system utilising VIPs over 5 years detected no deterioration in wall temperatures or accumulation of moisture, indicating that the VIPs had not failed or degraded over the monitoring period [33].

Another investigation of VIP failure in an ETICS installed in Switzerland revealed that the foil barrier of the VIPs was subject to an almost 15% failure rate [34]. This was attributed to manufacturing defects, which resulted in premature failure and vacuum loss giving an estimated thermal conductivity range of 0.004 – 0.020 W/mK for the insulation panels fitted to the building [34].

The body of research identified for in situ degradation of insulation is much less comprehensive than laboratory-based research, with fewer insulation materials represented within the in situ literature. Importantly, direct measurement of insulation thermal conductivity was also not carried out in all in situ research.

The findings from the in situ research shows some similar trends to laboratory-based research. Moisture accumulation is observed to occur, even where installations are in good condition. Degradation of system performance due to the effects of ageing also occurs in situ.

It is worth noting that the reviewed in situ research did not take place in the UK, which places a limitation on their value for evaluating retrofit deterioration in the UK context. Regional differences in both weather and construction heritage may be a relevant factor in the studies' findings.

Degradation of installations

Degradation of the overall insulation system installation can also lead to reduction in thermal performance through complete system failure. A Delphi survey of stakeholders and experts on the subject of failure in ETICS installations found that the majority of defects visible within the first few years of installation were due to shortcomings during construction/installation. Substrate preparation and adhesive application at the construction stage were found to have a high impact on the severity of defects and were the most likely to result in complete system failure compared to lifetime influences such as weather and accidental damage. Additional detailing such as windowsills and penetrations were found to be a significant cause of degradation and highly likely to result in moisture penetration. Poor sealing of the outer coatings was found to increase the risk of degradation due to weather [35]. As shown previously, moisture accumulation within the insulation is linked to degradation in thermal performance of the wall.

Although not a domestic context, poor fitting of a vapour barrier in the roof structure of an industrial building leading to failure of the barrier was also observed. This allowed humid air to pass into the roof space, resulting in moisture accumulation in the mineral wool roof insulation [21].

Externally fitted insulation is also vulnerable to degradation on the external surface. 71 apartment blocks in the Czech Republic fitted with ETICS were surveyed for biological growth on the external surface, with surface render samples taken from 10 buildings [36]. Analysis of biological growth found it to consist mostly of algae and to a lesser extent fungi. The biological growth was not found to be causing deterioration of the ETICS, however the potential for future degradation could not be ruled out. Other research has also observed a high rate of biological growth on ETICS installations. For instance, 80% of buildings surveyed in Slovakia were subject to biological growth, which could in turn lead to spalling of the external finish [37]. Lack of coatings that inhibit biological growth or scheduled maintenance to clean the external surfaces allows biological growth to accumulate.

Shortcomings of insulation system design or during the construction process can lead to future deterioration or failure of insulation systems in use. Defects that allow moisture to accumulate within the insulation system are likely to result in degradation of thermal performance.

A lack of best-practice, scheduled maintenance of insulation systems, particularly ETICS which is exposed to the external climate, can lead to degradation on the external surfaces, which may progress to more severe degradation of the insulation.

Degradation of the structure

Degradation of the insulation system is not the only risk when applying insulation to a building. There can also be degradation that occurs within the structure of the walls and at the boundary between insulation and wall. Hygrothermal simulation is often used to assess moisture risks in wall build ups, it can simulate the movement of heat and moisture through building materials and indicate whether there is a risk of moisture accumulation and potentially biological growth.

Biological deterioration of timbers embedded in walls are a particular concern when retrofitting walls with internal insulation (IWI). A hygrothermal simulation of solid brick walls in a building in Denmark fitted with IWI found that the retrofitted insulation increased the risk of degradation of floor timbers embedded in the brick structure, due to moisture accumulation. Introduction of a gap above and below the floor structure eliminates the risk [38]. Another investigation [39] used hygrothermal simulation to assess the risk of biological deterioration at embedded timbers in a masonry wall, investigating the effect of external renders when used in conjunction with IWI. Hygrothermal simulations found that the best strategy to limit risk to embedded timbers was to limit water ingress from the external environment, using renders with low capillary absorption.

Hygrothermal simulations are not the only way of assessing moisture risks following installation of insulation, with some laboratory tests and in situ tests also conducted. One such test involved a laboratory test wall between two climatic chambers, and 4 different insulation products [30]. Conditions in the climate chambers represented a cold external climate and an internal environment [30]. Relative humidity was found to be in the range conducive to mould growth at the boundary of all materials. Wood fibre was found to be higher risk for mould growth other materials such as EPS and mineral wool, with mould found at completion of the experiment. Divergence between hygrothermal simulations of the test setup and measurements highlight the importance of carefully considering the material properties of a wall before carrying out hygrothermal simulations to investigate the risks of moisture and biological growth.

In situ monitoring of an apartment block in Denmark fitted with IWI consisting of capillary active calcium silicate, which enables moisture to move through the material, was carried out to investigate whether using “breathable” insulation materials reduced moisture risks within the walls [40]. The interface between wall and insulation was monitored for 6 years for moisture accumulation, after 12 months the construction moisture was found to have dried out and at the end of the monitoring period it was found that hygrothermal conditions were within acceptable limits with a low risk of mould growth.

Looking ahead to future climate conditions is also important to assess the robustness of retrofits during their expected service life. A series of hygrothermal simulations of a solid wall fitted with 3 types of insulation in projected UK future climate scenarios was performed, assessing moisture accumulation and mould risk [41]. Under current climate conditions the insulation systems did not pose a risk, however in future scenarios with expected increases in average temperature the risks increased. Thinner insulation systems with lower thermal performance posed less of a risk in future scenarios, and of the materials simulated calcium silicate insulation, which is capillary active, performed the best as it could transport moisture away from the wall structure.

> Moisture accumulation within a wall structure following the retrofit of IWI is understood to be a risk, leading to potential biological deterioration of timbers embedded in walls and mould growth behind the insulation layer. IWI is the focus of this type of research.
>
> Uncertainties of material properties can lead to discrepancies between hygrothermal simulation outputs and measurements taken in laboratory tests or in situ. Future climate conditions are also highlighted as an issue, as these are the conditions that insulation will be subject to.
>
> Vapour permeable insulation systems pose the least risk of moisture related degradation in IWI applications, as they allow moisture to dry out.

Observations from academic literature

The following themes have been identified in the academic literature gathered as part of this review:

Unequal representation of insulation products

Published academic research on insulation focusses mainly on internal and external insulation systems (those that are applied either to the internal or external face of walls to be insulated) with 20 documents on IWI and 37 on EWI. Other insulation types were less represented: 2 documents on the subject of cavity wall insulation, 1 on timber frame insulation and 1 on roof insulation were found.

> This suggests that there is limited evidence in published academic literature on the long-term performance of cavity wall insulation and loft insulation. Incidentally, these are the most prevalent types of insulation in the UK housing stock and thus this finding represents a significant knowledge gap.

Lack of in situ or field measurement

Investigation methods used within the identified literature included various simulation techniques (predominantly hygrothermal simulations) in 47 documents, followed by laboratory measurements in 41 documents. *In situ* investigations were the least used, present in 18 documents.

> This finding suggests that there is a significant gap regarding in situ retrofit performance data and any Phase 2 data collection should prioritise in situ data.

Where deterioration of the insulation material was considered, this was mostly done through laboratory measurements, either of pristine materials which would undergo accelerated ageing techniques or, in fewer cases, materials that had been recovered from buildings.

This finding suggests that there is limited data from field study representing real scenarios. Any Phase 2 project should therefore aim to include measurement from realistic settings.

Research focus rarely considers energy/carbon implications

Investigations into deterioration were largely focussed on the accumulation of moisture, either within the insulation or the wall structure itself, and how the accumulation of moisture was affected by the hygrothermal properties of the original wall, or those of the insulation materials. Environmental condition’s impact on moisture risks was also present in a subset of documents. Studies that considered these factors were largely undertaken using simulation software.

It is apparent that existing literature does not consider retrofit deterioration over time from the perspective of energy saving or insulation performance. This represents a knowledge gap relevant to DRIP and highlights the requirement for additional exploration of the topic.

A leading cause of material performance degradation was identified as moisture accumulation, either through moisture movement or failure of protective barriers leading to moisture ingress from external sources.

Literature focus is predominantly on the failure of moisture barriers, such as external renders. There is limited follow-up on the impact of this failure on the energy performance of the insulation product, and this should be considered during Phase 2.

Differentiation between underperformance and deterioration

A leading cause of insulation system failure was identified as inappropriate design that failed to consider the situation insulation would be installed in. Inadequate installation practices in the fixing and/or finishing of insulation systems was also identified as a major potential for moisture ingress leading to failure over time, particularly in insulation systems exposed to the external environment.

Published literature appears to be aware of the issues of poor-quality retrofit design/installation and the consequences of this (e.g., moisture ingress). There appears to be limited exploration beyond this acknowledgement of an issue, however. This indicates a requirement for further exploration into the long-term energy effects of material degradation.

Unrepresentative assessment of ageing effects

Ageing was identified as a factor in the decline of some insulation material thermal performance, as chemical and structural changes within the materials occurred over time and exposure to heat and moisture.

> There appears to be a body of literature available to classify some causes of insulation underperformance, but this is limited to certain products with a reliance on laboratory experiments.
>
> Where tests have been undertaken to investigate ageing, these typically rely on unrealistic/unrepresentative scenarios, such as accelerated ageing cycles. Additionally, several tests (e.g. thin slicing of insulation materials) may not be an accurate characterisation of the bulk properties of an insulation product and may overestimate the significance of surface/edge effects on whole-system performance.
>
> Further research that includes a broader range of both deterioration factors and insulation products is required to better understand the energy performance impacts of material deterioration.

Grey literature review

Targeted literature review methods were applied to investigate grey literature resources, utilising internet search engines and industry catalogues such as the Construction Information Service. Efforts were also made to obtain resources not in the public domain via contact with industry stakeholders. Due to the broad scope of literature defined as ‘grey’ (i.e. not peer reviewed), this section of the report is arranged according to source with overarching observations summarised alongside the academic publications where relevant.

Insulation manufacturers’ trade associations

Publications from insulation manufacturers’ trade bodies were explored to identify information on claimed performance lifetimes of products and information on what interferes with those lifetimes (e.g., damage, poor installation, mistreatment). Whilst likely that such documents lack objectivity and may incorporate significant bias, the hope was that they may provide useful information on what risks apply to materials, together with supporting data.

The Insulation Manufacturers Association (IMA) is the representative body for the polyisocyanurate (PIR) and polyurethane (PUR) insulation industry in the UK. They claim that their products (solid foam panels) last longer than wool/quilt in summary literature [42] with reference to supporting literature [43, 44] specifically focussed on resistance to moisture ingress and settling effects over time.

The Federation of European Rigid Polyurethane Foam Associations undertook laboratory testing of previously installed Polyurethane insulation samples that were 28 and 33 years old, reporting that the “tests demonstrated that, after decades in application, these PU insulation boards were fully functional and still reached all originally declared values and performances" [45]. When considering the data, both samples appeared to show an improvement in performance, which would not be expected given the assumption for declining performance during product lifetime due to chemical deterioration.

Such claims of superior performance are countered by the Mineral Wool Insulation Manufacturers Association (MIMA), who state that fibrous materials have the advantage that they do not "rely on injected gas that can leak and result in a deterioration in thermal performance"[46], instead insulating with trapped air.

The European Insulation Manufacturers Association (EURIMA) conducted testing on mineral wool insulation products from seven samples (4 wall insulation, 3 roof insulation) aged between 20-55 years old, concluding that "the thermal properties of mineral wool in building applications are highly durable" and that "the energy-saving properties of the sampled insulations are not questionable" [47]. A subsequent press release from EURIMA states that "the assessment of the thermal properties as a function of time gave no evidence of a decline due to ageing effects" [48].

Although the reporting appears robust, with tests conducted by respected third-party laboratories, it is noteworthy that samples were selected from properties with no structural defects and that the research focussed on "natural ageing under regular conditions". Additionally, samples were selected from non-domestic buildings.

Manufacturer trade association literature suggests that product performance does not significantly decline over time, although this is predominantly in reference to the product(s) that each organisation represents and may involve bias. It is not uncommon for organisations to claim that other (competitor) products do deteriorate over time. Where testing has taken place, this typically involves materials in good condition from non-domestic buildings, which may not be representative of the insulation condition of the domestic housing population.

Manufacturer product literature

Product literature from manufacturers typically claims that performance is consistent for the product's lifetime regardless of product type [49-65]. Where product certification documents are available, reference is made to international standards as evidence for unchanged performance. It is relevant to note that these claims refer to insulation that is in good condition throughout its service life.

The role of standards is discussed later in this review, however it is worth noting that although the standards for many products do indeed state that conductivity does not change over time, they provide a condition for including compressive creep (i.e., the gradual compression of materials over time reducing their thickness and, thus, their resistivity). This consideration is notably absent from much product literature, where compressive strength is considered separately and the link with conductivity is not made.

When considering the anticipated life of products there appears to be some variability, although a consistent trend is for insulation manufacturers to claim long product service life. This is presumably to avoid classification of insulation products as "short lived materials" and adhere to the requirement for consistent property performance as stipulated by Regulation 7 of the building regulations [66].

In their paper, *Kono et al [67]* summarised stated product service life for numerous products, reproduced in **Table 3 below. Kono *et al* expanded that "service life may differ according to the surrounding environment of the buildings". The surrounding environment is not a trivial concern, with certain products likely to be more affected by moisture accumulation and air movement. This is a limitation of manufacturer documentation, which considers idealised conditions when presenting both performance characteristics and anticipated service life.**

Table 3: Manufacturer stated product lifetimes

Product	Service life (years)
Cellulose fibre	50
Fibreboard	50 / Building lifetime
Foam glass	Unlimited
Stone wool	Building lifetime / unlimited
Vacuum insulated panels (VIPs)	40
Polyurethane (PU)	50
Expanded polystyrene (EPS)	35 - 50
Extruded polystyrene (XPS)	Building lifetime

Source: Kono et al (2016) [67]

Manufacturer product literature appears to be limited in its usefulness for objective determination of performance deterioration over time, typically stating performance under idealised conditions. Despite requests being made, additional datasets to substantiate unchanged performance were not forthcoming.

International standards

Multiple standards exist for insulation products, which describe product characteristics and include procedures for testing, evaluation of conformity, marking and labelling. Within each standard there is a consideration of performance deterioration over time, summarised in Table 4. As can be seen, for most insulation products the international standards state that conductivity does not change over time. Where deterioration is acknowledged, a method for determining this is given, which is generally an accelerated ageing lab test with effects averaged over a 25-year period. Interestingly, this average period is substantially shorter than manufacturer-stated product service life.

It is important to highlight that where the assertion of no change in conductivity is made, there is an additional requirement to account for compressive creep. In other words, the standards consider the physical properties of the material unchanged but acknowledge that product thickness may vary due to loading or gravitational forces acting upon the material. This is particularly relevant for materials that derive their insulating qualities from trapped air/gas such as mineral wool. Furthermore, standards do not account for damage, moisture ingress or any other factors that may reasonably occur during a product service life.

Table 4: Summary of British Standard insulation deterioration over time statements

Standard	Material	Deterioration Statement
BS EN 13162:2012+A1:2015 [68]	Mineral Wool	"Thermal conductivity of mineral wool products does not change with time"
BS EN 13163:2012+A2:2016 [69]	Expanded polystyrene	"Thermal conductivity of EPS products does not change with time"
BS EN 13164:2012+A1:2015 [70]	Extruded polystyrene	Appendix C - Procedure for determination of the aged values of thermal resistance and thermal conductivity – 25-year average.
BS EN 13165:2012+A2:2016 [71]	Polyurethane foam	Appendix C - Procedure for determination of the aged values of thermal resistance and thermal conductivity – 25-year average.
BS EN 13166:2012+A2:2016 [72]	Phenolic foam	Appendix C - Procedure for determination of the aged values of thermal resistance and thermal conductivity – 25-year average.

Standard	Material	Deterioration Statement
BS EN 13167:2012+A1:2015 [13]	Cellular glass	"The assessment and verification of constancy of performance shall be carried out in accordance with EN 13172 [73]".
BS EN 13168:2012+A1:2015 [74]	Wood wool	"Thermal conductivity of factory-made wood wool products does not change with time"
BS EN 13169:2012+A1:2015 [75]	Expanded perlite board	"Thermal conductivity of EPB products does not change with time"
BS EN 13170:2012+A1:2015 [76]	Expanded cork	"Thermal conductivity of insulation cork board products does not change with time"
BS EN 13171:2012+A1:2015 [77]	Wood fibre	"Thermal conductivity of wood fibre products does not change with time"

International standards provide useful insight into product deterioration and methods, but they are lacking a real-world usefulness, considering only idealised laboratory performance.

There is also an apparent divergence between standards and manufacturer documentation when considering product lifetime. Furthermore, manufacturers appear to take durability statements for thermal conductivity out of context when considering product lifetimes, with standards requiring that accommodation is made for compressive creep.

Product guarantee/certification schemes

It is anticipated that any organisation offering a guarantee of performance over time must have evidence beyond the marketing documentation of product manufacturers. Both the Cavity Insulation Guarantee Agency (CIGA) and Solid Wall Insulation Guarantee Agency (SWIGA) offer guarantees on installations of wall insulation. These organisations offer cover on materials and workmanship for 25 years, although it is unclear where the guarantee for materials emanates from and why only the 25 years period, given the previously stated product lifespans from manufacturers. One notable caveat to the guarantee offered by CIGA is that "the guarantee is not valid if the insulation has been altered or disturbed" [78] and it is unclear whether disturbance includes unintentional damage.

It has not been possible to identify the origin of CIGA or SWIGA lifetime performance periods. Similarly, it has not been possible to identify additional data that underpin their guarantee of performance longevity. As such, these guarantee periods should not be considered indicative of actual product lifetimes.

Government reports

The most recently published analysis from government sources pertaining to DRIP is that derived from analysis of the National Energy Efficiency Data-Framework (NEED). In the most recent summary statistics, performance over time for insulation materials has been estimated using the ‘difference in difference’ method used for calculation of savings after single time periods [79] with the process repeated year-on-year for a 5-year duration. Whilst insightful the savings estimates are somewhat limited, being “indicative rather than precise” due to several unknowns about the retrofit installations and households.

Other published reports appear to focus on establishing the performance gap of retrofit immediately following installation, with any monitoring limited to one year following retrofit taking place [80-84]. Post-retrofit data collection was limited to occupied energy use, internal conditions and occupant feedback, and methods to determine HTC from these data (e.g. SmartHTC) were not applied. Whilst insightful for establishing immediate underperformance against predicted in use energy consumption following retrofit, there is limited scope to extrapolate the findings to a wider appraisal of performance deterioration.

Recent research produced by UCL and BRE explored the potential for waterproofing of cavity walls in exposed regions, and in doing so investigated the deterioration in performance caused by wetting of cavity wall insulation products [85]. This research demonstrated performance deterioration due to wetting with a 31% change in conductivity for untreated walls, a consideration that is absent in industry-produced reports and documentation that only observe idealised conditions.

Government datasets exist that evaluate the current quality of insulation materials, such as the report produced by the Office for National Statistics [86], which uses ratings data to infer quality based on a range of factors collected during EPC assessment. Similarly, the English Housing Survey [87] reports the extent of insulation in homes, together with data on quality e.g. depth of insulation in the loft space. Although valuable in providing context for UK housing, neither dataset is able to evaluate deterioration of retrofit products, and the associated impact of this on energy performance, with sufficient accuracy. When considering EPC-level specifically, “the assessment [of insulation quality] is often based on assumptions around the property’s age and does not involve visual inspection of insulation”[86].

Although not UK based, reports produced in the USA by the US Army Corps of Engineers [88] investigated the long-term performance of five commercially available insulation materials including nonwoven insulation liner, aerogel blankets, closed cell spray polyurethane foam, extruded polystyrene and fiberglass batt. Tests exposed materials to accelerated ageing processes in a laboratory, finding that moisture absorption was a major contributor to changes in the thermal properties of the materials, in addition to loss of blowing agent over time.

There is a wealth of literature that explores retrofit performance immediately following construction work taking place. There is, however, a lack of longitudinal data following retrofit to support evaluation of performance changes over time. Where studies include in-use monitoring, this is typically limited to one year following retrofit.

Non-public datasets

CIBSE & Studio PDP currently have a report in pre-publication [89] that is an independent UK case study comparing retrofit thermal performance as installed and after an extended time period. The report considers the performance of 10 properties a decade or more since undergoing ‘deep’ retrofits. All retrofits were considered ‘exemplar’ or ‘best practice’ at the time, with all 10 retrofits evaluated at the time of the original retrofit, allowing a ‘then and now’ comparison, although in some cases further retrofit work had been carried out.

The cohort’s overall air permeability increased slightly, with an average of 2.54 $m^3/h.m^2$@50Pa (up from an average of 1.98 ~10 years ago), and remained a high standard compared to pre-retrofit condition. The report suggested that much of this increase was due to door and window seals deteriorating since the original retrofit, rather than material degradation of the building fabric or de-bonding of specialist tapes and membranes.

No coheating tests or other reliable measurement of heat transfer coefficient (HTC) was conducted on the original retrofits, but SmartHTC assessments were undertaken using monitored data at the 10-year post retrofit stage. 9 of the 10 properties showed an increase in HTC, but it was unclear whether this was due to the performance gap of the original exemplar retrofit or due to performance deterioration over time since then.

Material degradation appeared to be limited to small areas and was often determined to be due to damage, faults and poor maintenance regimes rather than problems with the products themselves. Water ingress through lack of cleaning of gutters and shrinkage cracks in renders were noted in a number of properties.

In one property an issue with phenolic EWI was highlighted, where solar exposure was cited as the reason for expansion of the insulation panels to cause issues at panel edges, but not in the centre. In another property the installation of IWI was cited as the main reason for the accelerated deterioration of the external facing brick and mortar. Whether issues such as this have a noticeable effect on the thermal performance is questionable, as the thermal conductivity of the walls are now dictated by the insulation layer, but the risk of failure of the system as a whole is significantly increased.

Requests were made to numerous stakeholders within the insulation industry, together with associated independent bodies and those associated with building energy performance. No additional datasets were forthcoming.

Literature review summary

Existing literature does not provide a comprehensive appraisal of ageing and deterioration for all insulation types. There is need for further investigation into roof and cavity products specifically, with acknowledgement of the effect that movement and compressive creep have on such products.

Where energy performance testing has taken place, this is typically done for idealised or extreme contexts in a laboratory setting, with a lack of field-based assessments. This leads to a bias in reporting, with findings from material sample studies lacking external validity as they do not represent realistic insulation conditions for UK housing. There is a need for testing of materials that have been exposed to realistic settings to identify thermal performance impacts.

There is limited research specifically on the energy efficiency changes resulting from insulation deterioration, with previous studies focussed on hygrothermal and structural effects. Where future energy demand has been considered, the effects of deterioration of performance are unclear. There are few studies that undertake longitudinal monitoring or repeated visits to measure performance change over time.

There is a limited range of UK based studies, and this is compounded by further limits for local geography and housing archetypes. Many existing studies are not from the UK and/or are from non-domestic dwellings, limiting their applicability for DRIP.

There is an apparent disagreement between academic and grey literature concerning product lifetimes and ageing effects, suggesting a need for impartial assessment of insulation products.

Taken together, the observations from the literature suggest that Phase 2 of DRIP should take a field-study focus with emphasis on covering a range of insulation types and ages. This should include in situ observations and samples from the field, the former to classify realistic deterioration and the latter to enable lab-based performance analysis of naturally aged insulation products.

Phase 2 study should include a variety of insulation degradation mechanisms, including poor quality install, accidental disturbance, and material breakdown. Specifically, data should be captured to represent suboptimal conditions.

Phase 2 scope should be large enough to address the range of housing archetypes and geographical spread present in the UK, to determine whether “one size fits all” estimations of performance decline are appropriate.

Technical analysis

The review of existing literature on retrofit deterioration indicates that there are several datasets currently in existence that may be used to address the aims of the wider DRIP project. Identifying and evaluating the quality of existing datasets that may be applied to DRIP will help guide recommendations for a future Phase 2, avoiding unnecessary repetition of data collection and informing key aspects of sample size and variable requirements. Salient datasets are analysed, to provide novel insights on retrofit performance deterioration.

Overview

Phase 1 of the DRIP project aims to establish the current understanding of retrofit deterioration, primarily through engaging with existing literature on the subject. Existing datasets may be able to answer the research questions of the wider DRIP project, which would negate the need for supplementary data collection during Phase 2.

Firstly, it was necessary to identify any datasets that may have potential use for evaluating retrofit deterioration. Datasets were then evaluated to establish their quality and usefulness for DRIP objectives. Any datasets that were of sufficient quality were then analysed to generate new insight into retrofit performance, supporting the development of Phase 2 recommendations.

Existing dataset review

Any data that aims to investigate the deterioration of insulation performance will likely have to meet certain criteria:

1. As insulation will likely deteriorate over a long period of time, these datasets will need to be longitudinal.
2. Datasets will need some metric by which to assess insulation or building performance. This could be via traditional methods of building performance evaluation (BPE) such as the coheating test [15] or thermography, or via in-use energy monitoring.
3. Some knowledge of what insulation products are installed in the properties will be required.
4. Homes often display unique behaviour even if they share identical construction details. A large sample size would therefore be beneficial to ensure the results are applicable to the wider UK housing stock.

While conducting the literature review, a paper by Thomson & Jenkins [90] was found which neatly summarises recent datasets that contain data on energy use. Searches were also conducted for additional publicly available datasets, though none could be found. These identified datasets are summarised listed in Table 5 below. The table has been colour-coded and ranked based on the above criteria, where green indicates the criteria is likely met, red indicates the criteria is not met, and amber indicates a partial meeting of the criteria. The colour-coding should be used as an indication only as full access to datasets was not always available requiring certain characteristics to be inferred from secondary source interpretation.

Table 5: Identified datasets

Dataset	Sample size	Time period covered	Potential BPE method	Data on insulation
National Energy Efficiency Data-Framework (NEED)	22 million+	2004 - 2021	Fuel use analysis	Installations of insulation through government schemes
Energy systems catapult 'living lab'	2,000+	2017- present	Fuel use and internal temperature analysis	None, but potential to obtain
Smart Energy Research Lab (SERL) observatory data	13,300	2017-2022	Fuel use analysis	Obtained from EPC
Energy Follow Up Survey (EFUS)	750	2011 - 2018	Fuel use analysis and internal temperatures	Obtained from EPC. Earlier surveys linked data to English Housing Survey.
REFIT Smart Home Dataset	20	2014-2015	Fuel use and internal temperature analysis	Obtained via survey
SMETER Technologies Project Phase 2 Data	15	2019-2020	Fuel use analysis and internal temperatures	None. Measured Airtightness and HTC exist, but not in public data.
DEFACTO (Digital Energy Feedback	400	2015-2018	Fuel use and internal temperature analysis	Obtained from EPC

Dataset	Sample size	Time period covered	Potential BPE method	Data on insulation
and Control Technology Optimisation) Field Trial				
Energy Demand Research Project (EDRP)	61,344	2007-2010	Fuel use analysis	None
North East Scotland Energy Monitoring Project (NESEMP),	215	2010–2012	Fuel use and internal temperature analysis	Self-reported survey
Solent Achieving Value from Efficiency (SAVE)	~4,000	2017–2018	Fuel use analysis	None
SmartMeter Energy Consumption Data in London Households	5567	2011-2014	Fuel use analysis	None
Cornwall Local Energy Market (LEM) Residential Electricity Dataset	100	2018–2020	Fuel use analysis	Obtained from EPC
Renewable Heat Premium Payment (RHPP)	696	2011-2014	Fuel use and heat meter analysis	None
Customer Led Network Revolution (CLNR)	13,000	2014-2015	Electricity use analysis	None

Dataset	Sample size	Time period covered	Potential BPE method	Data on insulation
Low Effort Energy Demand Reduction (LEEDR)	20	2011-2014	Fuel use and internal temperature analysis	None
Low Carbon London (LCL) Project Heat Pump (HP) Load Profiles	19	2014	Fuel use analysis	None
Household Electricity Survey	250	2010-2011	Fuel use analysis	None
One-Minute Resolution Domestic Electricity Use Data,	22	2008–2009	Fuel use analysis	None
REFIT Electrical Load Measurements	20	2013-2015	Fuel use analysis	None
UK Domestic Appliance-Level Electricity (UK-DALE)	5	2012-2017	Fuel use analysis	None
Measuring and Evaluating Time-use and Electricity-use Relationships (METER): UK Household Electricity and Activity Survey	264	2016–2019	Fuel use analysis	None
Intelligent Domestic Energy Advice Loop	255	2016-2018	Fuel use analysis	None

Dataset	Sample size	Time period covered	Potential BPE method	Data on insulation
(IDEAL) Household Energy Dataset				

Notably, all the datasets use data on energy use to assess building performance, as no datasets could be found which involve use of traditional methods of BPE over long periods of time. However, obtaining an assessment of a building's performance from energy data alone is complex, as variables such as occupancy, heating system efficiency and levels of thermal comfort all contribute to total energy use. Measuring internal temperature can help to account for these variables, and any studies that measured this were therefore ranked higher. It is also notable that many studies rely on EPC data. There are known issues with the quality of EPC assessments [91], which is why they were ranked as amber.

It is apparent that no existing datasets are perfectly suited to answering the questions posed by the DRIP project, and only 3 datasets have entries that are all either green or yellow. These datasets are discussed in greater detail below.

National Energy Efficiency Data-Framework (NEED)

The National Energy Efficiency Data-Framework (NEED) was established with the aim of enhancing understanding of energy usage and energy efficiency in residential buildings across Great Britain. This framework integrates data on gas and electricity consumption, gathered for energy companies, with information regarding energy efficiency enhancements implemented in residences through government programs like the Energy Company Obligation (ECO) and the Green Homes Grant. Additionally, it encompasses data related to property attributes, which are principally sourced from Valuation Office Agency data, household characteristics, and EPCs.

NEED is by far the largest existing dataset under consideration, covering 20.2 million homes' gas use, and 25.1 million homes' electricity use. NEED contains consumption data back to 2005, so presents the data with the longest time span of any existing dataset. The full dataset is not publicly available, however, summary statistics, reports, and anonymised data from NEED have been made accessible to both researchers and the public.

Analysis of the NEED data typically relies on a "difference in difference approach", in which data from members of an intervention group (properties where insulation was installed) is compared to data from similar properties in a control group (where no insulation was installed) [79]. This method helps to avoid impact of other factors which can change energy use, such as energy prices and weather. However, insulation measures that are installed outside of government schemes will not be recorded in the data. Properties in the control group having energy efficiency measures installed which are not known about can lead to savings being underestimated.

Regardless of the analysis method, the exact details of the insulation install (e.g., area covered, thickness of insulation, and products used) are not measured within NEED. It would therefore not be possible to determine the cause of any detected degradation in insulation.

Smart Energy Research Lab (SERL)

The Smart Energy Research Lab [92] was created to provide smart meter data to researchers. Around 13,000 homes were recruited into the study, and data has been collected since 2017. To enhance the potential of smart meter data, additional data were gathered for each home. These data included occupant details and heating habits gathered from a survey, and EPC data linked to the address. As with the NEED data, SERL has been released as both an anonymised version, and a full version which is only available in a secure environment. The SERL data is recorded at greater time resolution than the NEED data, but otherwise suffers from the same challenges as NEED.

Energy Systems Catapult living lab

The Energy Systems Catapult living lab was created to accelerate the transformation of the UK's energy system [93]. They use over 2,000 homes to install and test innovations that aim to reduce emissions. The data that they gather can vary depending on the innovation installed, but previous technologies often recorded energy use and internal temperature. One significant limitation of the living lab data is that any data collected is assigned to a specific project and it is not straightforward to obtain the historic data used within these projects. However, the living lab does present a unique option for potential future research into insulation degradation, as their set-up allows for data collection outside of simple energy bill analysis. The homes could, for example, be fitted with heat flux plates for an extended period of time to monitor insulation. The living lab is currently undertaking government funded research as part of the Homes for Net Zero project [94], which involves 1,000+ homes and may also present an opportunity for further research and data capture that is beneficial for investigating retrofit performance deterioration.

Datasets not in public domain

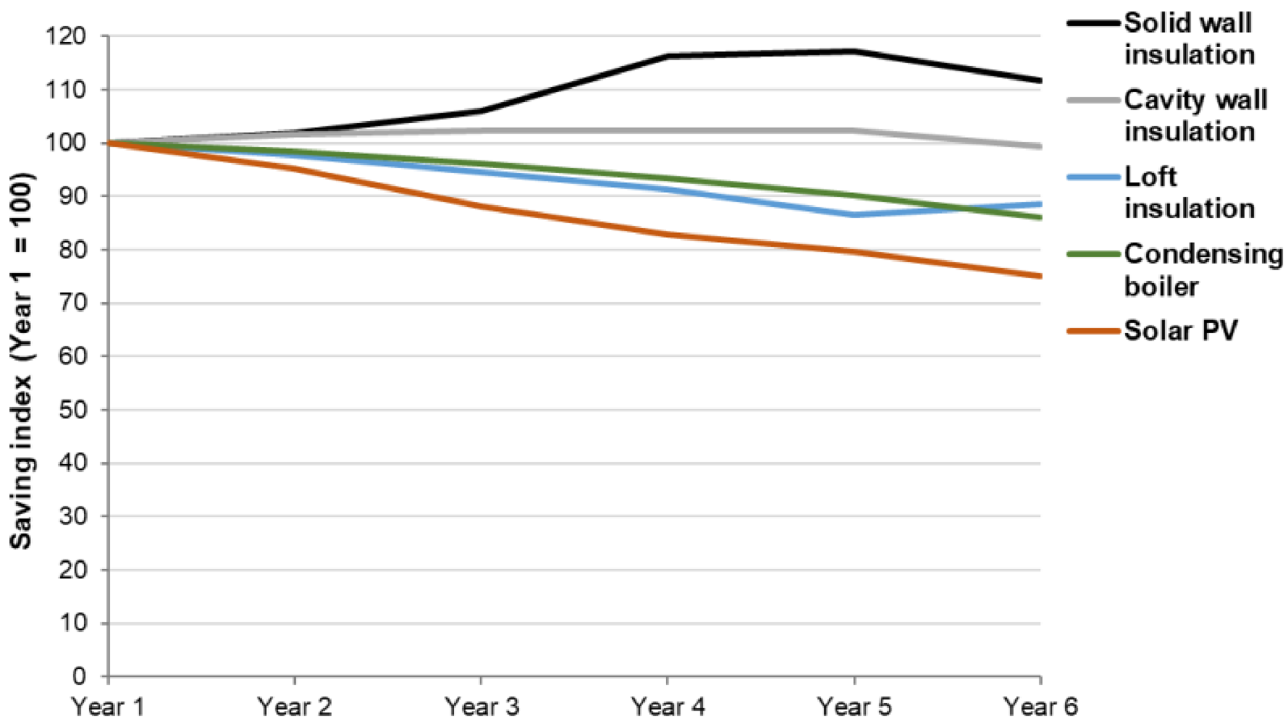
The above datasets are either public, or accessible after agreeing to certain licenses. However, there may be existing datasets which are not publicly available which could answer the DRIP questions. Insulation manufacturers often perform testing of their own products. They may, therefore, hold data either from a laboratory setting, or from real homes, which tracks how insulation is performing. Furthermore, Universities often conduct programs of BPE. While no published studies could be found that use a longitudinal BPE method, such data may either exist, or could be obtained with follow-up measurements to those performed in the past.

Enquiries about existing datasets that are not in the public domain were made to industry stakeholders, many of whom were also contacted for grey literature requests. Unfortunately, no additional datasets were provided for use in analysis.

Analysis of existing datasets

Given the preceding discussion, it was determined that the dataset with the greatest existing potential for evaluating retrofit performance deterioration is NEED. NEED records, at the household level, how much gas and electricity a property uses annually in Great Britain. Data on any efficiency measures installed via government schemes are also recorded, along with details of the property from sources such as the Valuation Office Agency. These data are used to publish a typically annual report describing, among other things, the savings that energy efficiency installs appear to achieve over time. Figure 6 shows such a graph, taken from the most recent report at the time of writing and showing data from England and Wales.

Figure 6: Median annual percentage gas savings (electricity savings for Solar PV), in the 6 years following installation, relative to savings in Year 1, averaged over the installation years 2011 – 2015, England and Wales [79]



Source: NEED Summary of Analysis, Great Britain (2023) [79]

This graph suggests that savings from solid wall insulation and cavity wall insulation were sustained in the 5 years after installation but may decrease for the other insulation measures that were monitored. The report cautions that this may be due not to degradation of the products but may instead be due to "comfort taking", where residents tolerate slightly higher bills as they achieve a significantly warmer home [79].

It may be of interest to know if any variables, such as the properties' location, have any bearing on the savings achieved in the years following retrofit. For example, cavity wall insulation may degrade more in regions which are more exposed to wind driven rain. While the government's NEED reports do breakdown savings by different variables such as location of the property, these are limited to the year following installation of the energy efficiency measure. The published figures cannot therefore be used to assess degradation over a longer period of time for different locations.

Technical analysis summary

Following a review of existing datasets in the public domain, the NEED dataset was identified as the most likely to provide useful insight into retrofit deterioration. Further analysis of the full NEED dataset may provide some further insight on shorter term degradation.

Expert stakeholder engagement

The construction sector comprises various stakeholders, from manufacturers and designers through to surveyors, contractors, and housing associations. Many of these stakeholders do not routinely publish their experience of retrofit yet may have valuable insight to offer. To capture this unpublished expertise, two research activities were carried out during this project.

Overview

The exploratory phase of the DRIP project is primarily concerned with using existing literature and datasets to establish the existing understanding of retrofit deterioration, with a view to understand what evidence gaps remain and what if any data collection may be needed to address this in a subsequent phase. This places an obvious limitation on the comprehensiveness of the review, by restricting it to only published and available resources.

The construction industry encompasses a broad range of stakeholders, extending beyond the manufacturer supply chain to include landlords, insurance providers and regulatory bodies. Many of these stakeholders are likely to have insight into retrofit deterioration, however, do not routinely publish their findings.

Two research activities were carried out to capture some of this unpublished knowledge, to supplement the review of published literature and provide additional recommendations for Phase 2 research activity.

Expert stakeholder workshop

The first research activity was a workshop, which centred on the research question:

How do we classify poorly performing insulation in retrofit?

When investigating retrofit underperformance, one of the challenges facing a surveyor is establishing the cause of an issue. Typically, the surveyor must work backwards to infer the cause on an issue, based on the current material condition. This presents a challenge when attempting to separate issues due to lifetime deterioration from issues that were present at the point of initial installation. To explore this issue further, 20 industry experts and professionals attended an in-person round table workshop, the full details of which may be found in Appendix 3 – Expert stakeholder workshop. The findings from the workshop are summarised in the following section.

Expert stakeholder workshop findings

Initial deterioration classifications fell into one of two groups. This centred around where retrofit insulation performance deteriorated, either: 1) at the point of install, i.e. the thermal performance of the insulation could never meet design assumption targets, as the installation was sub-optimal, or 2) over time after the point of installation.

Classifications assigned to the first group were omitted from further development, as this type of retrofit performance deterioration is directly related to the performance gap, not the insulation deteriorating over time. Where poor quality installation was deemed to also have the potential to exacerbate or accelerate deterioration, for example directly causing moisture accumulation, this was included.

Classifications in the second group refer to retrofit insulation performance deteriorating over time as the result of numerous external factors. The final set of classifications is shown below. Having established an approach for classifying poorly performing retrofit, these different classifications were tested in the next stage of the project, the Delphi study.

Loft

Four different ways in which the performance of loft insulation could deteriorate over time were identified:

1. The loft insulation has not been designed to allow access to services, which means that the insulation would be damaged when access is required.
2. The loft insulation blocks ventilation at the eaves, which means condensation could damage the insulation.
3. The loft insulation has been disturbed by humans or animals, e.g. compressed by storage.
4. The loft insulation has been damaged by weather, water or debris (e.g. dust).

Cavity

Two different ways in which the performance of cavity wall insulation could deteriorate over time were identified:

1. The material composition of the cavity wall insulation has changed over time.
2. The cavity wall insulation has been poorly installed, which has accelerated deterioration of the insulation, e.g. slumping.

Internal wall insulation

Four different ways in which the performance of IWI could deteriorate over time were identified:

1. The IWI product or system used is inappropriate for the building, which has accelerated deterioration of the insulation.
2. The building was not sufficiently prepared or maintained which has accelerated deterioration of the insulation, e.g. a leak that has not been fixed prior to IWI install.
3. The IWI has been damaged post install e.g. DIY, subsequent works.

EWI

Four different ways in which the performance of EWI could deteriorate over time were identified:

1. The EWI product or system used is inappropriate for the building, which has accelerated deterioration of the insulation.
2. Lack of maintenance of fixings or sealants used for the EWI has accelerated deterioration of the insulation.
3. Cut arounds in the EWI for penetrations have never been sealed, which has accelerated deterioration of the insulation.
4. The EWI has been damaged post install e.g. DIY, subsequent works.

Expert workshop summary

20 experts in retrofit insulation attended a workshop to explore what causes insulation to deteriorate and how it affects performance. Using a world café approach, research participants discussed four types of insulation: loft; cavity; IWI and EWI.

While it was reported that poor installation is the primary cause of retrofit underperformance, the participants also explored how and why insulation performance can deteriorate over time. These discussions were used to identify 13 different classifications of insulation deterioration that were used for the next stage of the research: the Delphi study.

Delphi study

The Delphi method [95] is particularly useful in areas of limited research, as it draws on the expertise of a knowledgeable participant pool. Delphi methodology was used to develop recommendations for the design of a national survey of retrofit deterioration. The Delphi research was designed around three questions:

1. **What classifications of insulation deterioration should be included in a national survey?**
2. **How should they be measured and graded?**
3. **What sample should be included in a national survey?**

Full details of the Delphi progress, including detail about the participants, their responses, and the progression of responses throughout the 3 rounds of questioning are described in full in Appendix 4 – Delphi methodology. The findings from each round are summarised below, with associated implications for any future rounds and for a prospective DRIP Phase 2.

Delphi round 1 and 2

The first and second round of the Delphi explored how deterioration should be categorised, measured, and graded. The summary of results for this process are shown by Table 13. These findings provide the basis of what could be measured in a national building survey of insulation deterioration.

Table 6 Summary of Delphi round 1 and 2

<table>
<tr><th>Classification</th><th>How to measure</th><th>Risk factors</th></tr>
<tr><td>Loft 1: The loft insulation has been moved, e.g. to allow access to services.</td><td>• Visual inspection</td><td rowspan="3">• Older homes with older roofs and no roof felt
• Where loft used for storage
• Where plant/services in loft space
• Homes with flat roofs
• Homes with shallow roof pitch
• Dormer bungalows</td></tr>
<tr><td>Loft 2: The loft insulation blocks ventilation at the eaves, which means condensation could damage the insulation.</td><td>• Visual inspection</td></tr>
<tr><td>Loft 3: The loft insulation has been damaged by weather, vermin, water, age, debris (e.g. dust) or compressed by storage.</td><td>• Visual inspection
• Insulation depth measurement
• Infrared thermography</td></tr>
<tr><td>Cavity Wall 1: The cavity wall insulation has deteriorated over time (e.g. crumbled)</td><td>• Borescope
Visual inspection and infrared thermography suggested too.</td><td rowspan="3">• Exposed/ coastal location
• 1950-1970s non-traditional homes
• Poorly maintained homes
• Social housing/rented homes
• Homes with extensions
• Homes retrofitted by contractor known for poor installs
• Homes with pre-2012 CWI</td></tr>
<tr><td>Cavity Wall 2: The cavity wall insulation has been poorly installed, which means it has deteriorated (e.g., slumping).</td><td>• Visual inspection
• Infrared thermography
• Borescope</td></tr>
<tr><td>Cavity Wall 3: The cavity wall insulation has been contaminated by water penetration, debris, or vermin.</td><td>• Visual inspection
• Infrared thermography
Borescope suggested too.</td></tr>
<tr><td>IWI 1: The IWI product, design or system used is inappropriate for the building, which has caused the insulation to deteriorate.</td><td>• Visual inspection
• Infrared thermography</td><td>• Older solid wall homes
• 1950-1970s system-built homes</td></tr>
</table>

Classification	How to measure	Risk factors
IWI 2: The building has not been sufficiently maintained, which has caused the insulation to deteriorate.	• Visual inspection • Infrared thermography	• Poorly maintained homes • Social housing/ rented homes • High occupancy homes • Exposed/ coastal location • Flood risk areas
IWI 3: The IWI has been damaged post install e.g. DIY, flood, subsequent works.	• Visual inspection • Infrared thermography	
EWI 1: The EWI product, design, system used, or detailing is inappropriate for the building, which has caused the insulation to deteriorate.	• Visual inspection • Infrared thermography	• Poorly maintained homes • Social housing/ rented homes • Exposed/ coastal location • Homes with complex brickwork/roof details • High vandalism risk areas • Homes with CWI and EWI • Flood risk areas • Homes with extensions
EWI 2: Lack of maintenance of fixings or sealants used for the EWI has caused the insulation to deteriorate.	• Visual inspection • Infrared thermography	
EWI 3: Cut arounds in the EWI for penetrations have never been sealed, which has caused the insulation to deteriorate.	• Visual inspection • Infrared thermography	
EWI 4: The EWI has been damaged post install e.g. DIY, subsequent works, weather.	• Visual inspection • Infrared thermography	

Delphi 3: How common is insulation deterioration?

To help calculate a sample size for a potential national survey, participants were asked to estimate the percentage of UK retrofits of different ages that would have any of the different classifications of deterioration. They were also able to state that they did not know. The mean responses are shown in Figure 14, while Table 15 shows the mean and standard deviation of each type, along with the number of participants who were able to estimate a percentage.

Loft insulation was estimated as being most likely to have deteriorated, followed by cavity wall insulation. Estimates were very similar for IWI and EWI. Most participants (90%) were able to provide an estimate for loft and cavity insulation deterioration. Fewer were able to provide an estimate for IWI deterioration (66%).

It is important to note that that the numbers shown in Figure 14 and Table 15 are estimates with large standard deviations, derived from expert elicitation and not empirical data. Indeed, several of the participants stated that it is not possible to estimate the incidence of the different types of insulation deterioration. These figures should be treated as a way of estimating an appropriate sample size for a national survey, rather than an indication of the actual incidence of insulation deterioration.

Figure 7: Expert estimates of the percentage of insulation retrofits showing deterioration.

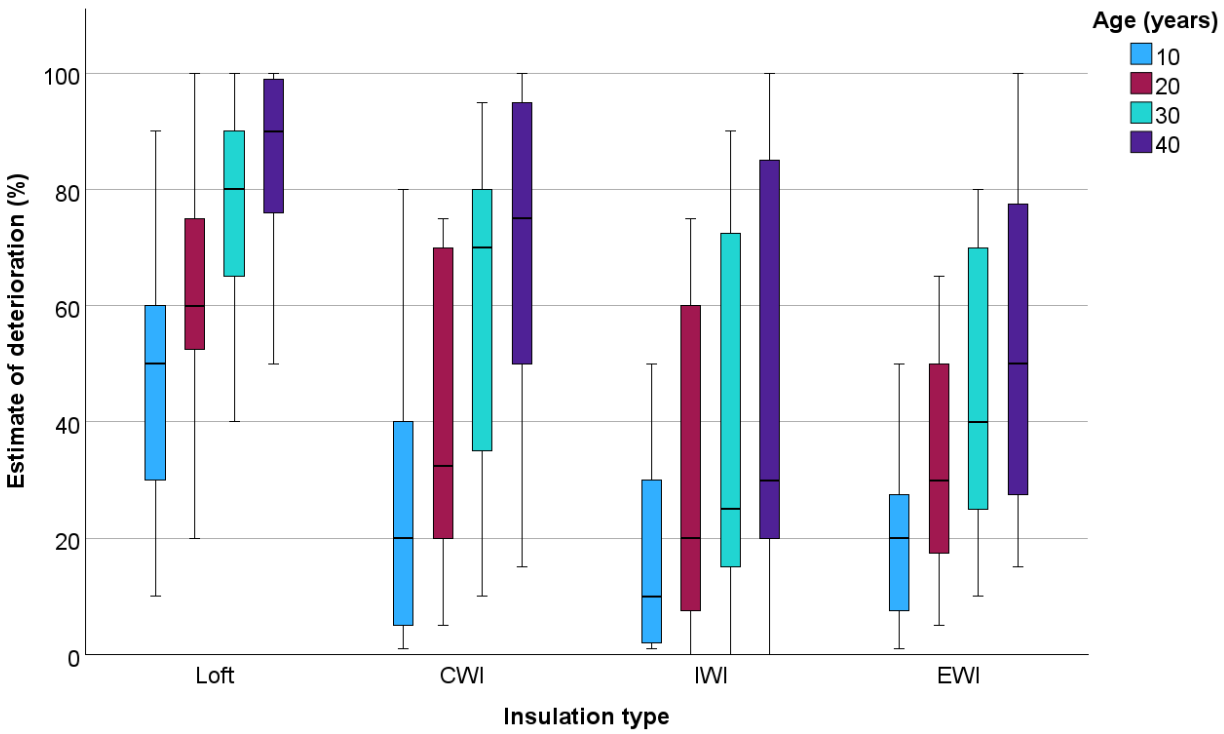


Table 7: Estimates of the average percentage of insulation deterioration. Standard deviation shown in brackets; n value denotes sample size.

	Insulation age (years)			
Insulation type	**10**	**20**	**30**	**40**
Loft	47.1 (23.3), n=19	62.4 (21.9), n=19	76.9 (17.5), n=18	85.6 (15.8), n=18
Cavity Wall	24.2 (22.0), n=18	40.3 (25.0), n=18	59.1 (27.6), n=17	70.5 (28.5), n=17
IWI	18.4 (18.2), n=17	30.3 (27.4), n=15	40.7 (32.8), n=15	48.3 (36.7), n=15
EWI	19.0 (13.5), n=19	31.8 (18.4), n=19	44.4 (23.5), n=17	52.5 (27.9), n=16

Participants were also asked to comment on any types of homes that are more likely to have each type of insulation deterioration. Examples given include the construction type, the age of the home, the geographical location, the tenancy type, occupancy patterns, and how well the home has been maintained. These are elaborated in Table 16 in Appendix 4.

Participants' estimates of the incidence of insulation deterioration can be used to guide estimates of the required size of a national building survey. The figures produced form a very approximate guide, however, as there are many uncertainties over the incidence of insulation deterioration and the risk factors that make it more or less likely. Nevertheless, with this caveat, we can use the figures in Table 13 together with data on the level of insulation in the current UK housing stock [96] in a sample size calculator.

To accommodate the range in expert estimates (and the resulting high standard deviation for the average estimate), the standard error of the mean is applied to produce upper and lower confidence intervals. Using a 95% confidence interval and a 5% margin of error, the data indicates:

- Assuming there are 16.8m properties with loft insulation (66% of properties with a loft) [96], and 47.1% of properties with insulation 10 years or older will have deteriorated to some extent, a sample size of between 357 and 383 homes is required.
- Assuming there are 14.5m properties with cavity wall insulation (70% of homes) [96] and 24.2% of properties with insulation 10 years or older will have deteriorated to some extent, a sample size of between 187 and 347 is required.
- Assuming there are 794,000 properties with solid wall insulation (9% of properties with solid walls) [96] and 18.4% of properties with IWI insulation 10 years or older will have deteriorated to some extent, a sample size of between 135 and 303 is required.
- Assuming there are 794,000 properties with solid wall insulation (9% of properties with solid walls) [96] and 19% of properties with EWI insulation 10 years or older will have deteriorated to some extent, a sample size of between 173 and 289 is required.

Taken together, these figures – which provide only a very approximate guide – suggest that the minimum sample comprise:

- 187 homes with loft and cavity wall insulation installed at least 10 years ago.
- 135 homes with loft and internal wall insulation installed at least 10 years ago.
- 173 homes with loft and external wall insulation installed at least 10 years ago.

Hence a minimum sample of approximately 495 homes could be used to give 95% confidence that the true incidence of insulation deterioration lies +/- the measured amount. However, it should also be noted that this assumes a representative distribution of other relevant variables such as location, building type, building age and tenancy. Any effort to account for these additional variables separately would have a substantial multiplication effect on sample size. It is therefore suggested that, to give a "worst case scenario", homes at higher risk or of greater significance be over-sampled in an approach similar to that taken in the English Housing Survey [87], for example homes in an exposed coastal region, and homes at risk of flooding.

Delphi summary

An expert panel of 26 surveyors were recruited for a Delphi study in which three rounds of questionnaires were used to gain consensus on what should be included in a national building survey of insulation deterioration. Initial classifications of retrofit deterioration were refined during this process until a consensus was reached on what should be measured, how it should be measured, how the deterioration should be graded, and risk factors that surveyors should be aware of. From participants' estimates of the incidence of insulation deterioration, an approach to sampling for a national survey is suggested.

Expert stakeholder engagement summary

In the workshop, industry experts identified poor retrofit performance as coming from two sources. First, sub-optimal performance arises from poor installation, which creates a performance gap. This was believed to be the primary cause of poor performance. Second, and to a lesser extent, performance deteriorates over time due to external factors interacting with the insulation. The Delphi study has developed the classifications of insulation deterioration derived from the second source, as those are within scope of this research.

Three classifications of loft, cavity wall insulation and IWI deterioration were identified by study participants, and four for EWI. A consensus was reached that the classifications could be measured through a combination of visual inspection, infrared thermography and borescope survey, as well as taking physical measurements. Participants agreed that the approximate retrofit insulation age should be recorded as well as using a scale based around "good", "fair" or "poor" to rate its condition. The percentage of insulation deemed in a poor condition should also be recorded. Using statistical methods for sample size generation together with expert opinion on the likelihood and prevalence of retrofit deterioration, a sample has been proposed for field surveys.

Recommendations for future phase

This report has presented the findings from the Deterioration of Retrofit Insulation Performance (DRIP) Phase 1 project. Based on these findings, the following recommendations for a future phase aimed at addressing evidence gaps have been developed.

Systematic review of the available literature has shown that there is a lack of evidence around retrofit performance deterioration from which to base future policy and decision-making. Specifically, the current body of literature lacks depth, consistency, and quality in several key areas:

- There is a lack of data on long-term insulation performance from UK contexts, with limited data from regions similar to the UK in terms of construction heritage, climate, and demographics.
- Existing literature does not provide good coverage of all UK-relevant insulation products; most notably a lack of research evaluating change in cavity wall insulation performance.
- There is a lack of research from real world, in situ contexts. Many retrofit material performance assessments are based on unrepresentative methods (e.g. accelerated ageing), idealised “best case” samples, and simulations based on broad assumption.
- Current literature is heavily weighted towards retrofit assessment immediately following completion. There is a lack of research addressing retrofit performance deterioration over time, with little evidence exploring causes and effects of retrofit performance change during full product lifetime.
- Where assessment of the long-term performance of retrofit materials has taken place, this is inconclusive, with conflicting findings across academic and grey literature.
- Existing datasets lack the detail required to establish causation for observed patterns in energy consumption.

Given these limitations and knowledge gaps, any project Phase 2 should seek to address following data requirements:

- Energy performance data for aged insulation products that are taken from a diverse range of real-world (in situ) contexts in the UK.
- Appraisal of the existing quality of retrofit insulation materials in UK dwellings.

This would provide evidence on the extent and significance of retrofit performance deterioration in the UK. The following sections outline recommendations for gathering the required data.

Performance data for aged retrofit materials

Data requirements

Performance characteristics for a range of aged retrofit materials is required, to quantify change from the original condition. The overall aim should be to produce a library of retrofit performance characteristics relative to the level of degradation for a given insulation material. This may then be used as a reference to enable offsetting of the predicted insulation performance of any given home, relative to the degradation of the in situ insulation.

In the first instance, priority should be given to establishing the thermal properties of the aged samples. This may be extended to include other material properties related to material degradation (moisture content/mould growth etc.).

Methods and approach

Performance data should be measured using insulation samples taken from real domestic dwellings, encompassing a diverse range of contexts. Multiple samples should be taken at each site to allow for a range of tests to be conducted (e.g. thermal performance, gravimetric moisture sampling, mould spore sampling, etc.).

Any Phase 2 study should develop a protocol for the removal, storage, and transportation of insulation samples to maintain their integrity and ensure they are a true reflection of their in situ state when tested.

Testing should be conducted in a laboratory environment, to ensure accuracy and replicability of test methods. Laboratory tests for heat transfer characteristics should follow an approved method such as those described in the Standard for thermal transmission properties [97]. Similarly, any associated tests for moisture content should follow robust methods [98].

In situ tests such as coheating [15] and heat flux measurement [16] may have some application for investigating retrofit deterioration, but such methods should be treated with caution due to their measurement uncertainty and a lack of baseline data for comparison. In situ tests are used to characterise a thermal element as part of a system (e.g. the buildup of plaster, timber, block, brick, insulation, air gaps, etc. within a larger construction), meaning that it is unlikely that in situ experiments will be capable of detecting change specifically due to deterioration of the retrofit insulation product, unless the change is substantial.

There may be value in using existing in situ measurements from previously funded government projects to develop a library of measured elemental U-values, together with the associated contextual factors, construction buildups, and a visual assessment of retrofit quality. This database may then be supplemented with measured U-values during DRIP Phase 2 to fill any gaps, with the aim of producing a library of in situ elemental U-values to evaluate retrofit system deterioration (as opposed to individual insulation materials). The data will, however, include deterioration of all materials within an element (i.e. masonry, timber, insulation, cavities, etc.), adding a substantial number of variables that will need to be accounted for.

Insulation types

- Loft insulation
- Cavity wall insulation
- External solid wall insulation
- Internal solid wall insulation

Priority should be given to the measurement of loft and cavity wall insulation products as these represent the most common retrofit types in the UK. Additionally, these products were identified as being most likely to have deteriorated in performance during expert stakeholder workshops.

Insulation materials

All insulation materials should be considered within scope, however priority should be given to materials at risk of settlement and/or compression. Typically, this relates to 'loose' materials such as mineral wool, blown fibre and poly-bead products.

There are likely to be significant challenges associated with obtaining in situ wall insulation products. It may, therefore, be necessary to consider options for artificial ageing such as the construction of a wall sample that can be manipulated/weathered. Where samples are to be taken, this would require destructive methods; specifically, the deconstruction and extraction of materials. Materials would then need to be replaced to restore the wall to its previous form, taking care to avoid the creation of new thermal bridges.

In practice, this may be possible for homes where existing CWI, IWI or EWI is in need of replacement, or a home is being extended with existing external walls due for demolition. This would cause substantial disruption, so the recommendation is to target unoccupied homes – most likely void housing that has fallen into disrepair or is being converted/extended.

Where the removal of insulation is impractical, there may be scope for in situ heat flux measurement of wall U-values, although as stated previously, this will characterise the retrofit system, not the insulation material exclusively, adding complexity in the evaluation of deterioration. The in situ measurement of U-values may present added value, giving a more comprehensive picture of elemental deterioration, although any results will be heavily influenced by local context and may have limited external validity in isolation.

Insulation condition grades

It is important that a range of retrofit quality grades are collected, ranging from near-perfect quality to heavily damaged. Condition grades should consider various causes of damage, including both accidental (human/animal/environmental caused) and material (chemical/physical breakdown). When selecting samples, reference should be made to the contextual risk factors outlined in Table 16 to help with establishing causation for deterioration.

Sampling and recruitment strategy

Due to the wide range of variables that may affect retrofit deterioration, it is challenging to define a specific number of insulation samples required to provide coverage of all possible deterioration scenarios. To overcome this, it is recommended that material sampling is based on the quality rankings of ‘poor’, ‘fair’ and ‘good’ defined during stakeholder engagement, with rankings used to construct a stratified sample of insulation materials across a range of in situ contexts. Given the likelihood for greater variability in performance as condition gets worse, it is recommended that a larger proportion of physical samples are from ‘poor’ ranked retrofits.

Analysis provided by the Office for National Statistics outlining retrofit quality according to assessment during EPC creation may be used to construct stratified samples of retrofit quality [86] from which to base recruitment efforts. The full EPC database may also be used to stratify condition of insulation for regional samples.

It is recommended that sampling activities should involve early engagement with a range of property stakeholders, namely local councils, housing associations and private owners. Incentives should be included in costs to participate and provide insulation samples.

Appraisal of existing UK retrofit quality

Data requirements

An appraisal of the existing quality of retrofit insulation materials in UK dwellings is required to establish the occurrence and severity of retrofit deterioration. Although existing datasets provide an indication of insulation condition (EPC database [99]) and insulation type (English Housing Survey [87]) they do not provide sufficient detail on the specific topic of retrofit deterioration. Specifically, the surveys that underpin the data do not capture the necessary contextual data to determine causation for any observed deterioration.

Methods and approach

Data collection should involve surveys of homes with known energy efficiency retrofits, following the protocols outlined in expert stakeholder engagement section of this report. Surveys should employ visual assessment, thermal imaging, and borescope surveys to determine the quality of existing retrofit condition.

Surveys should also note relevant contextual features of the sample location to support efforts at determining causation and classify likely causes and impacts according to the definitions outlined in the expert stakeholder engagement section of this report.

Sampling and recruitment strategy

A suggestion for a minimum sample size of approximately 495 surveys has been provided using statistical methods for sample size generation together with expert opinion on the likelihood and prevalence of retrofit deterioration. This should be regarded with some caution, given the wide variation of relevant contextual factors present for domestic dwellings.

It is recommended that dwellings anticipated as having poor quality retrofit due to the presence of previously defined risk factors are over-sampled during surveying, to give a fuller understanding of the 'worst case' scenario and, thus, a more comprehensive understanding of the significance of deterioration impacts. It is, however, not recommended to only consider poor quality insulation, as this will not provide a full picture of in situ retrofit performance.

An alternative approach to suggest a necessary sample may be calculated using the EPC database, which evaluates the prevalence and quality of roof and wall insulation products. The breakdown of insulation quality across UK homes is shown in Table 17, although it should be noted that these judgements are based on assumptions linked to property age, and not necessarily supported by visual inspection. Additionally, wall insulation is regarded as a single group.

Thus, if targeting insulation by anticipated in situ quality and given the assumption of 16,800,000 properties with loft insulation and 15,294,000 properties with wall insulation [96], the following sample shown in Table 18 may be calculated.

Table 8: Proportion of insulation quality ratings in UK housing, taken from the EPC database

	Insulation quality rating – proportion of homes		
Insulation type	Very good / Good	Average	Poor / Very poor
Roof	62%	18%	20%
Walls	51%	12%	38%

Table 9: Required survey sample for insulation quality ratings in UK housing

	Insulation quality rating – required sample			
Insulation type	Very good / Good	Average	Poor / Very poor	Total
Roof	363	227	246	836
Walls	384	163	363	910

Given that the majority of homes have both wall and roof insulation, it is unlikely that the two populations require separate samples and may, therefore, be combined (although there may be value in including some homes with exclusively wall or loft insulation, for the purpose of determining causative impacts). If surveys are combined, this alternative sample approach indicates a similar sample size to that identified by expert stakeholders, providing some confidence for recommended scale. The analysis undertaken by the ONS [86] describing geographical spread of insulation ratings, supported by individual household EPCs, may be used to construct a stratified sample approach, based on insulation rating.

It should be noted that the described sampling approach is an attempt to characterise retrofit insulation quality with a view to assessing deterioration. Due to the vast number of relevant variables that may affect deterioration (location/building typology/tenancy/retrofit material/etc.) it is unlikely that this sampling process will encapsulate every possible context nor be deemed statistically representative of insulation quality in the UK. Targeting each variable that is likely to affect retrofit deterioration would involve substantial resources akin to the English Housing Survey. Rather, the intention is that, by grouping under a holistic assessment of retrofit quality and capturing relevant dwelling metadata during survey, correlations will emerge. This presents a pragmatic approach to addressing the wider project research questions. As noted above, it is recommended that dwellings anticipated as having poor quality retrofit due to the presence of previously defined risk factors are over-sampled during surveying, to assist in development hierarchies of the key factors affecting deterioration rate.

It is possible that recruitment for sampling may align with currently active research projects such as Homes for Net Zero [94] or the anticipated UK airtightness survey, where site visits may be used to determine existing quality of retrofit at the same time. Survey activities may also overlap with sample extraction defined in the prior recommended activity.

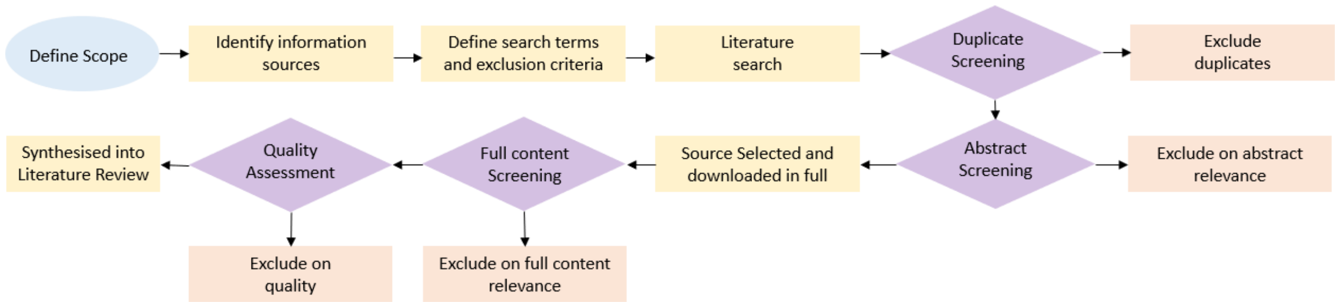
Anticipated contribution to knowledge

Undertaking both a detailed analysis of aged retrofit materials and a broader survey of existing retrofit installations should provide the ability to define both the scale and significance of retrofit deterioration in UK housing, when used together and supplemented by existing datasets such as the EPC register and the English Housing Survey. A library of performance characteristics for aged retrofit materials will also be a valuable resource for future modelling exercises aimed at predicting current and future energy demand of UK housing and provide valuable context for associated building condition assessments.

Appendix 1 – Literature review methods and process

Establishing current knowledge on longevity and degradation of insulation retrofits requires a multifaced approach to literature review. Firstly, researchers will systematically review peer-reviewed academic literature using critical review methods that apply Boolean logic. This approach is suited to academic literature, which is typically accessed through aggregated databases that support the use of search term filters. Using these filters, search terms specific to the DRIP study may be specified to identify and include/exclude publications in a rigorous, transparent, and repeatable way. An entire database of academic publications can, therefore, quickly be interrogated to identify relevant papers, which will then be taken forward for full content review. The process of review is illustrated by Figure 15.

Figure 8: Process of systematic literature review



Relevant literature is not limited to academic publications, however. Governments, businesses, and independent associations routinely publish useful reports on the topic of insulation and retrofit, and it is important to capture this 'grey' literature in the DRIP Phase 1 review. Due to the nature of these publications, which often exist on individual websites, review takes a more targeted approach using internet search engines and referring to bibliographies from associated studies (snowball review). This approach relies heavily on the researcher knowing where to search for publications, and places greater emphasis on filtering for quality, with bias often present in such documents (particularly those published by industry).

In addition to reviewing publicly available resources, researchers will also contact organisations that are known to undertake research into products and systems to request any information they may have that is not in the public domain. This includes data that may be commercially sensitive, such as insulation performance data. At time of writing the interim report, no supplementary unpublished reports/data have been received.

The review of existing literature was centred on the research question:

What is the current state of knowledge on longevity and degradation of insulation retrofits over time?

This overarching question was supplemented by several sub questions for consideration during full document reviews:

1. What are the causes of insulation degradation?
2. How does degradation vary by insulation type?
3. What is the impact of insulation degradation on thermal performance?
4. How long does degradation take to set in?
5. How does one distinguish between poor installation and degradation?

Systematic academic literature review

Considering the specified research questions, the PICOS limiting factors shown in Table 19 were established to define eligibility criteria for inclusion in the systematic review:

Table 10: PICOS eligibility criteria for systematic literature review

Population	Intervention	Comparators	Outcomes	Study design
UK Housing that has undergone insulation retrofit Limit literature to domestic buildings, retrofitted with insulation post-construction	Internal solid wall insulation External solid wall insulation Cavity wall insulation Loft insulation	No insulation Phased insulation Alternative insulation	Deterioration of energy performance Longevity of retrofit Unintended consequences Degradation causes	In-situ case study Laboratory experiments Survey, observations

Literature searches were undertaken using the Scopus and ProQuest academic research databases. Google scholar was also considered, however the lack of advanced search capability and inclusion of grey literature in search results led to it being removed from the systematic review process.

To ensure comprehensive coverage, snowball review was carried out on a selection of most relevant literature, evaluating the sources referenced by these papers for other literature that is relevant to the DRIP project.

Search terms were chosen to return literature relevant to the DRIP project, displayed in Table 20:

Table 11: Search terms for systematic literature review

1st term	2nd term	3rd term
Insulation	Retrofit	Degradation
	Refurbishment	Deterioration
	Renovation	Breakdown
	Upgrade	Failure

Insulation was included as the 1st search term that must be present in all results. The 2nd and 3rd search terms were also required to be present, but as a list of synonyms to encompass the variations in terminologies used in different regions and disciplines. Boolean logic was used to search Scopus and ProQuest, AND functions were included for the 1st, 2nd and 3rd search terms, OR functions were used within the multiple 2nd and 3rd search terms.

A second search was conducted using the Scopus database no longer limiting the search criteria to retrofit. To do this the 2nd search term was omitted. To further limit the search, "building" was added as a 1st search term.

Systematic review results

The screening process presented in Table 21 yielded 17 full papers for full review from the first search of the Scopus database:

Table 12: Screening stages for Scopus database results, first search

Screening Stage	Scopus results - 1st search
Search terms only	2,452
Limit to abstract	142
Screen for building-related topic	62
Screen for title and abstract relevance	29
Screen for full content relevance	17

Following the modification to search criteria outlined previously, the screening process presented in Table 22 yielded 36 full papers for full review from the Scopus database:

Table 13: Screening stages for Scopus database results, second search.

Screening Stage	Scopus results - 2nd search
Search terms only	1,297
Limit to abstract	871
Screen for building-related topic	205
Screen for title and abstract relevance	45
Screen for full content relevance	45

The screening process presented in Table 23 yielded 32 full papers for review from the ProQuest database:

Table 14: Screening stages for ProQuest database results

Screening Stage	ProQuest results
Search terms only	5,737
Exclude terms “transformer” and “wire”	2,950
Screen for building-related topic	574
Screen for title and abstract relevance	42
Screen for full content relevance	32

In both databases, the search terms returned a great deal of documents related to electrical installations and transformers, due to similarity in terminology. Only 1 common document was identified between the final Scopus and ProQuest results. The literature was supplements with 6 salient papers highlighted during snowball review, resulting in a total of 99 papers for full content review. Summarised details of the identified papers is provided in Appendix 2, with full details in the reference section of this report.

Appendix 2 – Academic literature bibliography

#	Title	Authors	Reference
1	Long term durability of Vacuum Insulation Panels: Determination of the Sd-value of MF-2 foils	De Meersman G.; Van Den Bossche N.; Janssens A.	[25]
2	Risk analysis of biodeterioration of wooden beams embedded in internally insulated masonry walls	Guizzardi M.; Carmeliet J.; Derome D.	[39]
3	Guidelines for internal insulation of historic Buildings	De Place Hansen E.J.; Møller E.B.; Ørsager M.	[100]
4	Selection of retrofit measures for reasonable energy and hygrothermal performances of modern heritage building under dry cold and hot humid climate:A case of modern heritage school in Korea	Chae Y.; Kim S.H.	[101]
5	Assessment of the actual hygrothermal performance of glass mineral wool insulation applied 25 years ago in masonry cavity walls	Stazi F.; Tittarelli F.; Politi G.; Di Perna C.; Munafò P.	[32]
6	Modelling the technical-economic relevance of the ETICS construction process	Sulakatko V.	[35]
7	Research on deterioration of wooden housings with thick insulation performance	Maruyama S.; Mori T.; Ooyanagi Y.	[102]
8	Evaluation of 5 years' performance of VIPs in a retrofitted building façade	Johansson P.; Adl-Zarrabi B.; Sasic Kalagasidis A.	[33]

#	Title	Authors	Reference
9	Biodegradation processes on the facades of residential housing from the point of view of energy savings	Kubečková D.; Vrbová M.	[36]
10	Durability considerations of refurbished external walls	Hradil P.; Toratti T.; Vesikari E.; Ferreira M.; Häkkinen T.	[103]
11	Aesthetic and technical problems of renovated residential buildings facade. prevention of defects	Minarovičová K.; Antošová N.	[37]
12	Impact of ETICS on Corrosion Propagation of Concrete Facade	Ilomets S.; Kalamees T.; Lahdensivu J.; Klõšeiko P.	[104]
13	Investigation of interior post-insulated masonry walls with wooden beam ends	Morelli M.; Svendsen S.	[38]
14	Simulation technique for service life assessment of façade refurbishment	Vesikari E.; Ferreira R.M.	[105]
15	Long-Term, Hygrothermal Performance of Exterior Insulation and Finish Systems (EIFS)	Bomberg M.; Lstiburek J.; Nabhan F.	[106]
16	Use of exterior insulation and finish systems on U.S. army facilities	Lampo R.G.; Trovillion J.	[107]
17	Design and renovation of a high-rise retrofit EIFS cladding: a case study	French W.R.	[108]
18	Evaluation of the hygrothermal performance of external thermal insulation applications on the outer walls of existing buildings	Kılıçaslan A.E.; Kuş H.	[109]

#	Title	Authors	Reference
19	Influence of natural ageing on the chemical composition of hemp mortars	Kosiachevskyi D.; Abahri K.; Daubresse A.; Prat E.; Chaouche M.	[110]
20	Investigation on the thermal degradation, moisture absorption characteristics and antibacterial behavior of natural insulation materials	Ahmed A.; Qayoum A.	[111]
21	Prediction of biofilms colonization process using computational modelling technique	Kočí V.; Kobetičová K.	[112]
22	Analytical methods of foamed plastic insulation deteriorated by water	Leem Y.; Kitagaki R.	[113]
23	Assessment of the hygrothermal, microstructural and chemical evolution of a hemp-based cementitious mortar under ETICS total weathering ageing protocol	Kosiachevskyi D.; Abahri K.; Daubresse A.; Prat E.; Chaouche M.	[29]
24	Electrical impedance used for measurement of moisture distribution in thermal insulation plasters	Peterková J.; Sedlmajer M.; Michalčíková M.; Pařílková J.	[114]
25	Case Study: 6 Years of Monitoring of Hygrothermal Conditions Behind Internal Insulation on Masonry Walls	Hansen T.K.; Møller E.B.; Morelli M.	[40]
26	Influence of environmental factors favorable to the development and proliferation of mold in residential buildings in tropical climates	Silveira V.D.C.; Pinto M.M.; Westphal F.S.	[115]
27	Designing insulation filled masonry blocks against hygrothermal deterioration	Nagy B.	[116]

#	Title	Authors	Reference
28	Trilemma of historic buildings: Smart district heating systems, bioeconomy and energy efficiency	Blumberga A.; Freimanis R.; Muizniece I.; Spalvins K.; Blumberga D.	[117]
29	Deformation analysis and failure prediction of bonding mortar in external thermal insulation cladding system (ETICS) by coupled multi physical fields method	Zhu K.; Jiang W.; Yu L.; Guo P.; Yang Z.	[118]
30	Assessment of test methods for the durability of thermal mortars exposure to freezing	Maia J.; Ramos N.M.M.; Veiga R.	[119]
31	Experimental Verification of Thermal Insulation in Timber Framed Walls	Michálková D.; Ďurica P.	[23]
32	Assessing Water Resistance and Surface Properties of ETICS	Borsoi G.; Parracha J.L.; Caiado P.; Flores-Ole I.; Dionísio A.; Veiga R.	[120]
33	Comparative study of Chinese, European and ISO external thermal insulation composite system (ETICS) standards and technical recommendations	Xu H.; Wang H.; Huo Q.; Qin Y.; Zhou H.	[121]
34	Carrying Out of Researches for Determining the Term of Effective Exploitation of Thermal Insulation Materials for 100 Years (Part 2)	Farenyuk G.; Oleksiienko O.	[22]
35	Deterioration model of ETICS, based on stochastic Petri nets	Ferreira C.; Silva A.; de Brito J.	[122]
36	Evaluation of long-term performance of VIPs	Johansson P.; Adl-Zarrabi B.; Berge A.	[123]

#	Title	Authors	Reference
37	Numerical prediction of energy consumption in buildings with controlled interior temperature	Jarošová P.; Šť'Astník S.	[124]
38	Humidity conditions for exterior walls insulation (Case study of residential housing development in Saint-Petersburg)	Pukhkal V.	[125]
39	Vacuum insulation panels for building application: Basic properties, aging mechanisms and service life	Simmler H.; Brunner S.	[126]
40	Deterioration of masonry structure investigated by a thermal camera with a qualitative assessment of thermal image processing	Ziolkowski P.; Niedostatkiewicz M.; Szulwic J.	[26]
41	Methodological Framework to Assess the Significance of External Thermal Insulation Composite System (ETICS) on-site Activities	Sulakatko V.; Lill I.; Witt E.	[127]
42	Development and performance evaluation of natural thermal-insulation materials composed of renewable resources	Korjenic A.; Petránek V.; Zach J.; Hroudová J.	[128]
43	Interstitial Condensation Risk at Thermal Rehabilitated Buildings	Baran I.; Bliuc I.; Iacob A.; Dumitrescu L.; Pescaru R.A.; Helepciuc C.	[129]
44	Review of moisture behavior and thermal performance of polystyrene insulation in building applications	Cai S.; Zhang B.; Cremaschi L.	[17]
45	A Study on Variation of Thermal Characteristics of Insulation Materials for Buildings According to Actual Long-Term Annual Aging Variation	Choi H.-J.; Kang J.-S.; Huh J.-H.	[18]

#	Title	Authors	Reference
46	Modelling the degradation and service life of ETICS in external walls	Ximenes S.; de Brito J.; Gaspar P.L.; Silva A.	[130]
47	Probabilistic assessment of failure risk of the building envelope thermally insulated from the inside	Pasek J.; Kesl P.	[131]
48	Alternative Solution for Thermal Rehabilitation of Buildings with Polystyrene Panels	Bojan A.-C.; Popa A.-G.; Puskas A.	[132]
49	Vacuum insulation panels: Analysis of the thermal performance of both single panel and multilayer boards	Capozzoli A.; Fantucci S.; Favoino F.; Perino M.	[24]
50	Interior insulation for wall retrofitting - A probabilistic analysis of energy savings and hygrothermal risks	Vereecken E.; Van Gelder L.; Janssen H.; Roels S.	[133]
51	An example of deteriorated vacuum insulation panels in a building façade	Brunner S.; Stahl T.; Ghazi Wakili K.	[134]
52	Hydro insulation characteristics of plasters based on organic binders– Experimental procedures	Baeră C.; Szilagyi H.; Dico C.; Puskas A.	[34]
53	Analysis of the degradation of external plasters in the buildings with ETICS	Kučeriková V.; Kraus M.; Kubečková D.	[135]
54	Aerogel granule aging driven by moisture and solar radiation	Ihara T.; Jelle B.P.; Gao T.; Gustavsen A.	[28]
55	Investigation on the thermal degradation and kinetic parameters of innovative insulation materials using TGA-MS	Chetehouna K.; Belayachi N.; Rengel	[136]

#	Title	Authors	Reference
		B.; Hoxha D.; Gillard P.	
56	Study of Hygrothermal Processes in External Walls with Internal Insulation	Biseniece E.; Freimanis R.; Purvins R.; Gravelsins A.; Pumpurs A.; Blumberga A.	[30]
57	Vacuum insulation panels for building applications: A review and beyond	Baetens R.; Jelle B.P.; Thue J.V.; Tenpierik M.J.; Grynning S.; Uvsløkk S.; Gustavsen A.	[137]
58	Investigation of the moisture induced degradation of the thermal properties of aerogel blankets: Measurements, calculations, simulations	Lakatos Á.	[27]
59	Experimental research for determining the effects of climatic cycles on the durability of thermal insulating systems that use polysterene	Miron L.; Miron C.	[138]
60	Energy Analysis and Cost Efficiency of External Partitions in Low Energy Buildings	Fedorczak-Cisak M.; Furtak M.; Hayduk G.; Kwasnowski P.	[139]
61	Accelerated lifetime testing of thermal insulation elements	Göb R.; Lurz K.; Heinemann U.	[140]
62	Some performance aspects of glass fiber insulation on the outside of basement walls	Bomberg M.	[21]

#	Title	Authors	Reference
63	Improvement Effect of Green Remodeling and Building Value Assessment Criteria for Aging Public Buildings	Yong-Joon Jun, Seung-ho Ahn, Kyung-Soon Park	[141]
64	Performance and Durability of Rendering and Basecoat Mortars for ETICS with CSA and Portland Cement	Trigo, Tiago; Flores-Colen, Inês; Silva, Luís; Vieira, Nuno; Raimundo, Ana; Borsoi, Giovanni	[142]
65	Multiyear hygrothermal performance simulation of historic building envelopes	Libralato, M; De Angelis, A; P D'Agaro; Cortella, G; Saro, O	[143]
66	Moisture Accumulation in Building Façades Exposed to Accelerated Artificial Climatic Ageing—A Complementary Analysis to NT Build 495	Asphaug, Silje Kathrin; Time, Berit; Kvande, Tore	[144]
67	The Influences of Moisture on the Mechanical, Morphological and Thermogravimetric Properties of Mineral Wool Made from Basalt Glass Fibers	Ivanič, Andrej; Kravanja, Gregor; Kidess, Wadie; Rebeka Rudolf; Lubej, Samo	[145]
68	Experimental Studies Involving the Impact of Solar Radiation on the Properties of Expanded Graphite Polystyrene	Krause, Paweł; Nowoświat, Artur	[19]
69	Influence of the Water Vapour Permeability of Airtight Sheets on the Behaviour of Facade	Torres-Ramo, Joaquín; Arriazu-Ramos, Nerea; Sánchez-Ostiz, Ana	[146]
70	Interior Insulation of Masonry Walls—Selected Problems in the Design	Orlik-Kożdoń, Bożena	[147]

#	Title	Authors	Reference
71	Climate Resilience of Internally-Insulated Historic Masonry Assemblies: Comparison of Moisture Risk under Current and Future Climate Scenarios	Lu, Jacqueline; Marincioni, Valentina; Allan-Orr, Scott; Altamirano-Medina, Hector	[41]
72	Analysis of Long-Term Change in the Thermal Resistance of Extruded Insulation Materials through Accelerated Tests	Hyun-Jung, Choi; Ahn, Hosang; Choi, Gyeong-Seok; Jae-Sik Kang; Jung-Ho, Huh	[148]
73	Reliability of Existing Climate Indices in Assessing the Freeze-Thaw Damage Risk of Internally Insulated Masonry Walls	Sahyoun, Sahar; Ge, Hua; Lacasse, Michael A; Defo, Maurice	[149]
74	Towards an integrated moisture-safe retrofit process for traditional buildings in policy and industry	Marincioni, V; Altamirano-Medina, H; Rickaby, P; Griffiths, N; Aktas, Y D; King, C	[150]
75	Durability Assessment of ETICS: Comparative Evaluation of Different Insulating Materials	Landolfi, Roberto; Nicolella, Maurizio	[31]
76	Experimental Study on the Performance Decay of Thermal Insulation and Related Influence on Heating Energy Consumption in Buildings	Diana D'Agostino; Landolfi, Roberto; Nicolella, Maurizio; Minichiello, Francesco	[151]
77	Multiscale Thermal Investigations of Graphite Doped Polystyrene Thermal Insulation	Lakatos, Ákos; Csík, Attila	[20]
78	Durability Analysis of Building Exterior Thermal Insulation System in Hot Summer and Cold Winter Area Based on ANSYS	Huang, Zhijia; Sun, Yadong; Gan, Lin;	[152]

#	Title	Authors	Reference
		Liu, Guo; Zhang, Yang; Zhou, Tao	
79	Parametric Study of Lightweight Wooden Wall Assemblies for Cold and Subarctic Climates Using External Insulation	Caron-Rousseau, Alexis; Blanchet, Pierre; Gosselin, Louis	[153]
80	Using hygrothermal simulations to define safe and robust energy retrofit solutions: interior insulation of a mountain hut with extreme climate conditions	Larcher, M; Leonardi, E; Troi, A	[154]
81	Applied Research of the Hygrothermal Behaviour of an Internally Insulated Historic Wall without Vapour Barrier: In Situ Measurements and Dynamic Simulations	Andreotti, Mirco; Bottino-Leone, Dario; Calzolari, Marta; Davoli, Pietromaria; Luisa Dias Pereira; Lucchi, Elena; Troi, Alexandra	[155]
82	The Impact of Insulation and HVAC Degradation on Overall Building Energy Performance: A Case Study	Eleftheriadis, Georgios; Hamdy, Mohamed	[156]
83	Numerical study on the hygrothermal behaviour of retrofitted historical masonry buildings	Ghita, Ana-Maria; Bârnaure, Mircea	[157]
84	Regeneration of Panel Housing Estates from the Perspective of Thermal Technology, Sustainability and Environmental Context (Case Study of the City of Ostrava, Czech Republic)	Kubečková, Darja	[158]

#	Title	Authors	Reference
85	Evaluation of the Impact of Bricks of Various Characteristics on Internally Insulated Masonry Walls in Cold Climate	Freimanis, Ritvars; Blumberga, Andra; Vanaga, Ruta; Zundāns, Zigmārs	[159]
86	Numerical Evaluation of the Hygrothermal Performance of a Capillary Active Internal Wall Insulation System under Different Internal Conditions	Kaczorek, Dobrosława	[160]
87	Air Cavity Building Walls: A Discussion on the Opportunity of Filling Insulation to Support Energy Performance Improvement Strategies	Magrini, Anna; Marenco, Ludovica; Leoni, Valentina; Gamba, Roberta	[161]
88	Construction Process Technical Impact Factors on Degradation of the External Thermal Insulation Composite System	Virgo Sulakatko; Vogdt, Frank U	[162]
89	Hygrothermal Performance Evaluation of Internally Insulated Historic Stone Building in a Cold Climate	Blumberga, Andra; Freimanis, Ritvars; Biseniece, Edite; Kamenders, Agris	[163]
90	The Impact of Degradation on a Building's Energy Performance in Hot-Humid Climates	Taki, Ahmad; Zakharanka, Anastasiya	[164]
91	Toward the Sustainable and Efficient Use of External Thermal Insulation Composite Systems (ETICS): A Comprehensive Review of Anomalies, Performance Parameters, Requirements and Durability	Parracha, João L; Veiga, Rosário; Flores-Colen, Inês; Nunes, Lina	[165]
92	Hygrothermal Assessment of Insulation Systems for Internal Insulation of Solid Masonry Walls under Various Conditions	Freimanis, Ritvars; Vanaga, Ruta; Balodis, Viesturs;	[166]

#	Title	Authors	Reference
		Zundans, Zigmars; Blumberga, Andra	
93	Investigation of the Deterioration of Medium-Rise-Wall Type Reinforced Concrete Buildings with External Insulation in Snowy Cold Districts	Adachi, Y.; Hirakawa, H.; Fukushima, A.; Uematsu, T.; Kikuta, K.; Taniguchi, M.	[167]
94	Determination of the thermal insulation properties of cylindrical PUR foam products throughout the entire life cycle using accelerated aging procedures	Agnieszka Winkler-Skalna; Beata Łoboda	[168]
95	Study on Long-term Performance of Phenolic Foam Insulation through Accelerated Aging Test	Jin-Hee Kim, Sang-Myung Kim, Jun-Tae Kim	[169]
96	Long-term thermal conductivity of aerogel-enhanced insulating materials under different laboratory aging conditions	Umberto Berardi, Roya Hamideh Nosrati	[170]
97	Effect of Exposure to Environmental Cycling on the Thermal Conductivity of Expanded Polystyrene	Sergiu George Petre, Dorina Nicolina Isopescu, Marian Pruteanu, and Alexandra Cojocaru	[171]
98	Impact of building envelope and mechanical component degradation on the whole building performance: a review paper	Georgios Eleftheriadis, Mohamed Hamdy	[172]
99	Longitudinal prediction of the operational energy use of buildings	Pieter de Wilde, Wei Tian, Godfried Augenbroe	[173]

Appendix 3 – Expert stakeholder workshop

The first research activity was a workshop, which centred on the research question:

How do we classify poorly performing insulation in retrofit?

When investigating retrofit underperformance, one of the challenges facing a surveyor is establishing what has caused an identified issue. For example, an issue such as ceiling mould may easily be traced back to an area of loft insulation with reduced depth. Establishing what caused this reduced depth, however, is often less straightforward. Underperformance in this case may be due to poor quality installation, accidental damage, or a physical degradation of the insulation material itself.

The ability to identify and classify poorly performing insulation presents an opportunity for proactive mitigation rather than reactive remediation. Establishing the cause of underperformance also provides insight into how robust different retrofits are and may also provide insight into effective lifetimes and the likelihood and severity of issues that may occur.

On 18 December 2023, 20 industry experts and professionals attended an in-person round table workshop. It was hosted at Leeds Beckett University.

Participants were recruited via a mix of university and professional networks (Table 21). There was a quota for each professional group to ensure a balanced mix of knowledge, skills and experience. This approach provided in-depth input from a wide range of relevant stakeholders, encompassing expertise from different fields.

Table 15: Workshop 1 participants

Stakeholder group	Professional background	No. participants
Retrofit providers (supply side)	Insulation manufacturers Builders/installers Retrofit designers	6
Retrofit clients (demand side)	Social housing estate teams Local council estate teams	4
Associated groups	Building surveyors Insurance providers Regulatory bodies Trade associations Expert witnesses	10

Stakeholder group	Professional background	No. participants
	Retrofit co-ordinators	
Total no. participants		**20**

Participants were split into four groups, each containing representatives from the three stakeholder groups, following the principles of the World Café method [174]. The groups rotated around four different rooms, each focused on a different type of insulation: loft, cavity, internal wall insulation (IWI) and external wall insulation (EWI). In each room a facilitator guided them through a discussion about deterioration of that insulation type. Each facilitated discussion lasted around 25 minutes, and then the group moved to another room to discuss another type of insulation (Figure 16). Therefore, participants in each session were mixed to give a range of views on the four retrofits.

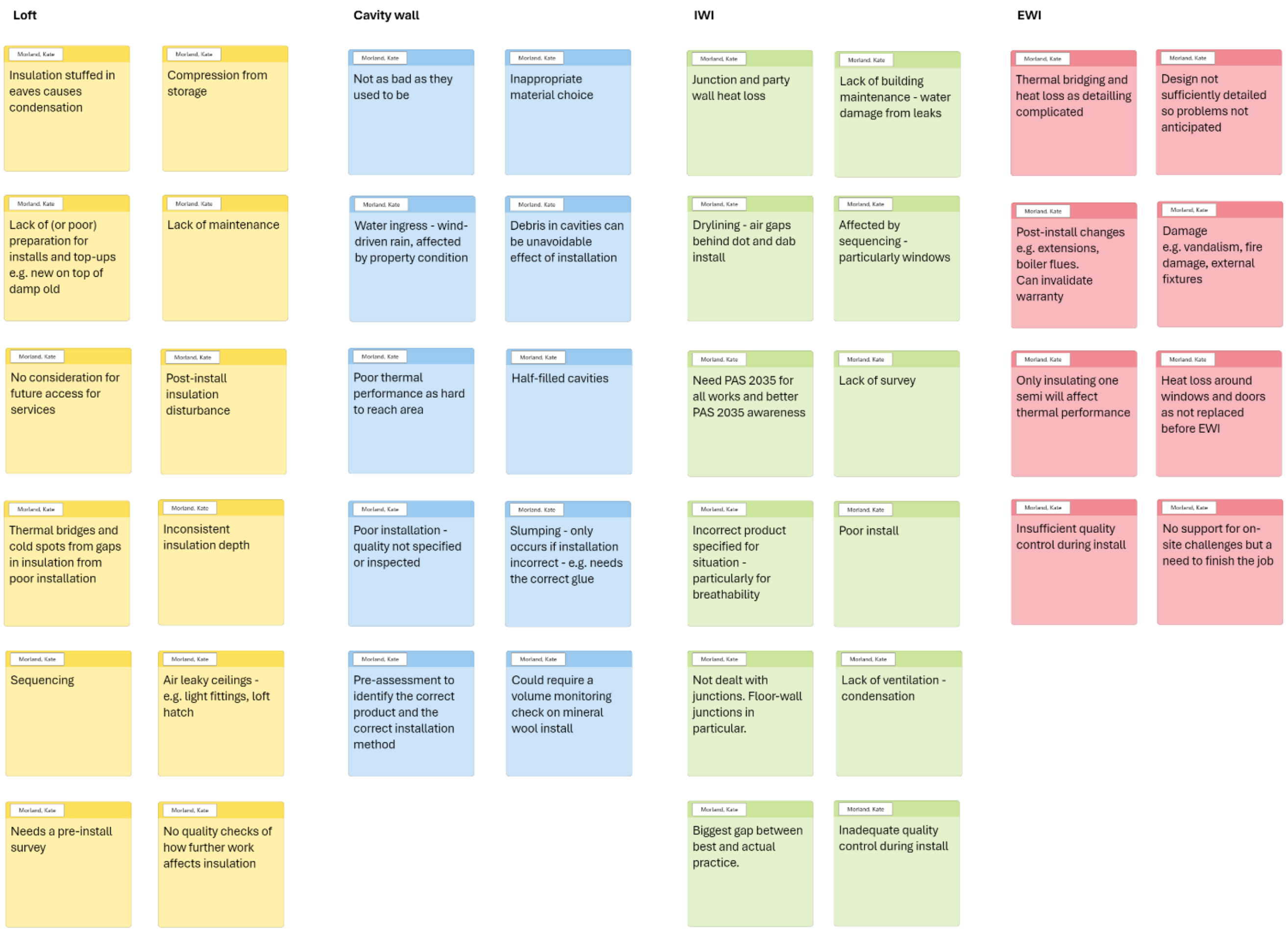
Participants in the three different stakeholder groups (providers, clients and associated groups) were allocated coloured post-it notes so that any differences in views between stakeholders could be identified. Providers were allocated pink, clients were blue and associated groups were green.

The process in each room was the same: a facilitator showed photographs of a loft, cavity wall, IWI or EWI retrofit case study and gave a brief account of some of the key aspects of the case study. Participants were then asked whether they thought the thermal performance of the retrofit was sub-optimal, and if it was, to write how and why the thermal performance was sub-optimal on their post-it notes. After five minutes, the facilitator asked participants to share and discuss what they had written. The facilitator then expanded the conversation to participants' wider experiences of performance deterioration in that specific type of retrofit. Facilitators made notes of participant comments on light blue post-it notes to differentiate them from those of the participants.

Figure 9: Photographs from the EWI and IWI rooms during the workshop.

When each group had visited the four rooms, facilitators collated the post-it notes from all 16 sessions, grouped them by retrofit type, and analysed them for common themes which could be used as the basis for classifying poorly performing retrofits. These initial classifications were added to a Microsoft Whiteboard and presented onscreen to all participants in a final whole-group review and feedback session (Figure 17).

Figure 10: Initial classifications of deterioration of retrofit used for the group discussion



Following the workshop, the post-it note and initial classifications were reanalysed and discussed within the research team. It was agreed that each of the initial classifications identified during the workshop fell into one of two groups. This centred around where retrofit insulation performance deteriorated, either: 1) at the point of install, i.e. the thermal performance of the insulation could never meet design assumption targets, as the installation was sub-optimal, or 2) over time after the point of installation.

Classifications assigned to the first group were omitted from further development, as this type of retrofit performance deterioration is directly related to the performance gap, not the insulation deteriorating over time. Where poor quality installation was deemed to also have the potential to exacerbate or accelerate deterioration, for example directly causing moisture accumulation, this was included. Classifications in the second group refer to retrofit insulation performance deteriorating over time as the result of numerous external factors. The final set of classifications is shown below. Having established an approach for classifying poorly performing retrofit, these different classifications were tested in the next stage of the project, the Delphi study.

Appendix 4 – Delphi methodology and Round 1 and 2 results

The Delphi method [95] is particularly useful in areas of limited research, as it draws on the expertise of a knowledgeable participant pool. The method is therefore well placed to explore areas where controversy, debate, or a lack of clarity exist. It is a way of gaining consensus across a panel of experts on a given topic. It starts with a questionnaire that is sent to a panel of experts within a specific field. They participate anonymously and are asked to rate a series of statements and provide feedback. The researchers assess all responses, taking forward the statements where consensus is reached amongst participants into another questionnaire round, and disregarding those where it is not. The process is repeated until participants have completed three rounds of questionnaires and a good level of consensus is reached [175].

Delphi methodology was used to develop recommendations for the design of a national survey of retrofit deterioration. The Delphi research was designed around three questions:

1. **What classifications of insulation deterioration should be included in a national survey?**
2. **How should they be measured and graded?**
3. **What sample should be included in a national survey?**

The Delphi study comprised three rounds of questionnaires which were sent to an expert panel.

Participants

Panel members were recruited from the same list drawn up for the workshop invitations, supplemented by names taken from the Royal Institution of Chartered Surveyors (RICS) member database. Participants were offered an industry-standard incentive to take part. The aim was to recruit a pool of between 20 and 30 experts. To ensure a large enough pool, 87 participants were invited to complete the first questionnaire, and of these, 26 experts responded. For rounds 2 and 3, only those who completed the first questionnaire were invited to take part. The response rate for round 2 and round 3 were 85% (22 participants) and 81% (21 participants) respectively. The summary of participant stakeholder groups is shown in Table 22.

Of the participants who chose to leave demographic details, their ages ranged from 31 to 72 (mean 50.4) and most (20/21) were male. Most were surveyors, with membership of the RICS. Alternative roles, qualifications and affiliations were architectural technicians and the Institute of Asset Management. The mean number of years of experience was 21.5.

Table 16: Summary of Delphi study participants by stakeholder group

Stakeholder group	Completed Round 1 questionnaire	Attended workshop & completed Round 1 questionnaire
Retrofit providers (supply side)	6	4
Retrofit clients (demand side)	4	3
Associated groups	13	6
Building surveyors from RICS database	3	N/A
Total no. participants	**26**	**13**

Procedure

Questionnaires were sent one week apart between January and February 2024 and participants were given a week to complete each one. In addition to building consensus from the previous round, each questionnaire had its own focus.

Round 1 asked participants for their thoughts on classifying retrofit insulation deterioration. Round 2 asked about how to measure and record the condition of each classification of insulation deterioration. Round 3 asked participants to estimate how common each type of deterioration is, based on retrofit age and whether specific house types are prone to one insulation deterioration classification or another. This is summarised in Table 23.

Table 17: Focus of, and participation in, each Delphi round.

Delphi Round	Research question	Participants invited	Responses received	Return rate
Questionnaire 1	How should deterioration be categorised?	87	26	30%
Questionnaire 2	How should retrofit insulation deterioration be measured and graded?	26	22	85%
Questionnaire 3	What sample should be included in a national survey?	26	21	81%

Delphi 1: How should deterioration be categorised?

The classifications of insulation deterioration developed from the workshop were used in the first Delphi round. Participants were asked to rate each statement against four questions, using a scale of 1 to 9. Participants were also able to leave comments.

The four questions (and their scale anchor points) were:

- Is this important to measure? (not at all important to extremely important)
- How much impact could this problem have on thermal performance? (very little to very large)
- How common is this problem likely to be? (extremely uncommon to extremely common)
- Is the statement wording clear? (extremely unclear to extremely clear)

The criteria for consensus, and therefore inclusion in the following round, are that at least 70% of participants voted 7-9, and no more than 20% voted 1-3 [176]. Criteria for exclusion are that 70% voted 1-3 and no more than 20% voted 7-9. The results are shown in Table 24. Ticks (✓) indicate where the consensus criteria have been met. Tildes (≈) indicate that consensus has nearly been reached, along with the number of votes short of consensus. Crosses (X) indicate that consensus was not reached.

Table 18: Results from the first Delphi Round.

Statement	Consensus	Comments
Loft 1: The loft insulation has not been designed to allow access to services, which means that the insulation would be damaged when access is required.	Importance ✓ Impact ✓ Common ✓ Clear ✓	Several comments highlighting level of disruption caused to insulation by tradespeople working in loft space.
Loft 2: The loft insulation blocks ventilation at the eaves, which means condensation could damage the insulation.	Importance ✓ Impact ≈1 Common ✓ Clear ✓	Concerns of condensation in roof space causing rot and mould rather than reducing thermal performance.
Loft 3: The loft insulation has been disturbed by humans or animals, e.g. compressed by storage.	Importance ✓ Impact ≈1 Common ✓ Clear ✓	

Statement	Consensus	Comments
Loft 4: The loft insulation has been damaged by weather, water or debris (e.g. dust).	Importance ✓ Impact ≈1 Common X Clear ✓	
Cavity Wall 1: The material composition of the cavity wall insulation has changed over time.	Importance ✓ Impact ≈1 Common ≈1 Clear ✓	Several comments about suitability of CWI given condition of the home. Concerns over water/contamination and vermin getting in. Some comments about performance relating to older insulation products and cowboy builders installing them.
Cavity Wall 2: The cavity wall insulation has been poorly installed, which has accelerated deterioration of the insulation, e.g. slumping.	Importance ✓ Impact X Common ≈1 Clear ✓	
IWI 1: The IWI product or system used is inappropriate for the building, which has accelerated deterioration of the insulation.	Importance ✓ Impact X Common ≈1 Clear ✓	Noted as being difficult to measure as continuity of IWI is hidden. Comments around mould and moisture risk being more problematic than reduced thermal performance. Degree of DIY or building works carried out after IWI installation could affect level of insulation degradation.
IWI 2: The building was not sufficiently prepared or maintained which has accelerated deterioration of the insulation, e.g. leaky roof that has not been fixed before the IWI installed.	Importance ✓ Impact ✓ Common X Clear ≈1	
IWI 3: The IWI has been damaged post install e.g. DIY, subsequent works.	Importance ✓ Impact ≈2 Common X Clear ✓	
EWI 1: The EWI product or system used is inappropriate	Importance ✓	Several comments around the possibility of damage

Statement	Consensus	Comments
for the building, which has accelerated deterioration of the insulation.	Impact ✓ Common X Clear ✓	from different external factors. EWI requires maintenance, as well as at below ground and roof levels. Some scepticism that classifications listed could lead to much insulation degradation.
EWI 2: Lack of maintenance of fixings or sealants used for the EWI has accelerated deterioration of the insulation.	Importance ✓ Impact ✓ Common X Clear ✓	
EWI 3: Cut arounds in the EWI for penetrations have never been sealed, which has accelerated deterioration of the insulation.	Importance ✓ Impact ✓ Common ≈1 Clear ✓	
EWI 4: The EWI has been damaged post install e.g. DIY, subsequent works.	Importance ✓ Impact ✓ Common ≈3 Clear ✓	

In response to the first round, the following changes were made:

- Loft 2 was changed so that it addresses actual rather than potential damage.
- Two of the loft classifications were combined (Loft 3 and Loft 4).
- An additional classification was added to Cavity Wall.
- Small changes were made to the wording of insulation deterioration.
- Additional examples were added to IWI 4.
- Additional examples were added to EWI 4.

Delphi 2: How should retrofit insulation deterioration be measured and graded?

In the second survey, a revised list of classifications were presented together with suggestions of potential ways that they may be measured. Participants were asked to rate each measurement statement, using a scale of 1 to 9, where 1 was strongly disagree and 9 was strongly agree. In addition to this, where the wording of a classification changed, participants were asked to rate how clear the new wording was using the same 1 to 9 scale, where 1 was extremely unclear and 9 was extremely clear. As in the previous round, participants were also able to leave comments.

The criteria for consensus was that at least 70% of participants voted 7-9, and no more than 20% voted 1-3 [176]. Criteria for exclusion was that 70% voted 1-3 and no more than 20% voted 7-9.

The results are shown in Table 25. Ticks (✓) indicate where the consensus criteria have been met. Tildes (≈) indicate that consensus has nearly been reached, along with the number of votes short of consensus. Crosses (X) indicate that consensus was not reached.

Table 19: Results from the second Delphi Round.

Statement	Consensus	Comments
Loft 1. The loft insulation has been moved, e.g. to allow access to services.	Measured using visual inspection ✓ Clear ✓	Some comments about capturing insulation type and where it is located in the loft.
Loft 2: The loft insulation blocks ventilation at the eaves, which means condensation could damage the insulation.	Measured using visual inspection and infrared thermography ≈3	Several comments that infrared thermography is unnecessary. Many participants describe how a specialist skillset and conditions are required to perform accurate thermographic surveys.
Loft 3: The loft insulation has been damaged by weather, vermin, water, age, debris (e.g. dust) or compressed by storage.	Measured using visual inspection, measuring insulation depth and infrared thermography ✓ Clear ✓	Some comments about the need to inspect the ceilings below, not just the loft.
Cavity Wall 1: The cavity wall insulation has deteriorated over time (e.g. crumbled).	Measured using borescope ✓ Clear ✓	Several comments suggest using a visual inspection and thermography in addition to a borescope.
Cavity Wall 2: The cavity wall insulation has been	Measured using visual inspection	Some scepticism around focusing on drill pattern as

Statement	Consensus	Comments
poorly installed, which means it has deteriorated (e.g., slumping).	of the drilling pattern, infrared thermography and borescope ✓ Clear ✓	it does not necessarily mean insulation is present.
Cavity Wall 3: The cavity wall insulation has been contaminated by water penetration, debris, or vermin.	Measured using visual inspection and infrared thermography ✓ Clear ✓	Several comments advocating use of borescope and removing a brick if feasible.
IWI 1: The IWI product, design or system used is inappropriate for the building, which has caused the insulation to deteriorate.	Measured using visual inspection, infrared thermography and protimeter ✓	Many participants have strong reservations about using protimeter in these circumstances.
IWI 2: The building has not been sufficiently maintained, which has caused the insulation to deteriorate.	Measured using visual inspection, infrared thermography and protimeter ✓ Clear ✓	Many participants have strong reservations about using protimeter in these circumstances.
IWI 3: The IWI has been damaged post install e.g. DIY, flood, subsequent works.	Measured using visual inspection and infrared thermography ✓	Several comments about possibly using a protimeter in these circumstances.
EWI 1: The EWI product, design, system used, or detailing is inappropriate for the building, which has caused the insulation to deteriorate.	Measured using visual inspection and infrared thermography ✓ Clear ✓	Comments about this being challenging to do without further detailed home and EWI specification information.

Statement	Consensus	Comments
EWI 2: Lack of maintenance of fixings or sealants used for the EWI has caused the insulation to deteriorate.	Measured using visual inspection and infrared thermography ✓	Comments about this being challenging to do without further detailed home and EWI specification information.
EWI 3: Cut arounds in the EWI for penetrations have never been sealed, which has caused the insulation to deteriorate.	Measured using visual inspection and infrared thermography ✓	Support for thermography to highlight cold spots and moisture ingress
EWI 4: The EWI has been damaged post install e.g. DIY, subsequent works, weather.	Measured using visual inspection and infrared thermography ✓ Clear ✓	Support for thermography to highlight cold spots and moisture ingress
How should the insulation condition be recorded?	Good, fair or poor ✓ Percentage of insulation affected ≈1 Approximate age of the insulation ✓	Several comments about the scale – define it and expand it to make it wider. Establishing age will be difficult, so surveyors will be guessing. Give options for age. Percentage of area most appropriate for insulation in “poor” condition.

Appendix 5 – Delphi questionnaires

Questionnaire	File
1	Adobe Acrobat Document
2	Adobe Acrobat Document
3	Adobe Acrobat Document

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