Retrofit Revisit: 10 Case Studies

Julie Godefroy and Marion Baeli

An important building performance evaluation project to inform the UK's approach to improving our housing stock and contribute to our net zero objectives

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Her projects outside CIBSE include the Building Regulations domestic energy calculation method, overheating in homes (for the Good Homes Alliance), retrofit and building passports, and building performance evaluation. She is the author of CIBSE TM40: *Health and wellbeing in building services* (2020).

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Marion Baeli is a Principal, Sustainability Transformation, at 10 Design, part of the Egis Group. She has authored the influential book *Residential Retrofits: 20 Case Studies*, published by the RIBA in 2013, which has served as a foundation for the Retrofit Revisit research. This award-winning publication has significantly shaped her career, focusing on retrofit techniques, adaptive reuse strategies, and low-energy design. With over 20 years of experience, Marion is proficient in designing and delivering large-scale, complex projects across the housing and office sectors.

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Julie Godefroy (left) and Marion Baeli (right)

Residential Retrofit (cover)

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Executive summary

What is Retrofit Revisit?

Retrofit Revisit is a building performance evaluation (BPE) of 10 retrofitted homes, carried out approximately 10 years after the original retrofit works. It aimed to gather lessons on retrofit and on BPE techniques.

On retrofit:

- What has stood the test of time?
- Are there any new lessons on how to carry out retrofit projects?
- Topics of particular interest included (but were not limited to): energy demand, moisture, insulation options (moisture and combustibility), degradation of original solutions (e.g. airtightness).

On BPE techniques:

- What can be learned in a relatively short and non-intrusive manner, from individual BPE techniques or packages of several techniques?
- Where are more specific or detailed BPE techniques useful? How can some BPE techniques being, or newly, developed help?

The sample of 10 homes was as follows:

- Six were part of the 2009 Retrofit for the Future programme. All were considered best practice or exemplar at the time, and employed a whole house 'deep' retrofit approach.
- Six were pre-1919 properties.
- Nine were houses, one a flat.
- Some were tenanted from housing associations, others occupied by private owners.
- The insulation strategies and properties varied, with a mix of external, internal, and cavity insulation and of permeable and impermeable materials.
- Heating, hot water and ventilation systems were very varied across the sample.

A two-tiered BPE approach was followed, as described below:

Core scope
All 10 case studies

Site visits

User survey: SOAP Retrofit

Energy use audit based on one year (e.g. bills)

One month of 'winter' monitoring:
— Energy meter readings in more detail
— Temperature and RH in a sample of rooms
— CO_2 in most occupied room

This monitoring allowed the production of:
— SmartHTC
— BTS Mould risk indicator

Airtightness testing: blower door and pulse

Detailed scope
Selection of case studies (4–5)

Independent witnessing of airtightness tests (most homes)

Thermal performance
— Plate *U*-value measurement
— Heat3D *U*-value measurement
— Thermal imaging
— Independent expert advice

Moisture
— Physical testing, e.g. moisture content, fungal tests count in ambient and cavity air, moisture content of fabric
— Detailed hygrothermal analysis of moisture damage
— In-situ monitoring

Overview of findings — Performance: have the ten retrofits passed the test of time?

Energy performance

- In most homes, no major change has been observed compared to the original retrofit energy use.
- The retrofit has delivered long-term benefits, with energy use still significantly lower than in the average stock.
- Tellingly, most homes have reported being satisfied or very satisfied with their energy bills(!).
- Where space heating could be estimated, it is in line with best practice retrofit standards, significantly below the national average.

Fabric

- Fabric efficiency improvements have been shown to be very effective in the long run, with heat demand remaining very low compared to the national average.
- Only a small number of instances have been found of material deterioration, and in most cases these have been very localised issues.
- Maintenance is key: this applies to all homes, whether retrofitted or not. Common issues found across the sample include clearing gutters and downpipes.

Systems

- Complex systems are often likely to fail (this is not a new finding).
- Mechanical ventilation with heat recovery (MVHR) has shown to be reliable in these case studies. This was not necessarily expected, as these systems were still quite innovative at the time. This is probably thanks to the significant attention given to the projects at the time, with the system design and installation probably receiving more attention to detail than the average.
- Ease of controls remains an issue, even in homes where residents report good comfort and relatively simple systems.
- Renewables: some issues with solar thermal; insufficient metering to assess performance.
- Looking at these 'Retrofit for the Future' low-carbon strategies now highlights how much the industry has evolved, in parallel with grid decarbonisation: 8 out of the 10 homes have a gas boiler, and several had solar thermal but only one (Culford) installed photovoltaics (PVs) at the time, with a further home (Grove) having installed them since. The more common approach now would be for an all-electric system (typically, heat pump) and PVs rather than solar thermal.

Residents feedback and the indoor environment

- Overall feedback is very positive, with the sample of 10 homes showing results significantly better than the SOAP Retrofit benchmark.
- Feedback shows comfort has been delivered in all houses.
- Winter comfort is rated very highly in the large majority of homes; summer comfort is less so, but no worse than benchmark.
- Temperature, relative humidity (RH) and CO_2 are within recommended ranges for most homes.

Overview of findings — The evaluation techniques

What worked well:

- The whole team was very motivated by the project, and experienced.
- Many evaluators already knew the projects well.
- The common methodology was useful to collectively check and agree an approach and bring some consistency, with input from all and an Excel spreadsheet for basic energy reporting.

- The core and detailed BPE methods proved complementary, and the detailed techniques brought useful additional findings.
- The project benefitted from a balanced input from practitioners, academics and specialists.
- All homes used the same IEQ sensors provided by BTS and Ian Mawditt: this helped with consistency of data, allowed the use of the BTS platform for many of the tests, and provided support to the evaluators for training and queries.

What we would do differently:

- Allow more preparation time. Funding was obtained in early January 2023: at that point, with only some homes and team members had been identified, and only 'in principle'. Monitoring to be complete by the end of March to meet funding requirements and to capture a month of winter conditions.
- Despite initial enquiries with the residents and housing associations about their willingness to engage and the availability of energy data, in a small number of homes this proved a challenge once the study had started.
- Despite the creation of a common methodology and reporting templates, with collective input, this did lead to a certain level of iterative work, and time-consuming cross-project data collection and analysis.
- More developed templates (not possible with the limited preparation time), to make reviewing and cross-project data collation and reporting quicker and more consistent.
- Detailed aspects of the methodology could have been modified or made more explicit, e.g. requiring air leak finding as part of the airtightness testing, requiring more systematic use of thermal imaging on site and in the performance analysis.

Key lessons for future BPE

- The BPE activities in this study corresponded to a scope between the BS 40101:2022 'Preliminary' and 'Standard' BPE levels, as well as the addition of detailed techniques. This provided a comprehensive coverage of building performance aspects (energy use, residents feedback, indoor conditions), with more detailed techniques due to the nature and purpose of this project, and less detailed investigation of energy use (annual energy use, and monitoring over a month, rather than monitoring over a full year). This is considered to have met the purpose of the study.

- The assessment of energy use for space heating could be done in some homes thanks to monthly meter readings from residents over the years, with the summer months used to estimate the hot water and cooking load. However, this is only an estimate and, crucially, this is only possible in homes with gas heating. Going forward, it will be very important to plan for metering of heat in the design of homes and in setting-up BPE studies. One way to address this would be for all heat pump products to include, on manufacture, metering of their heat output as well as electricity use; the data should be logged and easily available for download or other data transfer form.
- Similarly, as on-site renewable systems become more common, it is essential that their output, their contribution to the home, and their exported energy, be metered, as a reliable assessment of the home's performance is otherwise difficult.
- The detailed techniques deployed to investigate fungal and allergen levels provided valuable insights, which could not have been found otherwise. While the results are reported against a scale, this is still relatively new and not necessarily straightforward to translate into recommendations. As the technique matures in the future, it would be more accessible and directly relevant to practitioners, residents and stock owners if the scale (whether in levels and/or species) was associated with clear recommendations such as safe/caution/severe, actions required etc. This conclusion was expected, since the purpose of this study was not only to investigate performance in detail, but find out more about what these innovative techniques can bring to building performance evaluation.

Abbreviations

BDT	blower door test
BPE	building performance evaluation
BUS	Building Use Studies
CO_2	carbon dioxide
DHW	domestic hot water
DPC	damp proof course
EAHP	exhaust air heat pump
EPC	Energy Performance Certificate
EPS	expanded polystyrene (insulation)
EUI	energy use intensity (kW·h/m^2 GIA)
EWI	external wall insulation
GIA	gross internal area (m^2)
GRP	glass reinforced plastic
HFM	heat flow meter
HLP	heat loss parameter (W/m^2·K)
HTC	heat transfer coefficient
IEQ	Indoor environmental quality
IR	infrared
IWI	internal wall insulation
LETI	London Energy Transformation Initiative
LPP	low pressure pulse (test)
MEP	mechanical, electrical, plumbing
MIT	mean internal temperature
MVHR	mechanical ventilation with heat recovery
NEED	National Energy Efficiency Data-Framework
OSB	Oriented strand board
PHPP	Passivhaus Planning Package
PIR	polyisocyanurate (insulation)
POE	post occupancy evaluation
ppm	parts per million
PV	photovoltaic cell
RH	relative humidity
SAP	Standard Assessment Procedure
UFH	underfloor heating
UKCMB	UK Centre for Moisture in Buildings
VCL	vapour control layer
WUFI®	Wärme Und Feuchte Instationär (heat and moisture transiency) (modelling software)
XPS	extruded polystyrene (insulation)

Foreword

Innovate UK

Over 10 years ago, Innovate UK (then known as the Technology Strategy Board) invested £15 million in implementing deep retrofit (seeking >80% carbon emissions reductions) on over 100 socially managed houses. As part of the project outcomes, every property was evaluated to understand what really worked when it came to improving the performance of existing homes. Over winter 2022/2023, we welcomed the opportunity to revisit some of the properties to understand if the interventions made back then continued to deliver improved comfort and performance.

In the interim decade, building performance evaluation (BPE) technology and practice have both moved on considerably. How robust, meaningful and useful data are collected in an affordable and accessible manner are important additional questions considered in this work. This report will inform the understanding of BPE for occupants, designers and decision-makers, as well as the retrofit industry.

Scaling up of retrofit is a priority for the Net Zero Heat programme now at Innovate UK and learning lessons from previous investigations is critical to delivering net zero heat effectively and consistently. The clarity and certainty the current report provides on both the impact of interventions made and how to measure building performance are incredibly valuable. It makes a significant contribution to Innovate UK's work on creating market demand for the decarbonisation of heat in building by providing confidence to owners, investors and occupants through data.

Historic England

Historic England is committed to climate action; supporting the drive to net zero through collaborative research is central to our strategy. A significant proportion of the UK building stock is pre-1919 and therefore it is imperative that historic buildings, both listed and those of traditional construction, are part of the solution. By engaging with, and working to improve, building performance evaluation we strive to find appropriate measures and demonstrate successful solutions.

Historic England provided funding and technical support to enable specific evaluation work to be undertaken on the traditional buildings in this study. These include the packages evaluating moisture, air tightness and thermal performance. Findings highlight that maintenance, both of buildings and services, is a key part of successful retrofit. Additionally, the findings related to moisture, including fungal and allergen testing, are highly valuable. These offered insight and evidence that could not have been otherwise achieved. This demonstrates that where practicable, evaluations of this nature are of fundamental importance and a critical addition to robust understanding of performance.

Our built environment and heritage is looked after by a wide variety of individuals, communities, owners and organisations; we need to equip people with the information and support they need to make good decisions. This report has highlighted that by working collaboratively we can ensure that cross sector advice on best practice is evidence based, balanced and rigorous.

Cross-project briefings

Briefing 1: BPE overall approach

1.1 The case study homes and overall approach to the retrofit revisit

The 10 case study homes were selected to offer varying characteristics and provide insights on several issues. Broadly speaking, the selection criteria were as follows.

The home retrofit took place about 10 years ago.

The retrofit was best or exemplar practice at the time, i.e. 'deep retrofits' and following a whole-house approach, considering the building as a system of interconnected components. This was to avoid selecting projects which were already known to be bad practice and would not bring new lessons. Within these, one caveat is Hensford Gardens, which does follow best practice, and a deep comprehensive and systematic approach, but does so step-by-step (in phases over several years). The original retrofit was therefore only Step 1, while the Retrofit Revisit captures the outcome after Step 3 (party walls, floor, roof, elevations and whole-house ventilation system).

The retrofit was evaluated at the time of the original retrofit, providing performance comparator for the revisit. While pre-retrofit performance and design stage targets are used in this study where available, the performance of the original retrofit is the key comparator for this revisit: has the retrofit performance been maintained, and are there new lessons or findings?

The team had to have reasonable confidence that key data would be available, including energy use.

The residents had to be available and willing to take part in the study.

The sample should include both pre- and post-1919 homes.

The sample should include a mix of characteristics and retrofit strategies:

- Internal, external and cavity insulation, and presence or otherwise of a cavity (i.e. gap) in the case of internal wall insulation.
- Permeable and impermeable insulation, with the particular interest of finding out whether moisture degradation had occurred in the case of impermeable insulation.
- Specific characteristics of interest, with the potential for useful findings to industry, e.g. cold loft; EPS-insulated suspended timber floor; air brick in homes with internal wall insulation.

The selection also sought to include case studies that exhibited specific design and retrofit characteristics considered of interest to industry. For example, where integral components of the retrofit were relatively untested or potentially presenting a moisture risk, such as cold loft and exposed joist ends subject to cold conditions.

These characteristics, typically, had not been considered problematic at the time of the retrofit, or the uncertainty was acknowledged but not resolved (e.g. what happens to joist ends). The 10-year revisit therefore aimed to provide the start of an answer to these questions, albeit on a limited sample.

Other characteristics varied and were investigated as part of the study (e.g. airtightness strategies, and the type of heating, hot water and ventilation systems), but they were not part of the selection criteria. They are described in more detail in the relevant briefings (e.g. Briefing 8, 'Maintenance', includes a tabulated description of systems in all the homes), and in the individual case study reports.

The following table provides an overview of the 10 homes against these selection criteria. Six homes were part of the Retrofit for the Future programme (and in *Residential Retrofit: Twenty Case Studies* (Baeli, 2013)), and four others. More details are provided in the individual case studies. The rationale for selection of the properties to which detailed tests would be applied is explained in Appendix 1, 'Briefing to evaluators and BPE methodology'.

Table 1.1 Retrofit Revisit case studies and key characteristics

Case study	Typology	Age	Main insulation approach (IWI = internal wall insulation; EWI = external wall insulation)	Other point of interest?	Detailed tests
Culford Road (Retrofit for the Future)	Mid-terrace	Pre-1919	IWI (incl. polyurethane foam with cavity between existing wall and new insulation layer)	13 years of full monitoring of cavity void*.	Yes
Grove Cottage (Retrofit for the Future)	End terrace	Pre-1919	Mixed EWI and IWI (incl. small polyurethane foam on masonry)	Uninsulated cellar	Yes
Princedale Road (Retrofit for the Future)	Mid terrace	Pre-1919	IWI (incl. polyurethane foam with cavity between existing wall and new insulation layer)	Certified full PassivHause of cavity void*.	
Rectory Grove	Semi-detached	Pre-1919	IWI (mostly permeable except small area at lower floor)	Variety of insulation types Several years of monitoring	Yes
Hawthorn Road (Retrofit for the Future)	Mid-terrace	Pre-1919	IWI (incl. sheep's wool), external at back	Variety of insulation types	Yes
Shaftesbury Park Terrace (Retrofit for the Future)	Mid-terrace	Pre-1919	IWI	Suspended timber floor w/ expanded polystyrene (EPS) beads	Yes
Blaise Castle Estate	Detached	Post-1919	EWI and some IWI on filled cavity	Cold loft	
Hensford Gardens	Mid-terrace	Post-1919	Stage 1: cavity Stage 2: reconstruction	Phased retrofit	
Passfield Drive (Retrofit for the Future)	Mid-terrace	Post-1919	EWI		
Wilmcote House	Apartments	Post-1919	EWI	Flats; previously difficult to test	

* Humidity sensor inside wall cavity to measure moisture content, kit accessible via airbrick.

1.2 BPE approach

1.2.1 Overview

All 10 homes were analysed using a 'core BPE' package intended to:

- cover whole building performance including fabric, energy use, indoor environment, and user feedback
- utilise reasonably common and/or non-intrusive techniques.

While relatively intrusive, airtightness testing was included in the Core BPE package as it is very common and considered to provide information of high importance on home performance, and even more so in the context of this study, since one area of interest was the potential degradation of solutions over time.

The occupant surveys were carried out using SOAP Retrofit questionnaire[1]. The use of Building Use Studies (BUS) surveys was discussed with the evaluators and steering group; the SOAP Retrofit survey was selected for a number of reasons including ease of access (Zack Gill from SOAP Retrofit was on the Steering Group), full compliance with BS 40101:2022 (one reason why BUS is not BS-compliant is insufficient coverage of usability), and specific questions on retrofit intent and outcomes.

In addition, six homes received a more extensive package of 'detailed BPE' techniques. These homes were selected based on the following:

- willingness of residents, especially as these tests tended to be more disruptive than those of the core BPE package
- characteristics considered of interest and with the potential for useful lessons, e.g:
  - some situations were considered potentially at risk of deterioration, and needed to be checked, e.g. EPS-insulated suspended timber floors
  - some were considered low risk and high replicability, but with little evidence in the field, e.g. air brick in IWI homes.

Details are described in the relevant briefings, including Briefing 4, 'Thermal layer', Briefing 5, 'Details' and Briefing 10, 'Thermal and moisture techniques', and in Appendix 5, 'Comparison of BPE methodology with BS40101:2022'.

A building performance evaluation methodology document was produced and commented on by evaluators before being finalised — previously circulated to the steering group (see Appendix 1). The use of a common methodology is useful in any case, but it was deemed particularly so in this study, since many evaluators were involved in the original retrofit of the home they evaluated. This has significant benefits (i.e. they know the home very well and are likely to be in a

[1] https://www.soapretrofit.com/occupant-survey (accessed 3.04.24)

good position to understand the root causes for some issues), but the common methodology helped guarantee a minimum level of independence and consistency in the approach and reporting of results — this is of primary importance due to the range of projects and involvement of designers as evaluators.

Core scope
All 10 case studies

Site visits

User survey: SOAP Retrofit

Energy use audit based on one year (e.g. bills)

One month of 'winter' monitoring:
— Energy meter readings in more detail
— Temperature and RH in a sample of rooms
— CO_2 in most occupied room

This monitoring allowed the production of:
— SmartHTC
— BTS Mould risk indicator

Airtightness testing: blower door and pulse

Detailed scope
Selection of case studies (4–5)

Independent witnessing of airtightness tests (most homes)

Thermal performance
— Plate *U*-value measurement
— Heat3D *U*-value measurement
— Thermal imaging
— Independent expert advice

Moisture
— Physical testing, e.g. moisture content, fungal tests count in ambient and cavity air, moisture content of fabric
— Detailed hygrothermal analysis of moisture damage
— In-situ monitoring

Figure 1.1 Retrofit Revisit 'core' and 'detailed' building performance evaluation scope

1.2.2 Performance parameters and comparators

The performance parameters of interest are in large part similar to those of the original Retrofit for the Future study (energy use, space heating demand, airtightness, temperature and RH, ambient CO_2). This means that, in large part, comparators were available for the Retrofit Revisit with the original retrofit, and sometimes with pre-retrofit.

The study also includes new elements of performance evaluation, for which previous comparators are not available:

- heat transfer coefficient (HTC): where no co-heating tests were originally carried out due to cost and practical difficulties
- fabric moisture investigations, which have risen up the agenda since Retrofit for the Future
- user satisfaction: the application of occupant surveys in all homes (SOAP Retrofit), which is a significant addition compared to Retrofit for the Future.

1.2.3 Templates

A simple briefing sheet and consent form were produced and commented on by evaluators before being finalised, for all evaluators to use with their residents — see Appendix 2.

Reporting and data (energy and indoor environmental quality (IEQ)) record templates, in Excel were produced and commented on by evaluators before being finalised.

1.2.4 Sensors

IEQ sensors were the same across all homes:

- Temperature and RH sensors (Elitech), lent by BTS, with associated software, instructions and training. The data was also used for the production of SmartHTC[2] results. Ten sensors were installed in each home.
- CO_2 sensors (Rotronic CL11), lent by Ian Mawditt, with associated software and instructions. One sensor was installed in each home, in the most occupied room.

Details are provided in Appendix 1, 'Briefing to evaluators and BPE methodology'. In addition to the instructions and training, most evaluators required support on the deployment of sensors and downloading of the data; this was mostly in the form of simple queries to BTS or Ian Mawditt, to highlight or complement the instructions.

1.2.5 Comparison with BS 40101

The study's core BPE package falls between the BS 40101:2022 'Preliminary investigation' and 'Standard' BPE levels. The main difference is that compliance with the BS 40101 standard BPE level would require monitoring of energy use over a full year instead of start and end meters, as were used here. This was available for some homes, thanks to residents' records of meter readings over the years, but was not a requirement of the study — see comments in section 1.3, below.

The techniques within the study's detailed BPE package fall within the BS 'Investigative' BPE package.

Appendix 3, 'Comparison of BPE methodology with BS40101:2022', provides a comparison of the study's Core BPE scope with the BS 40101 Standard BPE level.

1.3 Lessons learnt and recommendations

1.3.1 Overall approach and scope

Overall, the core BPE scope worked well to provide a rounded picture of performance on the home, with complementary data on residents' feedback, the physical environment, energy use, and the performance of the fabric and systems. In particular, the availability of both qualitative feedback (survey results) and physical monitoring (temperature, RH and CO_2) was very valuable, and highlights that both are needed for an understanding of the indoor environment: see Briefings 6, 'IEQ' and 7, 'User experience'.

[2] The heat transfer coefficient (HTC) is a measure of the rate of heat loss per degree temperature difference between inside and outside. It is expressed in watts/kelvin (or watts/degree Celsius); e.g. if a building has an HTC of 100 it would require a constant power input of 100 W to maintain it at a temperature one degree warmer inside than out. Traditionally, HTCs are measured using co-heating tests. SmartHTC is a methodology developed by Build Test Solutions and supported by the SMETER programme, to estimate HTC based on smart meter readings, without the need for co-heating tests. For details of the SMETER programme, see HM Government (online).)

The selection of case studies worked well to provide information on home typologies and retrofit strategies which were varied, but still similar enough to provide useful findings; in particular, knowing that the retrofit design and works had received suitable attention was an important consideration in the analysis. Similar findings on benefits being delivered over time can be found in other projects which received similar attention to detail, for example the Glasheen House Enerphit project in Cork, from five years ago[3]. By contrast, it can be more difficult to draw conclusions from larger scale studies, as factors such as changes to occupancy or extensions are not necessarily known[4], and large samples typically include a large proportion (likely, a majority) of retrofits which did not receive suitable attention to detail and works on site and/or did not apply a whole house approach.

In several instances, performance could be evaluated as it was currently, but not compared with what it had been at the time of the original retrofit because of a lack of information or because these parameters (e.g. ambient mould levels, fabric moisture) had not been examined at the time. This is, to some extent, unavoidable since techniques evolve, and until such time that more homes are routinely evaluated and the results logged for future re-visits. Performance evaluation was also limited by metering, e.g. access to energy data from the supplier, lack of metering of on-site systems etc. — for details see Briefing 2, 'Energy use'.

The programme for this study was very tight, with instruction in early January 2023 and the need to finish the site monitoring by the end of March 2023 in order to capture a month of winter conditions within the same financial year. A longer period of preparation would have been useful.

- Despite the creation of a common methodology and reporting templates, with collective input, this did lead to a certain level of iterative work, and time-consuming cross-project data collection and analysis.
- Detailed aspects of the methodology could have been modified or made more explicit, e.g. requiring air leak finding as part of the airtightness testing.
- Despite initial enquiries with the residents and housing associations about their willingness to engage and the availability of energy data, in a small number of homes this proved a challenge once the study had started — see Wilmcote and Princedale case studies.

[3] 'It's a lovely house to live in now', Case Study - Glasheen Road, PassiveHouse+, issue 43, July 2023

https://passivehouseplus.co.uk/magazine/upgrade/it-s-a-lovely-house-to-live-in-now (accessed 3.04.24)

[4] For example: Peñasco C. and Díaz Anadón L., 'Assessing the effectiveness of energy efficiency measures in the residential sector gas consumption through dynamic treatment effects: Evidence from England and Wales', Energy Economics, Volume 117, 2023, 106435, ISSN 0140-9883

https://doi.org/10.1016/j.eneco.2022.106435 (https://www.sciencedirect.com/science/article/pii/S0140988322005643) (accessed 3.04.24)

1.3.2 Liaising with residents

- Despite access to residents being a key criterion for selection of the case studies, once the study started in earnest a few residents proved difficult to contact and engage with (despite small incentives such as a voucher).
- Some evaluators commented that a more detailed briefing would have been useful to the residents, to explain what the testing techniques implied in practice, especially the airtightness test (what happens during the test, what to do/not do during the test etc).

1.3.3 SOAP retrofit survey

The questions are written in simple language and cover a broad range of useful issues, including energy use, comfort, general satisfaction, design and usability.

Results are shown against benchmarks, though in a less detailed way than building use studies (BUS). This benchmarking is really useful, and in the case of this sample it highlighted how well the homes are performing against the average stock, even on questions where the feedback was not overwhelmingly positive.

Some questions are useful, which are not included in the BUS questions, e.g. questions on drying space and on visible condensation and mould.

There are questions on satisfaction with systems and ease of use (or otherwise) of the controls, but no specific question on maintenance of these systems. This could be a useful evolution to the questions in the future to differentiate satisfaction with the systems, even when they operate as they should, from specific issues of maintenance and repair, e.g. cost of MVHR replacement filters, difficulty of finding skilled maintenance teams (a recurring issue in this sample of homes, which often had relatively innovative and bespoke systems).

Some questions lead to ambiguous results if people do not provide answers, e.g. questions that ask respondents to enter a tick if it applies (e.g. 'I want more control with heating system — tick if applies'): if not ticked, it is not 100% certain whether that question was considered. This could be easily addressed by modifying the question to require a 'yes/no' choice.

Seven homes responded to the question asking for additional comments on air quality — out of these, five responded with comments on thermal comfort instead. This is not unusual, but could be addressed with minor re-wording or clarification of the question.

1.3.4 Departures from BS 40101

In several homes, 12 months of data on energy use were available from the residents’ own records, which allowed an estimate of gas use for space heating versus gas use for hot water and cooking. This was, however, not a requirement for this study, and was not obtained for all homes. It is a key area where having 12 months of data is useful.

The BS 40101 'Standard' BPE requirement goes further though, requiring the 12-month data to be in 30-minute intervals. Analysing this could bring additional insights on performance, but would represent a significant addition to the scope and resources required. In the context of the Retrofit Revisit study, it is not considered that this would have been justified, relative to the additional findings it could have provided.

Monitoring of internal conditions over a summer month would have been interesting to provide further insight to summer comfort levels, and for a comparison with residents' feedback (especially as many residents rated comfort in summer less positively than in winter). However, again this would have significantly extended the period of evaluation, where site activities and interactions with residents were broadly contained to January–March.

1.3.5 Other scope items

Several evaluators and expert advisors commented that measurement of the ventilation flow rates would have been useful, as site observations (e.g. noise, seemingly low air flow) would imply that the system was not operating properly, or as part of standard checks.

1.3.6 What worked well/not well with detailed techniques

The detailed techniques focused on thermal and moisture performance issues. Lessons from these techniques, and where they added value compared to the more standard 'core' BPE techniques, are described in Briefing 10, 'Thermal and moisture evaluation techniques'. Overall, the ones related to moisture (whether ambient air or fabric moisture) proved very useful, offering findings and observations that could not have been made otherwise.

Briefing 2: Energy use: current performance and evolution over time

2.1 Trends across the case studies

2.1.1 Overview

Overall, the properties have maintained an energy use that is much lower than before the retrofit and than the average UK home.

In the retrofit projects revisited, the energy use intensity (EUI) achieved is on average ~80 kW·h/m^2 GIA per year.

This compares very favourably with data on the UK housing stock, see table below. This is particularly true for gas consumption, which is around half the UK mean. Electrical use is around 20% higher; this may be due to a number of factors, including an overestimate for Grove Cottage (where, due to lack of PV sub-metering, all the electricity generated by the PVs is attributed to the home's energy use even if some may in practice be exported), and the fact that 2 out of the 10 homes are all-electric, a higher proportion than in the UK stock (around 9%). One home (Passfield) shows a much higher EUI than others (169 kW·h/m^2 GIA per year), close to the UK average. It would appear to be due to the prolonged use of the cooking area, and the number of occupants (five), as was also found 10 years ago.

Table 2.1 Energy use in Retrofit Revisit sample, and comparison with existing stock and retrofit benchmarks

		Annual gas use (kW·h)	Annual electricity use (kW·h)	EUI (kW·h/m^2 per year)
Retrofit Revisit sample		Mean: 6,840 (excluding Princedale and Wilmcote, which are all-electric)	Mean: 4,310 (including supply from PVs for Culford and Grove Cottage; for Grove, this means it is an overestimate)	79 (for some homes this is an underestimate due to lack of metering of on-site thermal systems, but it does allow the comparison with UK stock gas and electricity use)
Existing UK stock (*NEED* report) (HM Government, 2023)		Mean: 12,800	Mean: 3,600	Mean: 166 (gas: 129; electricity: 36)*
LETI Climate Emergency Retrofit Guide (LETI, 2021)	Best practice retrofit:	N/A	N/A	50 (+10 if constrained, e.g. heritage building)
	Exemplar retrofit:	N/A	N/A	N/A

* From LETI (2021)

2.1.2 Energy use over time

The energy use intensity in all 10 homes was compared over time, and is illustrated in the two graphs below:

(1) Figure 2.1: total EUI, with notes on uncertainty and comparisons with LETI and average stock benchmark.

(2) Figure 2.2: EUI broken down into gas, electricity grid, and on-site renewable supplies

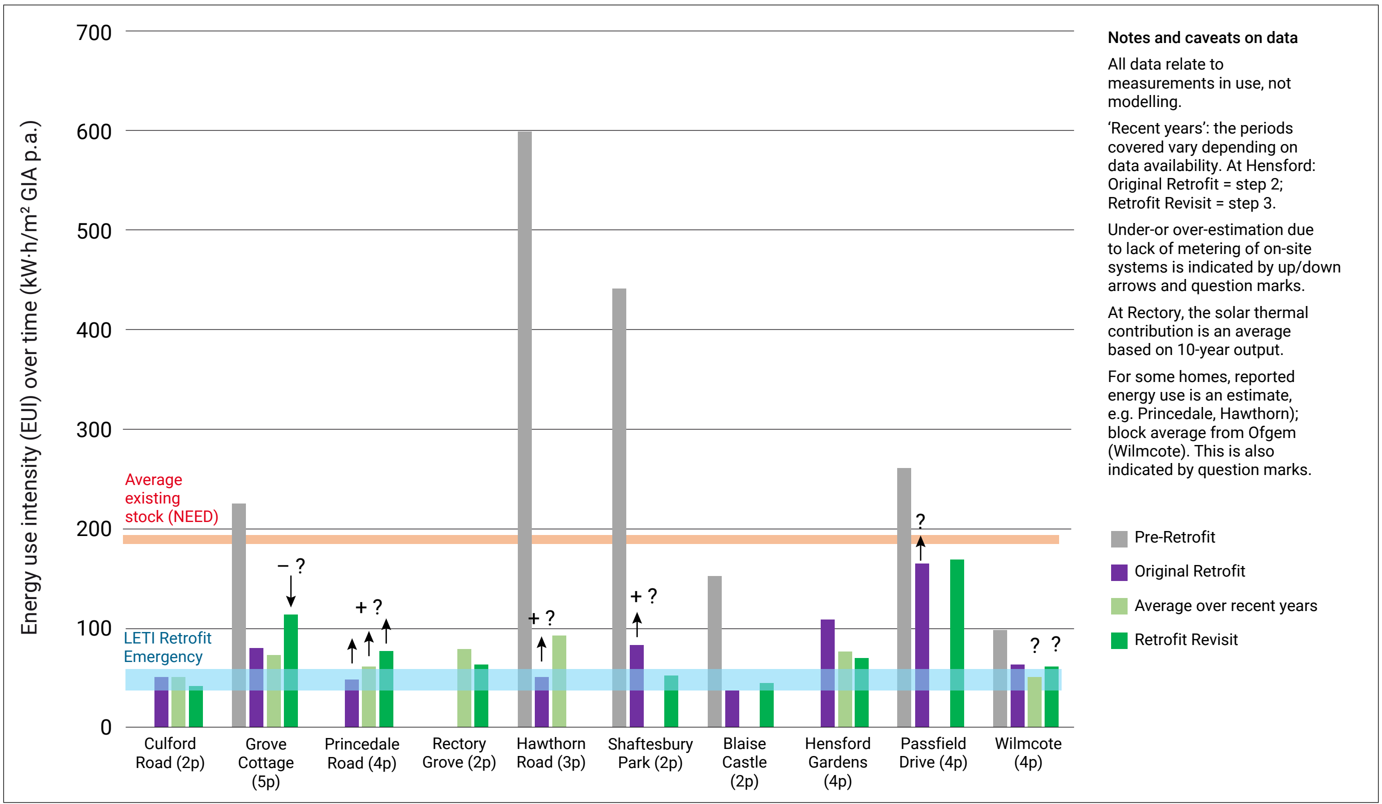


Figure 2.1 Total energy use intensity (EUI) (kW·h/m² GIA p.a.)

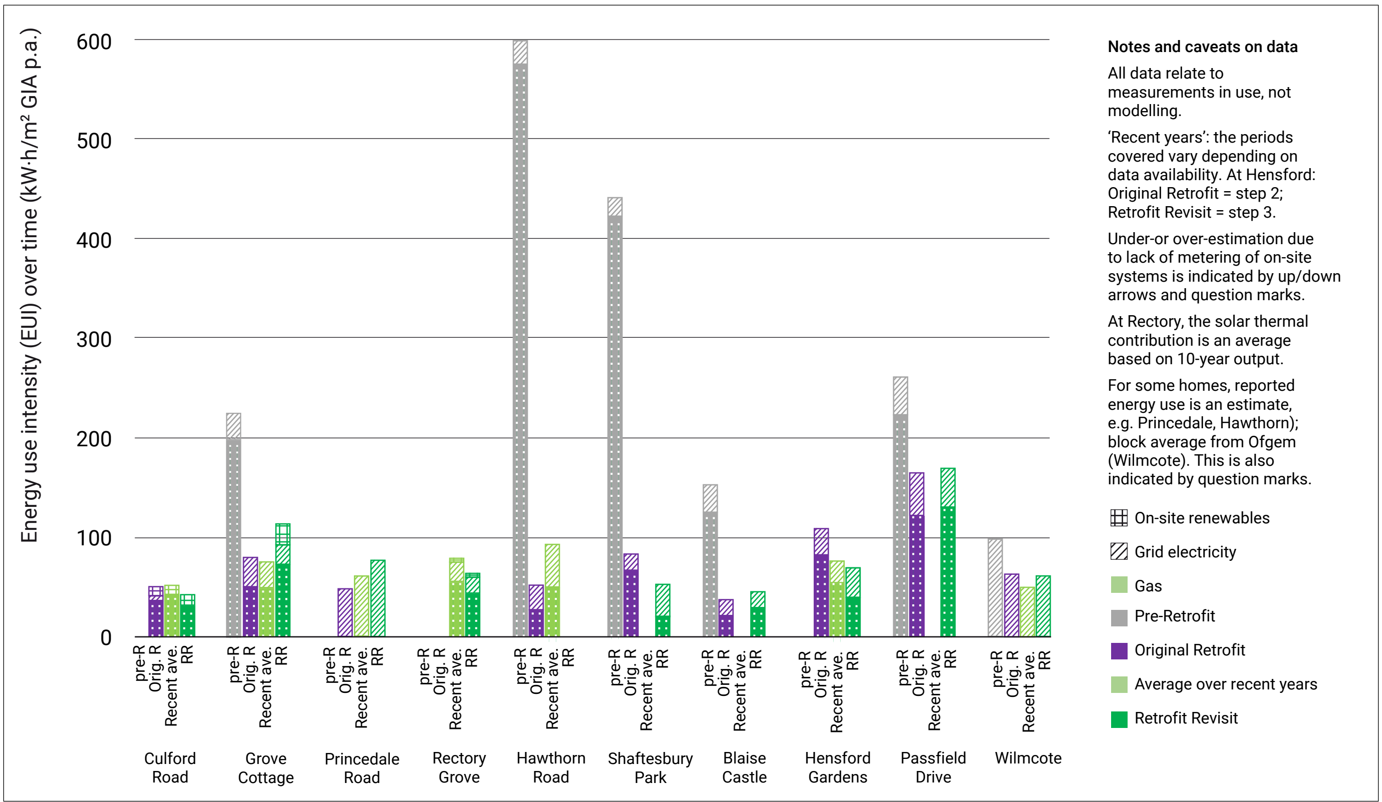


Figure 2.2 Energy use intensity (EUI) broken down into gas and grid/on-site renewable electricity (kW·h/m² GIA p.a.)

Compared with the data from the original retrofits, the energy use of the case study homes has increased in some properties and decreased in others.

While there have been some increases in energy use in several homes over the years since the original retrofit, in most cases they are not very high. The increases are much smaller than the original improvements achieved through retrofit. Across the homes where energy use has increased, a number of reasons have been put forward:

- Household changes: one home now has a baby which might have led to more frequent use of hot water and appliances; in some, children have grown and are now teenagers and considered to have a high hot water usage; several homes have longer occupancy hours post-pandemic, which is expected to have led to higher electricity use.
- Decrease in envelope performance, in particular air permeability which has increased (albeit not by a lot) across most homes (see Briefing 3, 'Airtightness'), letting more air (and heat) leak out.
- In two cases, the lack of data on the renewable energy contribution contributes to the appearance of an increase in energy use, which may not be real. At Grove Cottage, the Retrofit Revisit is an over-estimate as it includes all the output from the PVs (installed recently) whereas some is, in fact, exported. By contrast, at Hawthorn,

the original retrofit is an underestimate as the home received a contribution from an on-site solar thermal system, but that was not metered and the system is no longer functioning.

Some homes (Passfield, Wilmcote) show very similar energy use to the original retrofit.

Others are even showing small reductions in energy use compared to the original retrofit, for property-specific reasons:

- Culford: energy use was relatively stable over the 11 years since the original retrofit. It decreased in the past year, which is attributed to reduced occupancy.
- Hensford: this is a step-by-step retrofit, and the lower energy use in recent years reflects the effectiveness of the additional retrofit steps (Steps 2 and 3) compared to the original one (Step 1).
- Shaftesbury: the central heating system has been switched off, and heating is now with direct room heaters only. This may have been to the detriment of winter comfort, as the occupants only rated the winter conditions as 'somewhat comfy' (compared to much more positive feedback in most other homes), and they noted the presence of condensation — see case study CS8 for details.

Smaller factors may have been at play across the homes, see section 3.

2.1.3 Performance comparators

Ideally, comparing the performance of Retrofit Revisit with the original target would have been the preferred approach. However, this has often proven challenging or even impossible, since many projects were initially modelled in PHPP (PassivHaus Planning Package) and reported their design targets and energy consumption in terms of 'primary energy' as defined by the PassivHaus standard. The absence of recorded primary energy factors and a breakdown into specific fuels makes it challenging to make comparisons with Retrofit Revisit data. Instead, this study opts to present the energy use intensity (EUI), broken down into 'grid' and 'on-site' supplies as well as different fuels. The study then proceeds to compare this performance with the pre-retrofit and retrofit data, along with UK average and industry targets.

2.1.4 Metering issues: data availability and uncertainty

A number of issues related to energy metering have limited the evaluation of the homes and their systems:

- Difficulty of obtaining data on annual energy use, from the main meters: in several homes this required significant efforts from the evaluator and enquiries with energy suppliers. In large part this was not due to reluctance from residents.

- Lack of metering of on-site systems inputs, outputs and, in the case of PVs, export versus part used on site.
- Lack of metering of thermal energy use for both heating and hot water.

The metering set-up and availability of energy use data across all homes are detailed in Table 2.2, at the end of this briefing. The specific issues found on site are detailed in the case study reports and include, for example:

- energy providers failing to issue energy bills to one property for over a year following the installation of a smart meter
- energy providers taking excessive time in issuing energy bills and engaging with the tenants, resulting in the bills not being available in time for the study
- meter box being in a location difficult to reach, hence regular readings were not taken.

2.1.5 Thermal energy use

Eight of the ten homes are heated by gas, though one (Shaftesbury) now uses direct electric heating. In some of these gas-heated homes, monthly records of gas use were available from residents and an estimate of space heating demand has been made on the basis of summer gas use (assumed to be for hot water and cooking, and calculated as monthly average over the summer, multiplied over the whole year and subtracted from total gas use to estimate annual gas for space heating), and an assumed gas boiler efficiency of 90%. This is acknowledged to be a simplification (since the water feed is colder in winter), and only an estimate, but it is useful as indication nonetheless. In the five homes where this could be carried out, the estimated space heating demand is quite low, broadly speaking between Passivhaus (15 kW·h/m^2 p.a.) and LETI Exemplar Retrofit (25 kW·h/m^2 p.a.) levels:

- Hensford: approx. 18 kW·h/m^2 p.a.
- Passfield: approx. 18 kW·h/m^2 p.a., though in this home the residents to some extent rely on long cooking periods to heat the occupied room
- Blaise Castle: approx. 22 kW·h/m^2 p.a.
- Culford: approx. 25 kW·h/m^2 p.a.
- Grove Cottage: approx. 27 kW·h/m^2 p.a.

Supplementary analysis was made of thermal performance, including through the use of SmartHTC estimate, see Briefing 4, 'Thermal layer'.

2.1.6 Energy use and weather

A check was made against degree days. Largely, this does not affect the conclusions:

- When normalising for degree days, mostly the same homes show increases or decreases in energy use, as when non-normalised energy data is used. The exceptions are for Passfield, where non-normalised energy use is very similar, but when normalising for degree days it has increased; and Wilmcote, where it is the opposite i.e. non-normalised energy use is very similar, but when normalising for degree days it has decreased. However, that home is an estimate only based on the whole block rather than the specific home.
- When normalising for degree days, mostly the same homes have the lowest energy use (i.e. Culford and Blaise, followed by Shaftesbury and Hensford); Wilmcote also performs very well once heating degree days are accounted for. The same home is the highest energy user (i.e. Passfield, by some margin).

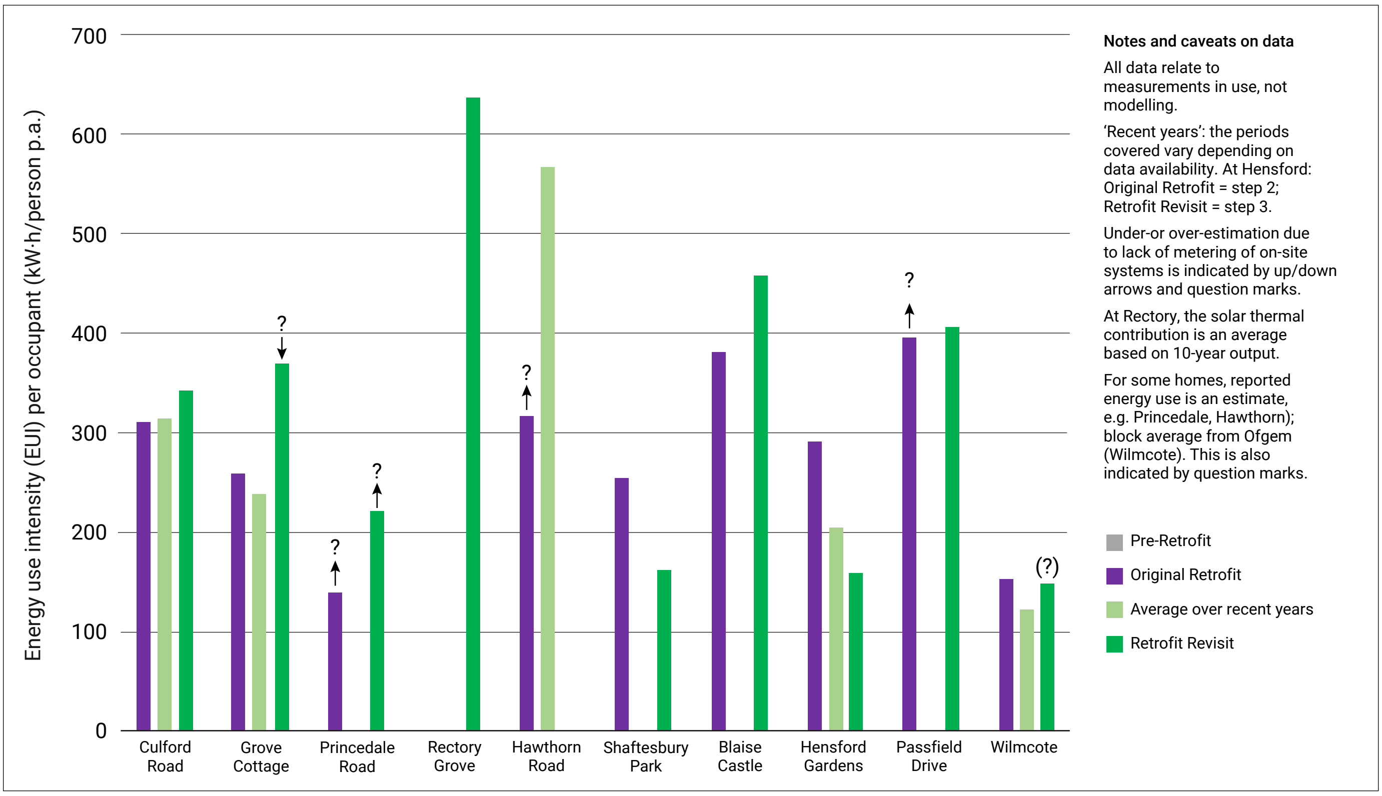


Figure 2.3 Energy use per occupant (kW·h/person per annum)

2.1.7 Energy use per occupant

EUI is a useful measure of comparison, particularly when looking at the evolution of a specific home over time and against benchmarks. However, the number of occupants is also a known influencing factor in energy use (see, for example, NEED data (HM Government, 2023) in Table 2.1 above), and some of the homes in the Retrofit Revisit sample are quite large.

- *Energy use by floor area*: if energy use is normalised by floor area, i.e. using an EUI, the best performing homes (those demanding the least energy) are Culford, Blaise and Shaftesbury, and the highest (those demanding the most amount of energy) is Passfield.
- *Energy use by occupant*: however, if energy use is normalised by the occupant, then the homes using the least amount of energy are Shaftesbury (this may be due to failing systems but occupants still reported 'somewhat comfy' winter conditions — see details in case study CS8), Wilmcote (with some uncertainty on the data) and Hensford, all performing in a similar manner, followed by Princedale; the highest (i.e. most energy hungry) is Rectory Grove, followed by Blaise Castle; both are the largest homes in the sample (around 200 m²) and occupied by two people.

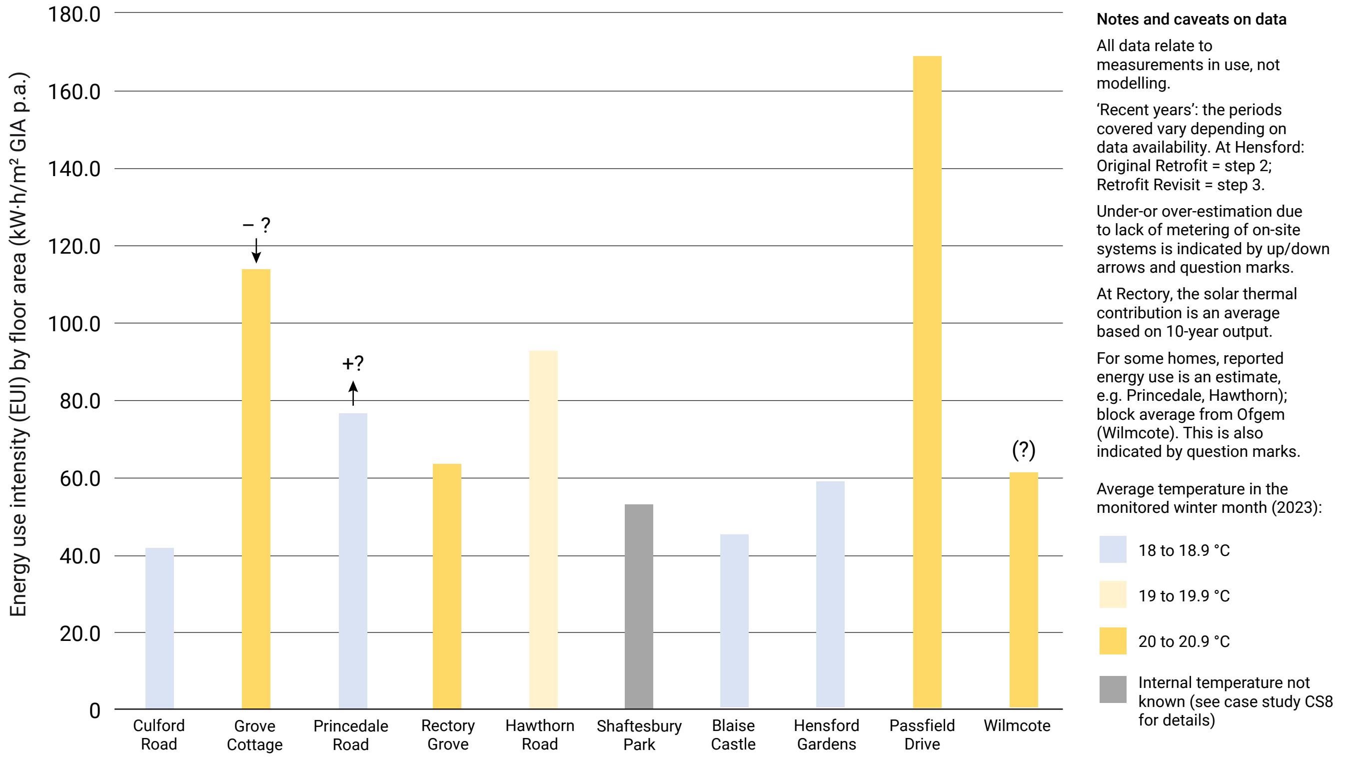


Figure 2.4 Energy use by floor area (kW·h/m² GIA per annum)

2.1.8 Energy use and internal temperature

The phenomenon often referred to as 'thermal comfort take-back,' or the 'rebound effect,' is frequently cited as a reason why post-retrofit energy savings may not be as substantial as initially anticipated. This occurs because residents tend to maintain higher indoor temperatures after the retrofit, likely due to reduced concerns about energy costs, given the retrofit's effectiveness. Unfortunately, the study lacks information on pre-retrofit indoor temperatures, making it impossible to analyse this aspect. Nonetheless, as previously mentioned, energy consumption remains significantly lower than national averages and than pre-retrofit data, where available, regardless of whether any 'comfort take-back' occurred.

As elaborated in Briefing 6, 'Indoor environmental quality', internal temperatures were recorded within a relatively broad range (18–22 °C) and were reported as very comfortable for the vast majority of homes. This is visually represented in Figure 2.4 above, which juxtaposes these temperatures with the energy use intensity (EUI) of each home. There appears to be a trend where homes with higher (or lower) EUIs tend to maintain higher (or lower) average temperatures during the monitored winter month. However, it is important to note that the sample size is small, and any definitive conclusions should not be extrapolated from this data.

2.1.9 Variations/additional comments

Additional analysis of space heating demand against fabric performance was carried out; however, the number of homes where this is available is limited (five homes), and the range of fabric performance across the retrofitted homes is quite limited (i.e. all have SmartHTCs and airtightness figures relatively close to each other), so firm conclusions are not considered possible:

- Space heating demand (in kW·h/m^2 p.a.) versus air permeability (in m^3/h·m^2 @ 50 Pa): in this small sample, air permeability varied between 0.96 and 2.37 m^3/h·m^2 @ 50 Pa. There appears to be a trend for higher space heating demand at higher air permeability.
- Space heating demand (in kW·h/m^2 p.a) versus measured heat loss parameter (HLP) (in W/m^2·K): in this small sample, the measured HLP varied between 0.8 and 1.9 W/m^2·K. No trend was apparent between measured HLP and space heating demand. This may be due to the fact that the sample is small and the home characteristics are relatively close to each other (compared to wider variations in the existing stock), so that other parameters such as occupant behaviour and preferred temperatures become as significant.

2.2 Lessons learnt and recommendations

Comparators — original retrofit targets and energy performance: Having energy performance targets and original retrofit energy use reported as broken down into fuel and into grid and on-site systems would have allowed better comparisons; instead, in many projects:

- Targets and/or measured energy use were often reported in terms of primary energy and/or carbon emissions, without detailing the breakdown into fuels, and often without reporting the assumed primary energy and carbon factors.
- Space heating demand was often a key target, but it is difficult to measure (as it relies on heat metering, and on assumptions such as indoor temperature).
- Reported energy use was most often that supplied from the gas and electricity grids, without accounting for supplies from renewable systems.

This is probably an area where industry has progressed, with more awareness of using metrics which are measurable and which allow comparison over time, e.g. metered energy, broken down into fuels.

Systems complexity and reliability: Some of the MEP systems have not passed the test of time, often due to complexity of the systems and difficult maintenance (e.g. bespoke systems, maintenance parts from other countries — see details in the individual case studies, and in Briefing 8, 'Maintenance'). This has led some occupants to resort to less-efficient systems and additional energy use, and/or compromised comfort. Retrofits will best pass the test of time with systems which are not bespoke, are easy to maintain, and with a regular maintenance regime.

Better metering: it is notable that annual metered energy use has been difficult or even impossible to obtain in several of the homes, despite efforts by the evaluators. This is the case even in homes with smart meters. Where records are available of annual energy use, including past years, this is thanks to the manual records of the residents, who in these cases also happened to be built-environment professionals with an interest in the retrofit. The reliability of meters, the seamless transition of data when switching energy suppliers, and the ease of accessing data on-site, online, or when contacting energy providers, should all be significantly improved. These improvements are essential not only to assist residents in understanding and managing their energy consumption but also to facilitate the evaluation of building performance.

Measuring space heating only: the evaluation of space heating performance (specifically, rather than total energy use) has been difficult in many homes. This is an important factor to consider in future projects, given that reducing space heating demand and associated energy use (and peak demand) is a key objective of retrofit as it will inform the level of intervention on the building fabric.

As domestic heating systems transition to heat pumps, the approximation of 'summer gas energy use' becomes meaningless. Therefore, retrofit project teams should contemplate what metric to use for thermal performance (e.g. space heating demand, HTC) and how to evaluate it in-use post-retrofit, and compared to the pre-retrofit state.

Metering renewables: the very limited metering of renewable energy systems has presented a challenge when evaluating the overall energy use in numerous homes. It is imperative to consider this factor in the planning of future new construction and retrofit projects. Doing so will enable the assessment of the performance of these systems and their contributions to individual homes as well as the broader energy system.

2.2.1 Could it have been expected given the original BPE, including post completion review?

The limited increases in energy use over time have revealed the robustness of the original energy reduction strategies.

The difficulty of operating complex systems, and the failure of some such systems, was often pointed out in the original retrofit evaluation — these challenges are reaffirmed in this study rather than presenting a new insight.

2.3 Remaining areas of uncertainties/needs for further research

The quality of energy use feedback from each property has shown significant variation, primarily stemming from the factors mentioned earlier. Mostly, they relate to metering set-ups and availability of metered data, especially with renewable energy systems which are not sub-metered and whose contribution therefore cannot be assessed. This challenge is even more pronounced with solar thermal systems and air-source heat pump systems. Caveats and uncertainties are noted in this briefing and the relevant case study reports. One area of improvement for the industry would be to ensure that all renewable systems be heat metered at manufacture — the cost would be small and it would result in a transformation in how we ensure performance (of heat pumps and fabric).

This was a relatively short study (one month of monitoring), with limited intervention such as sub-metering, appliances surveys etc. Smaller factors influencing energy usage may have been at play across the homes such as gradual improvements in lighting and appliances electricity usage due to improved standards over the years. The inverse may also be true, e.g. degradation over 10 years of the performance of appliances installed at the time of the original retrofit. This has not been looked at in this relatively short study; neither has the possibly increased working-from-home patterns.

Table 2.2 Energy data: systems and metering across the case studies

Property	Total energy use, with reasonable confidence?	Smart meter?	Gas meter readings available?	Electricity meter readings available?	Solar thermal?	PVs?	Estimate of space heating demand or energy use?
Culford Road (Retrofit for the Future)	Yes. Annual readings from the resident since 2011	Unknown	Yes. Annual readings are available for 2011-2021 from the resident	Yes. Via resident	N/A	Annual readings are available for 2011-2021 from the resident, including total output and what is used by the building	Yes: estimated using the average gas energy use during the summer months, spread over the year and subtracted from total gas use
Grove Cottage (Retrofit for the Future)	No: reported energy use is likely an over-estimate, as all PV output is counted towards building use, while some may in fact be exported	Unknown	Yes. Annual readings are available from the resident	Yes. Annual readings are available from the resident	N/A	Data on annual output, but split between export and use on site is not known	Yes: estimated using the average gas energy use during the summer months, spread over the year and subtracted from total gas use
Princedale	No: due to lack of data from supplier and resident, the reported energy use is based on average between two electricity readings 12 years apart (as annual average over those 12 years), It is an underestimate as the energy provided by solar thermal panels is not known	Yes	N/A: all-electric	No – only start and end readings of a very long period (12 years)	Output not metered	N/A	No
Rectory	Yes, as estimate: the reported energy includes that provided by solar thermal panels, as annual average over 10 years	Installed July 2022	Yes	Yes	Yes; output is metered but not logged. The evaluator made an estimate based on 10-year output, as per reading taken on site visit	N/A	No
Hawthorn	Not for the past year, due to change of electricity meter. Reported energy use is for 2020 and 2021	Yes	Yes	Not latest, but for 2020 and 2021. Energy use figures for 2022 were not used in the study: the combined gas/electric online records are incomplete with electricity unrecorded from Feb 2022, and the new smart meter figures do not tally with historic record	Metering tbc . Not operating for years, understood to make no contribution to the home's energy use	N/A	No

Table continues

Table 2.2 Energy data: systems and metering across the case studies (*continued*)

Property	Total energy use, with reasonable confidence?	Smart meter?	Gas meter readings available?	Electricity meter readings available?	Solar thermal?	PVs?	Estimate of space heating demand or energy use?
Shaftesbury Park Terrace	Yes	Unknown	Yes	Yes	Not sub-metered. Not operating for years; understood to make no contribution to the home's energy use	N/A	No: heating systems were sub-metered but the monitoring system is not accessible; in addition, the system has stopped working so heating is by direct electric heating, not metered
Blaise Castle Estate	Yes	Unknown	Yes, annual readings available from the resident	Yes, annual readings available from the resident	N/A	N/A	Yes: hot water energy use was estimated using the average gas energy use during the summer months (minus the metered data for gas hob use) across the year. The rest is assumed to be energy used for space heating.
Hensford Gardens	Yes	Yes	Yes, monthly readings available from the resident for the last seven years	Yes, monthly readings available from the resident for the last seven years	N/A	N/A	Yes: estimated using the average gas energy use during the summer months, spread over the year and subtracted from total gas use
Passfield Drive (Retrofit for the Future)	Yes	Yes	Yes	Yes	Not operating for years, but metered and with energy data in early years	N/A	Yes: estimated using the average gas energy use during the summer months, spread over the year and subtracted from total gas use
Wilmcote House	No: the reported data is based on Ofgem block average data	No: pre payment meter	N/A	No: pre-payment meter	N/A	N/A	No

Briefing 3: Airtightness: performance, solutions and evolution over time

Figure 3.1 Blower door installation

Figure 3.2 Blower door measuring equipment

3.1 Trends across the case studies

3.1.1 Overview

Overall, the project's airtightness strategies have mostly held a very good level of performance with an average of 2.54 $m^3/h{\cdot}m^2$ @ 50 Pa (up from an average of 1.98 about 10 years ago). Airtightness in all homes is still significantly better than pre-retrofit (77% better as pre-retrofits achieved ~11 $m^3/h{\cdot}m^2$ @ 50 Pa) and that of the average UK home (commonly taken to be around 11 $m^3/h{\cdot}m^2$ @ 50 Pa[5]), and below the value assumed in the notional dwelling for new-build homes (HM Government, 2021), of 5 $m^3/h{\cdot}m^2$ @ 50 Pa.

All projects aimed to achieve substantial carbon reductions, which meant that they developed and implemented a strong airtightness strategy as part of their fabric first approach which helped secure long term performance (6 out of the 10 case study homes were included in the Retrofit for the Future program, which sought an 80% reduction in CO_2 emissions and achieved an average of 1.9 $m^3/h{\cdot}m^2$ @ 50 Pa post-retrofit at the time).

3.1.2 Limitations

While it has not been feasible to open-up and inspect the external envelope for airtightness material inspection, an analysis of the test results suggests that the meticulous detailing is paying off. It appears that airtightness tapes are still maintaining their adherence even after a decade with minimal performance degradation. Many projects used accelerated proprietary airtightness tapes between airtight materials, and some complemented the strategy with parge coats.

The uncertainties related to testing and measurement in the original test imply that, in certain cases, the observed changes fall well within the margin of uncertainty. Further details can be found in Briefing 9, 'BPE techniques: airtightness testing'.

However, the undeniable fact is that, in all homes except for one, the tested value during the Retrofit Revisit has increased, even if only by a small margin in some instances. The causes for this increased air infiltration can be mostly explained by the inspection of the fabric.

3.1.3 Most common issues

Most projects have seen their airtightness performance drop slightly (i.e. air leakage increase) except for two projects which saw an improvement: Passfield Drive and Wilmcote House. In the case of Wilmcote House, comparison is difficult though, as the tests were not carried out on the same flat as in the original retrofit.

Seals: the most common weak point reported by the projects was the reduced reliability of the external windows and doors seals after 10 years of use, in particular on large format elements such as doors. Apart from

[5] There is no large-scale recent data on airtightness in the existing stock, but the value of 11.5 $m^3/h{\cdot}m^2$ at 50 Pa is commonly quoted and can be traced back to studies by the BRE and Leeds Beckett University in the late 1990s/early 2000s, e.g. https://www.leedsbeckett.ac.uk/-/media/files/research/leeds-sustainability-institute/airtight/lsi_airtight6.pdf (accessed 9.04.24)

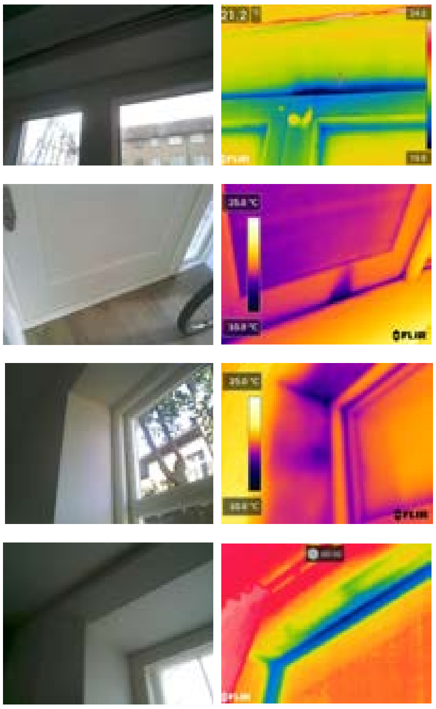


Figure 3.3 Thermal images illustrating the effects of leaky windows and door frame with cold air paths in blue

one home (Passfield Drive) where a set of doors has been re-adjusted, it is not known that seals have been replaced in any of the case studies houses. This could, however, be done and industry/suppliers should include the maintenance and/or replacement of seals in the future. Thermal imaging has revealed areas of air path along damaged seals. Refer to case study CS10: Passfield Drive.

Testing: it should be noted that these are mostly from observations by the evaluators, as smoke testing or thermal imaging during the (de-)pressurisation tests was not carried out systematically due to time constraints. Not conducting these smoke tests in homes where air leakage has notably increased was a missed opportunity, meaning that the origins of this additional leakage (i.e. worsened performance) remain unclear.

Material degradation: some houses suffered water ingress. The water is likely to affect vulnerable materials before the airtight layer. On the other hand, if there is a well-functioning airtightness layer and there is some biological growth behind it, we would not be able to identify this with the current tests, as the airtightness layer would prevent spore-laden air to travel to the indoor environment via depressurisation.

Measurements: the variation between the initial test results and the latest ones is also partially attributed to discrepancies in property measurements, area calculations and conventions between different professionals. (This is discussed further in Briefing 9, 'BPE techniques: airtightness testing'.)

3.1.4 Most common areas of success

Robust strategies: airtightness strategies used a wide variety of approaches — plaster, membranes, oriented strand boards (OSBs) etc. — and, overall, have all proven to have remained very effective. The airtightness tapes seem to have held overall as the drop in performance in some houses is very minimal.

3.1.5 Variations across the homes, and additional comments

The worst test result was 7.58 $m^3/h{\cdot}m^2$ @ 50 Pa for Shaftesbury Park Terrace; it is also the one with (by far) the highest increase compared to retrofit sign-off, i.e. +1.66 $m^3/h{\cdot}m^2$ @ 50 Pa. The evaluator identified missing seals to two of the front sash windows, bathroom windows that were not closing correctly and lack of compression on the loft hatch, which was just positioned on the opening without proper compression seals.

The best test result was 0.96 $m^3/h{\cdot}m^2$ @ 50 Pa for Hensford Gardens, but this was a phased retrofit rather than an evaluation 10 years after one-off works. Among the other homes, five achieved between 1.5 and 2 $m^3/h{\cdot}m^2$ @ 50 Pa.

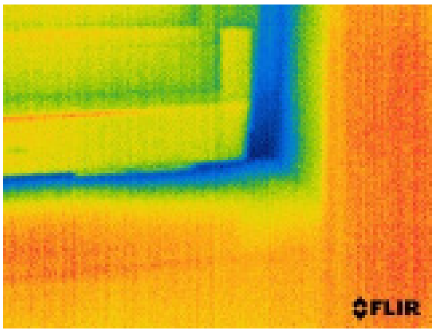


Figure 3.4 Blaise Castle: air leakage at window frame

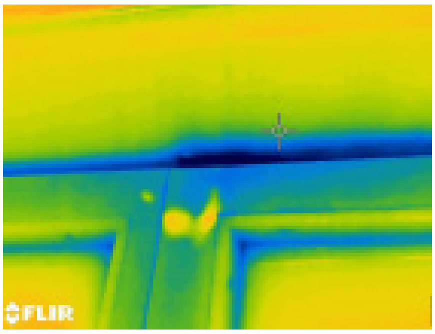


Figure 3.5 Passfield Drive: air leakage at door frame

At Hensford Gardens, the various phases of retrofitting (1st — internal spaces, party walls, floor and roof; 2nd — the facades) did not seem to affect the overall outcome. The first phase was designed in a way to make the second phase easy to 'link-up', such as internal wall insulation membranes left in place for the future window membranes to marry-up. The last air pressure test measured 0.96 $m^3/h{\cdot}m^2$ @ 50 Pa.

In one property, the measured airtightness at Retrofit Revisit BPE is better than original sign-off: at Passfield Drive, it has gone from an original build at 5.1 $m^3/h{\cdot}m^2$ @ 50 Pa, to a retrofit value of 1.78 $m^3/h{\cdot}m^2$ @ 50 Pa ten years ago, and now tests at 1.60 $m^3/h{\cdot}m^2$ @ 50 Pa. This is a little improvement, which may reflect that some of the fabric may have moved in the right direction to fill some air paths. It could also be due to testing uncertainty, as the level of change is well within the measurement uncertainty associated with the blower door test method.

In three homes, the increase in air leakage was non-negligable:

- Princedale Road and Hawthorn Road saw a relatively high increase in air leakage (increases of 1.26 and 1.11 $m^3/h{\cdot}m^2$ @ 50 Pa, respectively). At Princedale Road, this is starting from a very low air leakage in the original retrofit, and is mostly attributed to increased leakage around doors and windows. At Hawthorn Road, this is suspected to be mostly due to a difficulty in fitting the blower door test (BDT) equipment around the door frame and possibly to some material degradation as a result of water ingress. The original test value was 2.4 $m^3/h{\cdot}m^2$ @ 50 Pa. The result estimated from the Pulse testing was 3.07 $m^3/h{\cdot}m^2$ @ 50 Pa, lower then the blower door test result of 3.64 $m^3/h{\cdot}m^2$ @ 50 Pa.
- Shaftesbury Park Terrace saw the highest increase in air leakage (an increase of 1.66 $m^3/h{\cdot}m^2$ @ 50 Pa), with air permeability increasing from 5.92 $m^3/h{\cdot}m^2$ @ 50 Pa to 7.58 $m^3/h{\cdot}m^2$ @ 50 Pa. The result estimated from Pulse testing was 6.84 $m^3/h{\cdot}m^2$ @ 50 Pa. The increase is believed to be largely due to windows and door seals.

Pressurisation showed more leakage than depressurisation (9% more) suggesting that outward openings were more of an issue. This may be linked to various issues with windows seals and loft hatch seals robustness.

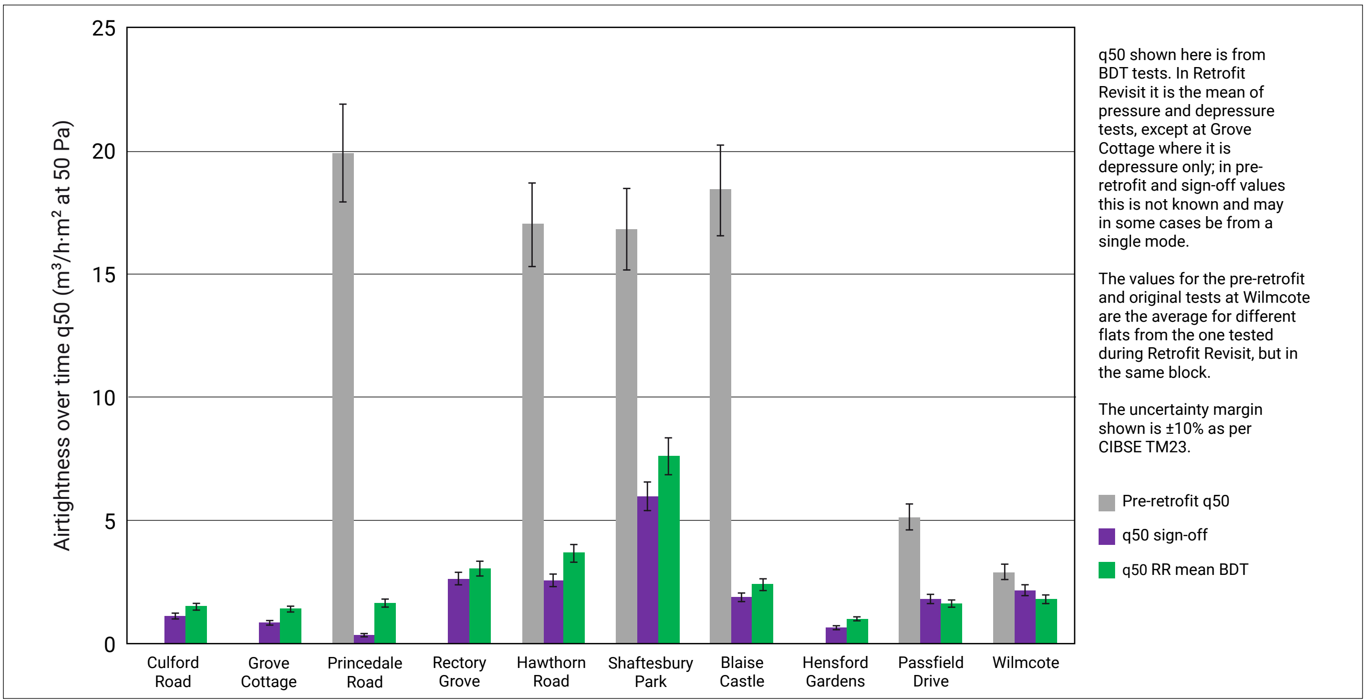


Figure 3.6 Airtightness (m^3·h/m^2 @ 50 Pa) q50 over time

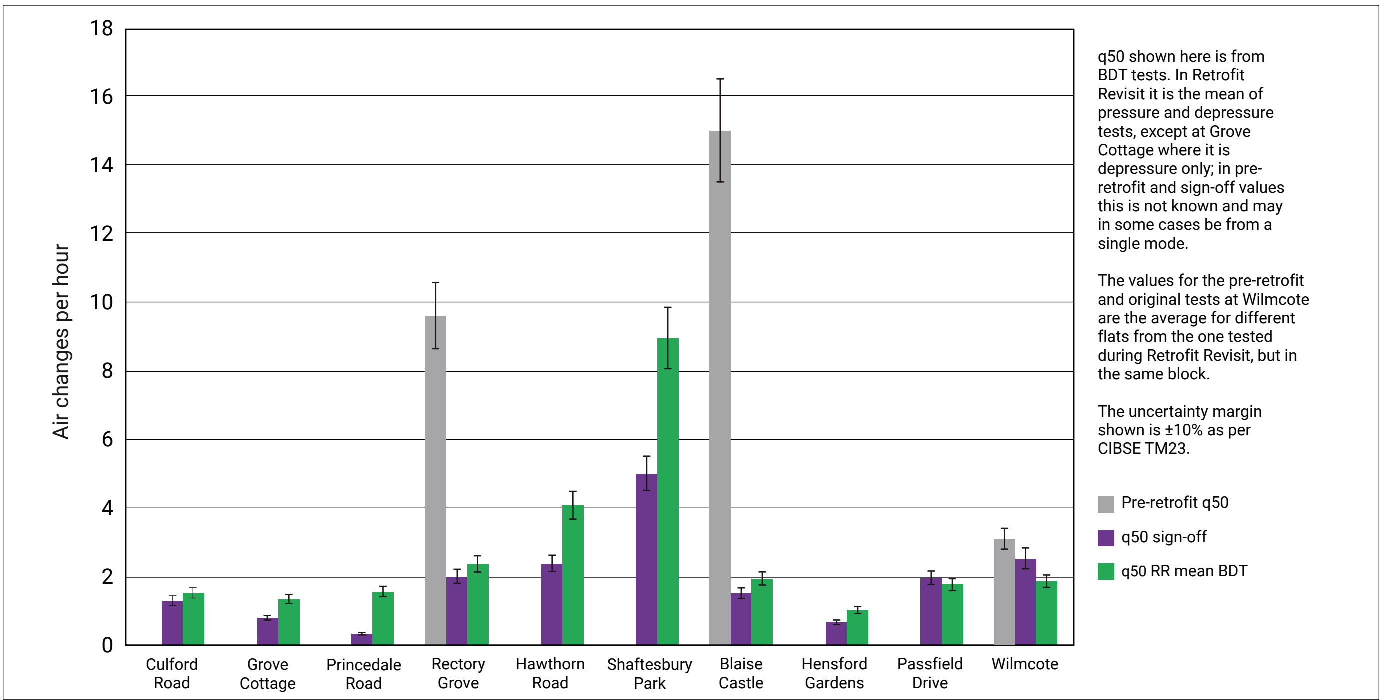


Figure 3.7 Airtightness (air changes per hour) n50 over time

3.2 Lessons learnt and recommendations

Window and door seals should be maintained and replaced when necessary.

Remedial works should be carried out with the same level of understanding of the building's fabric and the original airtightness strategy as per the original intent. Documentation can be provided to homeowners for potential use when hiring builders for works on property's external fabric.

Within the scope of this study, only one project required adjustments to the location of its airtightness layer due to remedial work following a flood incident. In this particular home, the meticulous craftsmanship that ensured a seamless connection between the original retrofit membranes and those used in the remedial work resulted in a situation where airtightness was not perfectly preserved but still maintained good resistance to air infiltration.

Airtightness tapes: attention to taping timber joists in most properties was at the time of the original retrofit very cumbersome and required considerable quantities of special tapes. These tapes seem to have held and not de-bonded around the variety of substrates (timber, concrete, insulation etc).

3.2.1 Could it have been expected given the original BPE, including post completion review?

Significant attention was given to airtightness at the time of the original retrofit. Some measures such as proprietary tapes were still uncommon on the market, and therefore there was some uncertainty about how long the measures would last. The results in this Retrofit Revisit are positive feed-back with a good and overall stable level of airtightness between original retrofit and the revisit measurements 10 years on.

3.3 Remaining areas of uncertainties/needs for further research

Additional research is required to investigate the specific methodologies employed in conducting the airtightness tests, which is covered in Briefing 9, 'BPE techniques: airtightness testing'.

Giving special consideration to the durability of high-quality windows and door seals is highly likely to contribute to the long-lasting airtightness of the building. This is an area worthy of further investigation.

Briefing 4: Thermal layer

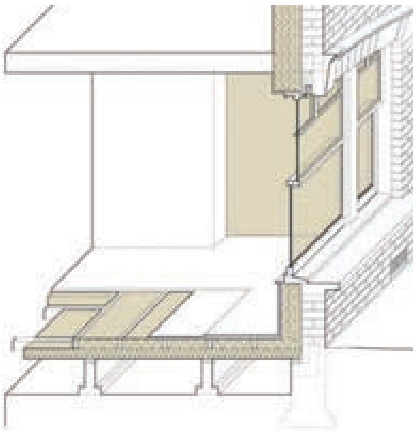


Figure 4.1 Example of internal wall insulation

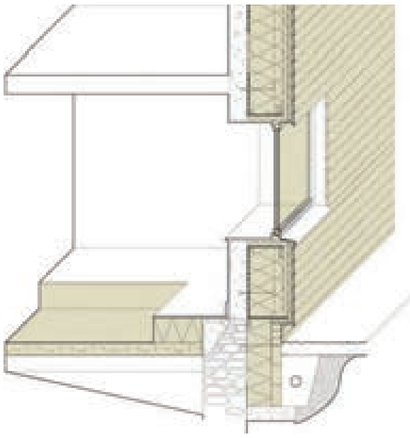


Figure 4.2 Example of external wall insulation

4.1 Trends across the case studies

4.1.1 Overview

The fabric first approach has been fundamental to the energy efficiency improvement strategies of each property. These improvements have been achieved thanks to the retrofit of a varied range of materials which have largely proven to pass the test of time with very minimal issues. This positive feedback from the 10 properties is very encouraging and will hopefully give the industry confidence to implement retrofit measures.

The fabric strategies were broadly in three categories, internal wall insulation (IWI), external wall insulation (EWI), cavity insulation and often a mix of all three to address the specifics of each property.

In total, there are more than 10 different insulation types used across all projects. There are broadly two main categories: insulation materials that allow moisture transfer (e.g. sheep's wool insulation, wood fibre insulation, insulating plaster), usually installed on the inner face of external walls and a good solution for walls that could not be insulated on the outer face, and vapour-closed insulation materials (e.g. PUR, phenolic, XPS), used most commonly externally with a render finish but has been used internally on two projects with a vented cavity (Princedale Road and Culford Road).

The detailing and interface of insulating materials with other retrofitted elements was critical and a key challenge during the design and installation process. Despite some projects implementing complex strategies using up to nine different materials in a single retrofit, the carefully considered and detailed strategy seems to have held-up to the test of time; all homes seem to still perform, with little signs of surface condensation (see user feed-back section), no significant heat loss paths or material degradation observed to date.

The integrity of insulation material was difficult to assess thoroughly without destructive access. However, a number of techniques were applied to assess their conditions:

- visual observations
- thermal imaging
- SmartHTC on all properties: this provides an indication of thermal performance overall, taking account of insulation, thermal bridging, airtightness, and losses through ventilation
- Heat3D: this was carried out on three properties; it is based on thermal imaging and is non-intrusive
- heat flow meter *U*-value measurements: this was carried out on five properties; it is more established than Heat3D method but is more intrusive

Figure 4.3 Blaise Castle: phenolic insulation board has bowed

Figure 4.4 Ceiling examined by thermal imaging

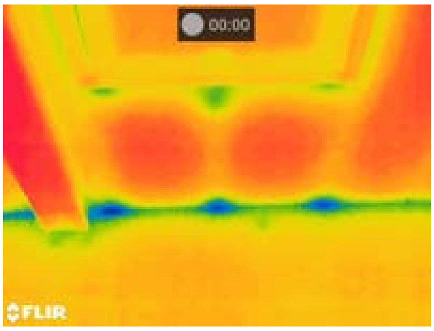


Figure 4.5 Thermal image of the ceiling shown in Figure 4.4

Figure 4.6 Heat loss parameter (HLP) across the Retrofit Revisit sample

- moisture content tests and mould sampling on four properties: this is more intrusive.

For a comparison and commentary on the testing techniques themselves, (see Briefing 9, 'BPE techniques: airtightness testing'). The following narrative focuses on observations about thermal performance. For details on the moisture testing and associated results, see Appendix 5, 'Detail testing: moisture'.

4.1.2 Materials

One property identified some material degradation of the external wall insulation (phenolic boards) which was witnessed during opening-up works related to the repairs of a leaky roof membrane that affected the roof and balcony timber structure. The outer insulation panels have bowed slightly (Figure 4.3) and highlights a material integrity issue which deserves more attention and raising with the manufacturer. It is suspected to be caused by solar gains as inner panels are unaffected. The impact on performance has not been evaluated.

4.1.3 Thermal imaging

It has proven to be a valuable tool in this BPE exercise. In various properties, the expert who attended the airtightness tests employed this technique to identify air leakage pathways as demonstrated in Briefing 3, 'Airtightness', which reveals, for example, air gaps around door frames, and also colder areas due to moisture in the fabric as a result of water ingress (e.g. accidental flood in Grove Cottage on the ground floor, small water leak from the mains feed to a WC cistern onto the wall).

4.1.4 Smart HTC measurement

The SmartHTC (heat transfer coefficient, in W/K) and SmartHLP (heat loss parameter, in W/m^2·K) results were obtained in nine homes (at Shaftesbury Park Terrace, the temperature sensors were not set up properly, so no logging was done and the SmartHTC results could not be obtained). All SmartHLP are rated 'good' or 'excellent' in the Build Test Solutions (BTS) scale, see Figure 4.6.

Design HTC and measured SmartHTC results are illustrated in Figure 4.6 and detailed in Table 4.1 below, along with a commentary on the comparison between both, and the confidence interval in the SmartHTC results. The uncertainty ranges attributed to SmartHTC results on many homes are relatively large (–40%/+28% on average across the sample), and higher than those reported in the SMETER trial (±18% confidence interval) (HM Government, online). This may in part be due to the relatively low HTC in the Retrofit Revisit sample, where uncertainties in measurements and assumptions have a larger relative effect than on homes with large heat losses.

For five of the nine homes with results, there is good or relatively good agreement between the SmartHTC results and the design stage calculated HTC (from SAP or PHPP), with less than a 21% difference, and 10% on average. In the remaining four homes, the difference is much larger and likely explanations are included in Table 4.1.

Unfortunately, no co-heating test had been carried out at the time of the original retrofit to assess the HTC, which could otherwise have been compared with the Retrofit Revisit SmartHTC results. The comparison of original retrofit design HTC and Retrofit Revisit SmartHTC results therefore incorporates two possible variations: design calculation to as-built installation; and evolution of the as-built installation to its Retrofit Revisit status.

It is useful to note the following on the SmartHTC methodology and associated uncertainty:

- Generally, the SmartHTC methodology is based on an energy balance, with the heat loss of a building inferred by its heat input.
- Party walls between neighbouring properties introduce an uncertainty because the internal temperature of these neighbouring properties is not known and heat loss to these properties can only be estimated. This is especially the case if the party walls are original, uninsulated and not well sealed, as heat exchange between the homes can then be significant. In this sample, this is identified by BTS as the main source of uncertainty in Princedale Road, Rectory Grove and Passfield Drive.
- Electricity use (whether or not the home is heated by electricity) is assumed to result in internal gains.
- The methodology includes a calculation to account for the amount of energy used for domestic hot water that results in internal gains, and the amount that is lost down the drain. Uncertainty in the split of energy use for DHW and space heating and the amount of hot water reaching the drain do affect the SmartHTC result, but less so than uncertainties in electricity use and other internal gains; they are included in the confidence interval calculation.
- If electricity is generated on site by PVs, but it is not known how much is used on site and how much is exported, this affects the estimate of internal gains and therefore the uncertainty range on the SmartHTC result. This is the case at Grove Cottage.
- If the home is served by solar thermal panels, but it is not known how much they contribute, this affects the estimate of internal gains and therefore the uncertainty range on the SmartHTC result. This is the case at Princedale Road.

Table 4.1 Retrofit design calculation HTC and Retrofit Revisit measured SmartHTC

Property	Original retrofit design HTC		Retrofit Revisit SmartHTC				Comparison between original retrofit design HTC and measured Retrofit Revisit SmartHTC	
	W/K	Method	W/K	Uncer-tainty range, (W/K)	Measurement period and source of energy data	Notes on uncertainty range	%	Notes
Culford Road	87	PHPP	97	−35/+33	Meter readings, 27 days	No specific comment	11%	Good agreement
Grove Cottage	85	SAP	175	−49/+36	Smart meter, 29 days	There are two significant sources of uncertainty, both leading to over-estimating the Measured SmartHTC: · Energy use is overestimated because there are PVs on site, but without sub-metering of what is used on site versus what is exported, therefore all electricity generated by PVs has been assumed to be used on site. This means that, in the SmartHTC calculation, the calculated internal gains from electricity use are likely to be over-estimated (because in reality, some electricity is likely to be exported), i.e. the heat balance calculation assumes higher heat gains than in reality, and therefore a higher heat loss and higher SmartHTC. · Energy use within the house is overestimated because some of it is used for a garden office, which is outside of the heated envelope of the house and is not sub-metered.	107%	The Measured SmartHTC being much higher than the calculated one. This could be explained by uncertainties in the measurement of energy use — see notes on the Measured SmartHTC uncertainty range. Other reasons were examined but are likely to play only a smaller part in the difference: · an increase in air leakage compared to the original retrofit; however, this is no more than average across the sample · no significant fabric degradation was observed · heat flow meter *U*-value measurements, where they were carried out, do not indicate significant degradation compared to design values.
Princedale Road	115	PHPP	136	−43/+42	Meter readings, 28 days	There are solar thermal panels but they are not metered, so their contribution is not known accurately, which introduces an uncertainty in the SmartHTC measurement: over-estimating their contribution will mean over-estimating the resulting heat gains and therefore the SmartHTC; and inversely, if their contribution is under-estimated.	18%	Relatively good agreement.
Rectory Grove	172	PHPP	208	−99/+81	Meter readings, 29 days	The primary driver of the uncertainty in this house is analysed by BTS as a large party wall, which is likely to be solid brick. Contribution from solar thermal panels was taken into account in the SmartHTC measurement.	21%	Relatively good agreement, although within large confidence interval

Table continues

Table 4.1 Retrofit design calculation HTC and Retrofit Revisit measured SmartHTC (*continued*)

Property	Original retrofit design HTC		Retrofit Revisit SmartHTC				Comparison between original retrofit design HTC and measured Retrofit Revisit SmartHTC	
	W/K	Method	W/K	Uncer-tainty range, (W/K)	Measurement period and source of energy data	Notes on uncertainty range	%	Notes
Hawthorn Road	80	PHPP	154	−85/+39	Meter readings, 36 days	The primary driver of the uncertainty in this house is analysed by BTS as a large party wall, which is likely to be solid brick.	93%	Large difference, probably explained: this property exhibits fabric moisture issues and associated degradation, often related to poor maintenance (e.g. leaky gutter, cement pointing): see details in the case study report. There has also been a higher than average increase in air leakage in that property. See also the notes on measurement uncertainty.
Blaise Castle	169	SAP	166	−30/+33	Smart meter, 39 days	No specific comment	−2%	Very good agreement
Hensford Gardens	67*	PHPP	109	−31/+27	Meter readings, 27 days	The evaluator, also home owner, noted there may be some uncertainty related to the attribution of gas use to space heating vs hot water: hot water is considered by the home owner/evaluator to be reasonably high, and may have been underestimated by the SmartHTC calculation	64%	Relatively large difference, possibly explained by measurement uncertainty — see notes on the left * The design HTC corresponds to retrofit Step 3, i.e. matching the home's state during Retrofit Revisit
Passfield Drive	57	PHPP	181	−87/+31	Smart meter, 27 days		218%	Very large difference, but can be explained: at the time of the original retrofit, the design HTC assumed the neighbouring properties would be retrofitted, and therefore zero heat loss to them. As discussed in more detail in that case study report, this has not happened and the home is expected to experiencing more heat loss to the neighbours than originally planned.
Wilmcote	96	PHPP	97	−65/+35	Meter readings, 29 days	The primary driver of the uncertainty is analysed by BTS as the party walls, floor and ceilings, as this is a mid-floor, mid-terrace flat.	1%	Very good agreement, although within a large confidence interval

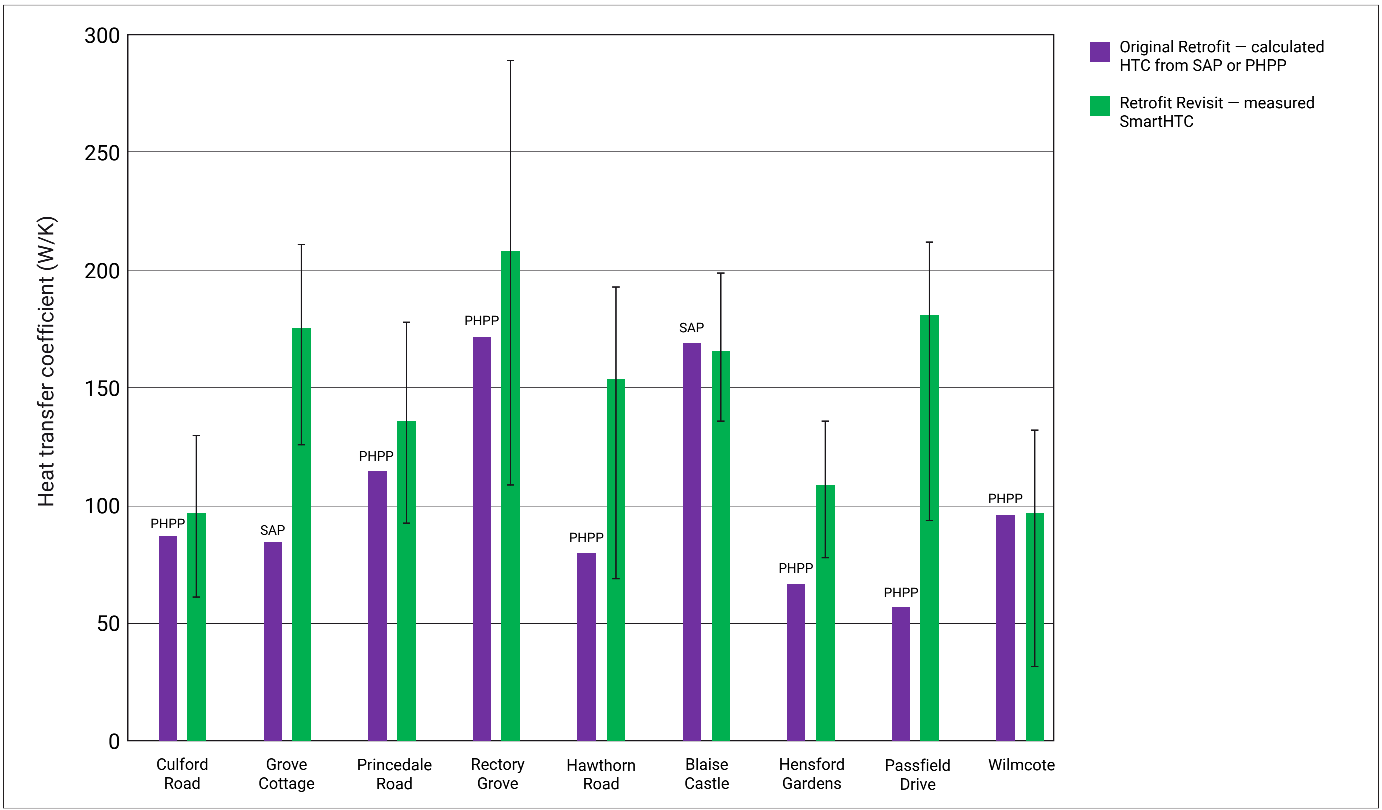


Figure 4.7 Retrofit design calculation HTC and Retofit Revisit measured SmartHTC (W/K)

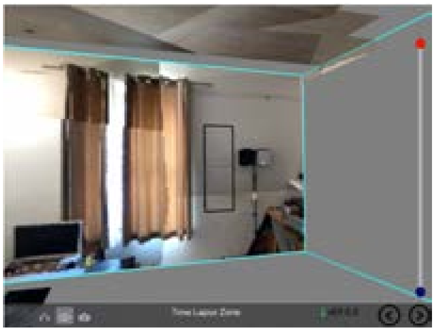


Figure 4.8 Wall examined by thermal imaging

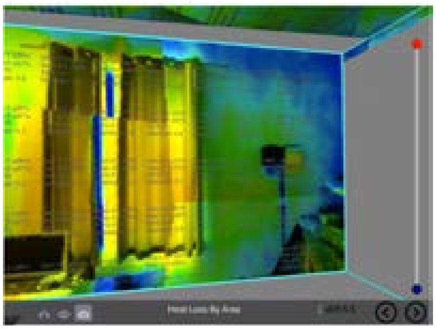


Figure 4.9 Thermal image of wall shown in Figure 4.8

4.1.5 *U*-values

In summary, the tests did not indicate significant issues with the installation or subsequent degradation, but they were quite limited in the number of elements tested:

- The heat flow meter (HFM) *U*-value tests were broadly consistent with the modelled values at design stage.
- This is also broadly the case for Heat3D tests, although the precision of the method is limited to ±0.1 $W/m^2 \cdot K$. The Heat3D tests show very good consistency across the walls examined, indicating good installation and no subsequent degradation.

See more details in Briefing 10: 'BPE techniques: thermal and moisture evaluation techniques'.

4.1.6 Windows

All properties replaced their windows for more efficient ones, including one timber sash look-alike which acts as a tilt-and-turn, while others were simple casement windows. On a visual assessment, most seem to be in good condition, only some minor signs of ageing have been observed in some casement and door rubber seals. This is likely to contribute to a drop in thermal and airtightness performance, hence seals should be the subject of better attention and a good maintenance regime.

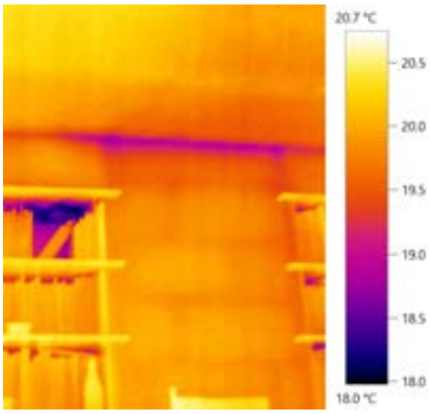


Figure 4.10 Infrared image of visible dampness in the living room of Culford Road

Figure 4.11 Area of remaining damp in Grove Cottage

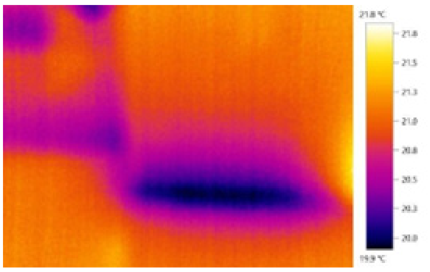


Figure 4.12 Thermal image of the damp area shown in Figure 4.11

4.1.7 Moisture

HR and particle count (refer to Briefing 6, 'Indoor environmental quality'); fungal testing (refer to Briefing 6, 'Indoor environmental quality'); hygrothermal performance (refer to Briefing 5, 'Construction details: corners, junctions, edges and interfaces').

Overall, there is good feedback from all projects and no major failures observed on the fabric elements.

4.1.8 Variations/additional comments

There has been several types of minor issues observed.

Rainwater ingress

The lack of maintenance of roofing (Princedale Road) and guttering material (Hawthorn Road) has led to water ingress. The impact on the thermal performance has not been measured. In Hawthorn, where the SmartHTC results came back worse than those for design (which may be attributed to the HTC, which has doubled but is still rated 'good') and the airtightness which has also worsened. Also, fungal tests came back 'class B' (medium risk). It is uncertain whether this medium risk of fungus is related to the slightly unbalanced ventilation system or a result of the potential moisture in the fabric. On visual inspection, there were no signs of mould or water damage inside this property, including in the tested rooms (living room and bedroom) and the loft. It may be possible that interstitial moisture is present and contributory — WUFI® modelling shows that this could be the case for a high absorption brick — but invasive works would be required to establish this, and it was not possible within the scope of this project. Caution should be taken to ensure the fabric is able to dry out and that the materials remain in good condition. In Princedale Road, it is uncertain whether the OSB board used as an airtightness layer has been impacted by water infiltration since it is situated between two layers of PIR insulation. However, it is suggested that this approach carries a risk as it is not able to handle interstitial moisture since the PIR insulation layer is impermeable to vapour and liquid water.

Accidental flooding of the ground floor in one property (Grove Cottage) led to remedial works which may have affected the robustness of the detailing and therefore possibly the performance of the retrofitted fabric. It is difficult to pinpoint precisely the implications of remedial works on energy demand as this is often the combination of various other elements (windows/doors seals, material ageing, movement in fabric etc.)

Water runoff from aluminium window cills on EWI would appear to indicate some surface condensation externally. This may affect the performance of the insulation — to be investigated (refer to case study CS1: Blaise Castle).

Figure 4.13 Blaise Castle: infrared image of front (west) and side (south) elevations (arrows indicate surface condensation with run-off from aluminium sills and interface with car port roof; this finding is subject to further investigations to confirm the cause)

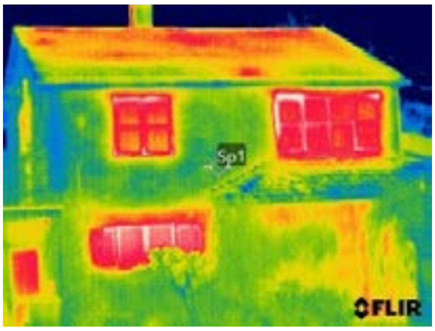


Figure 4.14 Blaise Castle: IR image of neighbouring house (not retrofitted) for comparison

Interstitial moisture

One house (Grove Cottage) with a portion of a brick wall exposed to rainfall was insulated with vapour-closed insulation — this resulted in interstitial condensation and saturation between insulation and masonry, leading to timber joist decay and replacement. *Note*: this joist was replaced before this Revisit but worth noting the experience since the original retrofit.

In Culford Road, infrared imaging was used to detect the presence of hidden moisture damage signs in the property and to determine the extent of a leak from the mains leading to a water cistern. The visible signs of dampness in the living room were confirmed via thermal imaging (Figure 23) and further investigations revealed the presence of moisture damage due to the same leak in the bathroom (Figure 24). Though invisible to the eye, the small but detectable temperature differences from the thermal imaging in Figure 4.10 shows the path of the moisture transfer in the wall.

The fungal and visual inspection did not however note any significant risk classifying the air as 'Class A' (dominant fungal species found were *Cladosporium cladosporides* (23.29%), *Cladosporium herbarum* (11.20%) and *Acremonium strictum* (54.88%)). RH and particle counts were found to be within acceptable limits based on literature. Refer to Appendix 4, 'Detail testing: moisture'.

Material degradation

The one property which observed some degradation on the external wall phenolic insulation boards beneath render (causing panels to bow very slightly) could benefit from further material integrity and dimensional stability investigations. Solar exposures may have caused the gases within the phenolic panels to expand and escape at panel edges, but not in the centre. This could lead to a drop in insulating performance (i.e. a higher *U*-value) therefore increasing the energy demand slightly.

Some cracking to the render has also been observed in some properties. It may be due to frost getting trapped between the render and the wall. Further scrutiny of the durability of the phenolic type of EWI is needed (Blaise Castle, Hawthorn Road).

Use of cement in brick pointing in the original retrofit project has contributed to brick cracking and evident spalling and frost damage (Hawthorn Road); a great part of the spalling is due to the interaction between the solid floor and the wall. The presence of a solid floor as 'risk determinant' is a key reason of the spalling. The decay of the brickwork has been accelerated as the brickwork remains cold (the internal insulation now prevents the indoor heat

Figure 4.15 Shaftesbury Park: pre-retrofit ground floor and joists

Figure 4.16 Shaftesbury Part: ground floor membrane below joists

Figure 4.17 Shaftesbury Park: EPS bead infill between floor joists

from reaching the brickwork). The airtightness layer will slow down the moisture transfer so water from driving rain is less likely to reach the internal layers, and may saturate within the brickwork for longer, and further exacerbates this issue. Cement pointing seems to be a real issue when combined with IWI. The degradation and water saturation of the brickwork might also slightly worsen the thermal performance of the overall wall build-up.

4.2 Lessons learnt and recommendations

4.2.1 Internal wall insulation (IWI)

Materials used were insulated plaster, woodfibre, polyisocyanurate (PIR) insulating boards, sheep's wool.

The use of lime mortar in combination with insulation systems that allow moisture transfer seems to be resilient and has not led to any fabric issues (aerogel, woodfibre etc.).

When combined with IWI, cement mortar brick pointing can affect moisture transfer patterns and could lead to fabric issues, which therefore should be carefully considered.

The PIR insulation boards installed internally and combined with vented cavities seem to have performed well; no significant moisture levels were found in the cavity in the period of analysis (Culford Road), but more data is needed to capture the behaviour in winter.

In the home where sheep's wool insulation was used, it was used as both IWI and loft insulation, with no visual signs of any issues. The roof sheeps' wool insulation was inspected and showed no degradation (Hawthorn Road).

IWI with aerogel did not show any material issues visually, but the onsite *U*-value (plate north facing wall (design 0.14 W/m^2·K, plate *U*-value 0.20±0.06 W/m^2·K)) test showed a higher figure than at original desktop calculations. The uniformity from the Heat3D suggests that either the initial calculation was wrong (e.g. perhaps the brick was thermally worse than expected), or the aerogel performance was less than expected (Shaftesbury). In Shaftesbury Park, the hygrothermal performance assessment also predicted high mould-growth risk behind the wall insulation, no visible signs of issues were noted, however. Further investigations would be useful.

4.2.2 External wall insulation (EWI)

Some PIR foam boards seem to have changed performance with age. Especially in specific locations such as corners and surfaces exposed to a wide range of temperature variations.

Durability of insulation materials carries a risk, however, after 10 years and varying levels of maintenance — the materials have mostly been reliable.

The move away from combustible PIR insulation may lead towards an increased use of rendered rockwool type of EWI.

The maintenance and cleaning of the render should be communicated so that occupant can maintain their homes.

4.2.3 Hybrid systems wall insulation

Junctions and overlap between IWI and EWI seem to have worked well. Thermal bridges were 'designed-out', which worked.

Party walls

Terraced properties that share a party wall with their neighbours can gain significant energy performance advantages from the expansion of retrofit strategies onto adjacent properties. When this is not the case, such as Passfield Drive, where retrofitting of the neighbouring properties was originally anticipated, it is very likely that it has contributed to higher energy use than anticipated. For example, the DEEP project (HM Government, online b) found significant air exchange with adjoining properties through party walls (or possibly through floor voids).

Floors

The one occurrence of an insulated suspended ground floor void with EPS beads (Shaftesbury) were a real innovation at the time of the original retrofit. Initial moisture level investigations 10 years on seem to reveal acceptable levels of moisture at floor joists level. There seems to be no signs of timber decay. However, the report from UKCMB (Appendix 5) reports a 'likely' risk of wood rot behind joist ends from modelling for both north-west facing and south-east facing walls, subject to brick and timber type, so the modelling is likely too conservative. The floor *U*-value, site tested, is also performing 12% better than designed.

Other floors with EPS, vacuum panels seem to have had no visible issues.

Roofs

One cold roof void reported high moisture content.

4.2.4 Could it have been expected given the original BPE, including post completion review?

While there was no absolute certainty about the longevity of the materials used over 10 years, except for one material integrity issue (Blaise Castle), it is reassuring that the thermal strategies overall seem to have been successful in achieving their intended results. This BPE highlights the crucial importance of basic maintenance of the building fabric (gutters etc.) to mitigate if not alleviate any localised drop in performance, for example in the case of excessive moisture in the building fabric which could be brought by water leaks for examples.

4.3 Remaining areas of uncertainties/need for further research

Having an in-depth understanding of the characteristics of each type of insulation, particularly with regards to their moisture balance, and knowing how to appropriately apply the right material in the right location is crucial.

The projects selected all displayed a good understanding of the movement of moisture in a building fabric, overall, the industry needs to rise to this level of expertise to deliver these robust projects.

Further research in the durability of EWI made of foam boards is needed. Avoiding the need for EWI replacement is crucial, as it can be highly disruptive, expensive, and demotivating to undergo a retrofit only to face further costly repairs. To mitigate this risk, manufacturers should offer a guarantee for the entire system, ideally for a minimum of 25 years.

Several projects have used insulation materials classed as combustible (PIR, EPS, polystyrene). Now, post-Grenfell, the construction industry is moving away from such materials and is favouring non-combustible ones. Insurance companies are also reluctant to cover the extensive use of combustible materials and hence they restrict professional indemnity cover very significantly for those projects which do. It would be very useful to carry out an extensive study on non-combustible materials and develop the industry to offer additional choice as the materials currently rated non-combustible are limited and very expensive (aerogel, insulating plaster etc.).

Briefing 5: Construction details: corners, junctions, edges and interfaces

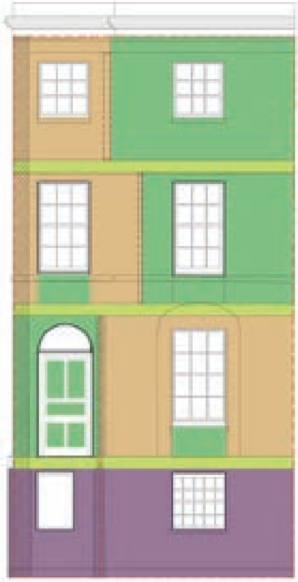


Figure 5.1 Rectory Grove: different insulation types

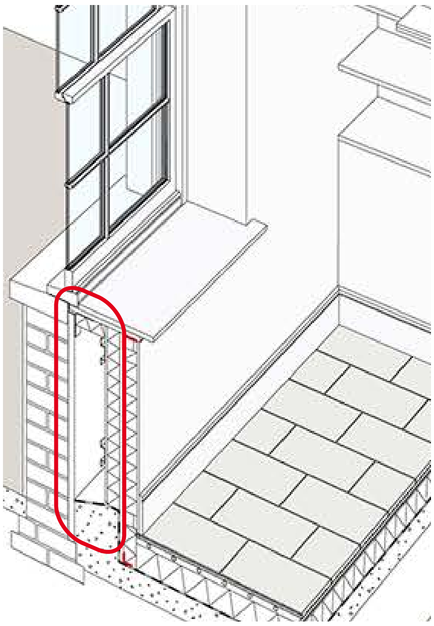


Figure 5.2 Culford Road: internal insulation with vented cavity and insulated reveals and insulated ground floor

5.1 Trends across the case studies

5.1.1 Overview

The retrofit strategies were originally designed by keen architects and engineers. This led to a very careful planning and consideration for the whole house strategy and corresponding precision in detailing including some assessments such as thermal bridge and moisture (hygrothermal) computer modelling.

Overall, the large majority of the houses have not shown fabric issues of concern in the revisit BPE exercise. However, it is important to highlight that there was restricted access to the different components comprising the fabric layers, both internally and externally, to prevent damage to the buildings.

5.1.2 Robustness of the strategies

The strategies and choice of materials are extremely varied across the 10 projects. Some of the most complex insulating strategies including nine types of materials (e.g. Rectory Grove) do not seem to show any more issues than the simpler approaches. IWI and EWI both seem to remain effective. On overall thermal performance, including *U*-values and heat transfer coefficient, see Briefing 7. For fungal testing and visual inspections in the four properties tested, RH and particle counts were found to be within acceptable limits. Hygrothermal (WUFI®) modelling showed some isolated risks on joist ends (the modelling was carried out with assumptions rather than actual values).

5.1.3 Robustness of the detailing

The details have largely held their installation quality. Some weaker points in the junction between windows and wall fabric have been observed, in particular at window cill locations. Some external doors (sliding/bi-fold) have shown signs of ageing due to long term repeated use.

For analysis of the details, see also Appendix 5, for testing results of fabric and ambient moisture. A common concern in retrofits relates to the placement of timber joist ends within brickwork and whether the retrofitted insulation may expose these joist ends to risks of rot over the long term.

The modelling carried out retrospectively within this report shows some minor risk in Hawthorn Road. The brick is of a type with relatively high water absorptivity (A = 0.38 or 0.183 kg/m^2·s$^{0.5}$). The less asorptive brick (A = 0.116 kg/m^2·s$^{0.5}$) showed no risk in the modelling. The results were the same for mould growth modelling with risks to the joists ends only with a high brick absorptivity. The time frame available for the BPE did not allow for material property testing to be carried out; this would have added more certainty to the results.

Figure 5.3 Karsten tube test for testing the porosity of the brick

Figure 5.4 Hawthorn Road: junction between IWI and EWI.

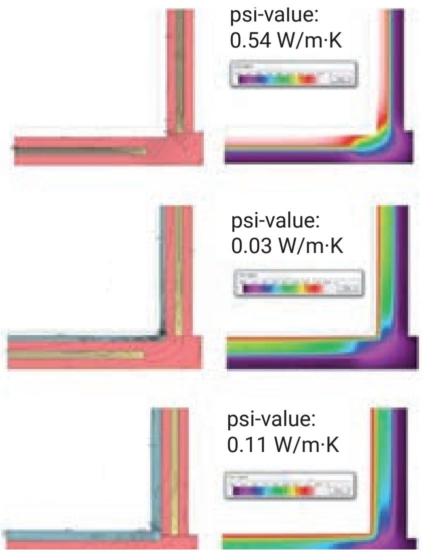


Figure 5.5 Hensford Gardens thermal bridge modelling

In the SOAP survey, see Appendix 4, surface condensation, at least localised, was reported by residents in 4 of the 10 homes. In winter 2023, an occurrence was observed in a bathroom for the first time in 10 years. This was thought to be largely due to user behaviour related to a lower thermostat setting and under-ventilation, aiming to save on winter energy bills, when energy costs had considerably increased over those for the previous nine years.

In places, some colder spots have been experienced due to lesser airtight windows and doors (those now need annual adjustments).

In one home, one thermal bridge which could not be avoided has led to a cooler environment in a particular room. In such insulated properties, just a small heat loss through thermal bridge will be more noticeable than is a non-retrofit property.

Practicalities: In two projects, the junction between insulation (IWI or EWI) and windows showed some issues on windows cills. These junctions proved to be very sensitive when regularly exposed to rainfall, and need a robust detail strategy and near-perfect installation quality.

Where vapour-closed insulation was installed internally with a vented cavity, the inspection of the cavity (Culford Road) identified that the wall insulation was functioning as designed, without condensation build-up inside the ventilated cavity after the wetting season (i.e. autumn and winter).

Coordination fabric and MEP: There have also been difficulties in sealing MVHR primary ducts and boiler flue onto an EWI surface; these were challenging details leading to potential compromised airtightness.

Roofs: In Blaise Castle, high relative humidity levels were reported in the loft during the tests. Surface fungal tests found high levels of DNA copies in this location. However, no mould was found in the loft insulation material which had been treated with fungicides. Remedial works have taken place post-revisit to increase the ventilation of the cold roof area.

5.1.4 Other items to note

- The one project which took a step-by-step approach reduced the amount of thermal bridges at each step. This clearly related to additional efficiencies and reduction in condensation risk. Although no condensation study was done pre-retrofit, the observation of significant condensation on identical adjacent properties and the thermal modelling of the thermal bridges confirm the effectiveness of the insulation detailing.

Figure 5.6 Minor hair line crack in external wall insulation (EWI) top render

Figure 5.7 Slight staining of the EWI render

Figure 5.8 Slight staining of the EWI render and traces of moss

- It is worth noting that most projects had to model thermal bridges to decide on the appropriate level and detail of insulation. These would appear to have paid off.
- One house has experienced a large number of moths: several samples were found in the MVHR filter and the tenants reported seeing some regularly. The house has sheep's wool insulation, which has in other projects been linked to the presence of moths (suspected to be due to the mixing of natural sheep wool with other non-organic materials and substances). While in this case there is no evidence that the two are linked, and moths are not unusual in London, this is something that could be further investigated.

5.2 Lessons learnt and recommendations

The main takeaway from the review of the detailing of these ten properties is that the retrofit strategies' detailing appears to have largely stood the test of time.

As these houses originally aimed for significant carbon emissions reduction (e.g. 80% for the seven which were part of Retrofit for the Future), the measures all come from 'deep' retrofits strategies, requiring detail modelling (thermal bridges in particular). These projects are not 'light touch' retrofits, hence they have eliminated many risks through careful design and computer modelling (thermal bridging and moisture in particular).

For the industry to achieve such results, upskilling in building physics will be preferred, at least for some professionals involved in the design and strategies of retrofits. The understanding of moisture behaviour, moisture modelling and thermal bridging modelling will be essential for the construction details to work. We understand that this will be difficult to implement on a large scale, but rule of thumb and precise guidance is essential for the various trades involved. To help with this issue, it would be very useful to establish freely available, robust, mandated specifications and construction details templates (with known psi-values, temperature factors, etc).

Thermal bridging calculations seem to have been useful in de-risking the building fabric issues as there has been very limited surface condensation issues identified or reported. *Note*: intrusive investigation of the mitigated thermal bridge elements constituting the retrofitted fabric was not possible.

5.2.1 Could it have been expected given the original BPE, including post-completion review?

The BPE showed that careful attention to detail has paid off. This level of fabric improvement with a variety of approach and materials shows that there are many ways to produce effective retrofits and that risks related to detailing has been minimal overall.

5.3 Remaining areas of uncertainties/needs for further research

All projects used modelling softwares to de-risk their details.

Modelling of thermal bridging is still a rather specialised and costly activity, done by specialists consultants. The retrofit industry would benefit from more-intuitive tools able to inform decisions early on. There are many software products available that could be more embedded in the drawing production process to avoid thermal bridging modelling having to be undertaken as a stand-alone exercise.

As mentioned above, a set of robust and typical specifications and details specific to retrofit conditions would also be very useful.

Briefing 6: Indoor environmental quality

Figure 6.1 Temperature and RH sensors used in the Retrofit Revisit case study homes

6.1 Trends across the case studies

6.1.1 BPE approach

Indoor environment quality (IEQ) was assessed using a number of methods, combining quantitative measurements with resident feedback:

- User surveys, with questions on the indoor environment (including overall comfort, temperature, perceived air quality etc): in all homes, with a single 'household' response per home.
- IEQ monitoring for one month in all homes: temperature (*T*) and relative humidity (RH) in several rooms, and CO_2 in the main occupied room. Due to incorrect installation, *T* and RH data was gathered in 9 out of 10 homes, and CO_2 data in 8 out of 10 homes. The *T* and RH data led to the production of a BTS MouldRisk score for each of the nine homes.
- Fungal and allergen testing was carried out in five homes.

6.1.2 Overall picture

In general, the indoor conditions received highly favourable assessments in the majority of homes. Specifically, they were deemed 'very comfortable' in seven homes, 'comfy' in two, and 'neutral' in the 10th. Comfort levels were notably high during the winter and slightly less so during the summer, although still seen positively.

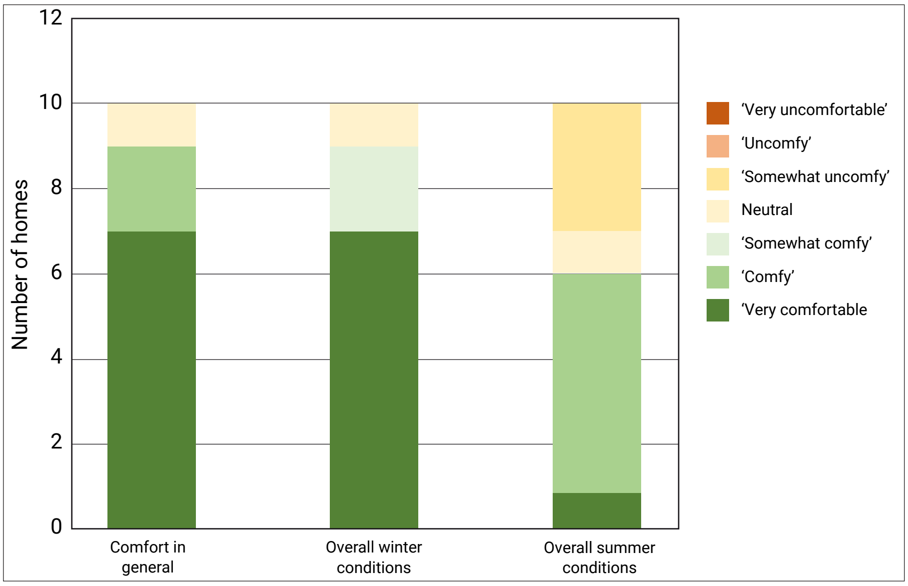


Figure 6.2 Feedback received on thermal comfort across the Retrofit Revisit case studies

Alignments of data: Regarding winter conditions, much of the resident feedback aligns with the monitoring results, as temperature (*T*), relative humidity (RH), and CO_2 levels fall within the recommended ranges in most homes.

Misalignments of data: Nonetheless, there are instances where this correlation does not hold, and the fungal testing identified problems that were not identified through resident feedback and temperature and relative humidity monitoring. These issues were linked to factors other than indoor temperature and relative humidity, as explained in further detail below.

Due to the short timescale of the study, no monitoring took place in summer.

Cross examination: The following sections examine specific IEQ parameters in detail: temperature, relative humidity, CO_2, and fungal testing (levels and species). In all of these, the physical measurements are reported as well as resident feedback on associated issues. Specific observations are also made on ventilation (including systems), since this is closely related to observed relative humidity and CO_2 levels.

6.1.3 Temperature

Winter temperature conditions in the monitored period (approximately one month over March–April 2023) were as follows:

- Average *T* in all rooms in all homes is above 18 ºC (the minimum temperature recommended by the World Health Organization).
- Whole house average *T*: 18.2–20.7 ºC, 19.4 ºC on average.
- Main bedroom average *T*: 17.7–21.2 ºC.

In the residents' feedback, the homes as an overall sample perform very well against benchmark: see Figure 6.2 above. The winter temperature conditions were rated as 'very comfortable' in seven homes and 'somewhat comfy' in two homes, and only 'somewhat uncomfy' in one. In the summer, the feedback is a bit less positive, with summer temperature conditions rated as 'very comfortable' in one home, 'comfy' in five, 'neutral' in one and 'somewhat uncomfy' in three homes; however, the overall sample still performs better than benchmark resident surveys.

There are wide variations in the temperature conditions residents state they prefer, and how they define it:

- In four homes the residents stated that they preferred 'warm' conditions; across the homes — this was defined as 17 ºC, 20 ºC, 21.5 ºC and 22 ºC, i.e. average 20.1 ºC.

- In four homes the residents stated that they preferred 'average' conditions — this was defined as 18 °C by two homes, 20 °C by one home (the residents of one home did not give a temperature), i.e. average 18.7 °C.
- The residents of one home stated that they preferred 'cool' conditions, which they defined as 18 °C.

While broadly speaking, 'cool' conditions were defined by lower temperatures than 'average', which themselves were defined by lower temperatures than 'warm', the spread is wide and there is clearly an element of personal preference in how conditions are perceived.

There are clearly caveats to the data:

- the sample is small

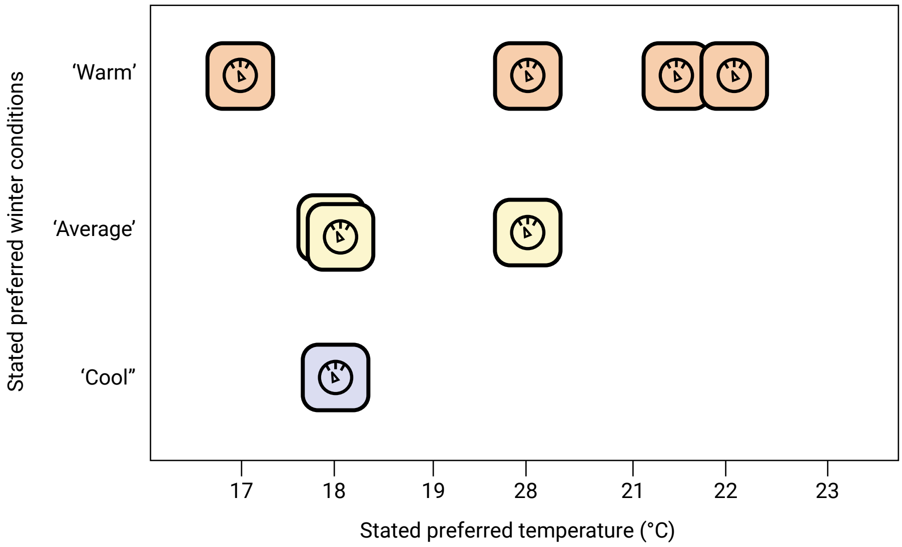


Figure 6.3 Feedback received from residents on preferred winter conditions versus stated preferred temperature

- the data covers 24-hour periods, during which homes may be empty part of the time, some homes more than others. This means that some homes may experience lower average temperatures because they were unoccupied for longer.

Within these limitations, it can nonetheless be observed that, broadly speaking, there was reasonable agreement between residents' stated preferred temperature, observed temperature, and their satisfaction with winter temperature, but with some variations:

- The monitored temperature was warmer than their stated preferred temperature in four homes, and cooler in four homes. It was as stated (20 °C) in the ninth home. On average, the temperature difference was 0.2 °C, varying between –1.9 °C and +1.9 °C.

- The residents in 8 of the 10 homes stated that the winter temperature was 'just right'. The difference between the stated preferred temperature and the average observed temperature in these homes (seven, since one had no data) was 0.01 °C, on average, varying between –1.8 °C and +1.9 °C. This is indicative of people generally being well aware of their preferred temperature, and well able (thanks to the home performance and its systems) to control the home to that preferred temperature.
- Only one home (Wilmcote) stated the home was 'too cold' in winter. They stated they preferred 'average' temperature conditions, but did not provide a preferred temperature. The monitored temperature in that home was 20.3 °C, varying between 20.2 °C and 21 °C across rooms, even with limited use of space heating (see Briefing 2). This would be considered comfortable by many people, so the stated dissatisfaction illustrates personal preferences.
- One home (Passfield) stated it was 'slightly too cold' but only on the top floor.

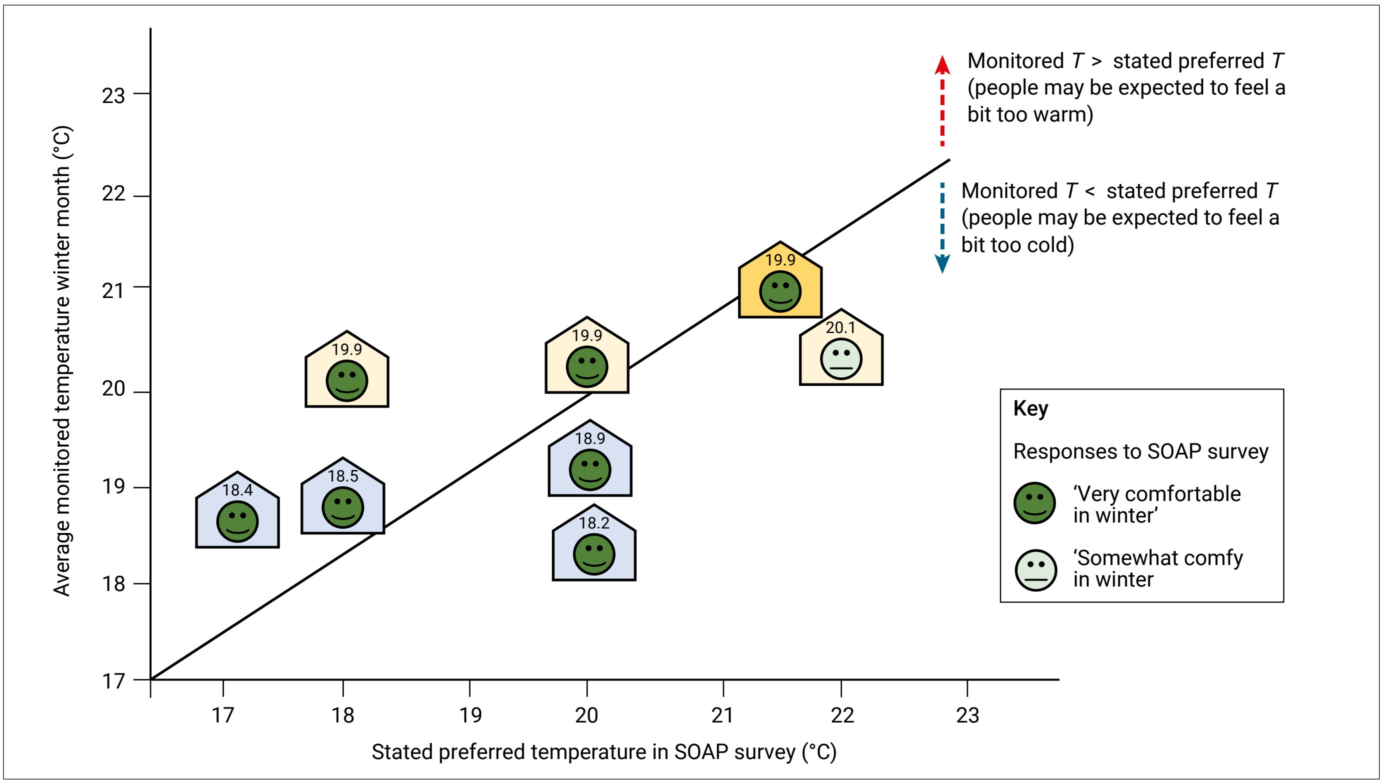


Figure 6.4 Feedback received from residents on preferred temperature and thermal comfort, versus average monitored temperature

See Briefing 2 for observations on observed temperature versus energy use.

Figure 6.5 Temperature and relative humidity sensors as installed in several locations within each house

6.1.4 Relative humidity

Winter RH conditions in the monitored period (approximately one month over March–April 2023) were as follows:

- *average whole house*: RH = 55%, varying from 48% to 65% across the nine homes (the 10th has no data), and in 8 out of 9 homes was below 60%
- *main bedroom*: average RH = 55%, varying from 47 to 63%
- *kitchen*: average RH (from three homes) = 58%, varying from 49% to 69%
- *bathroom*: average RH (from five homes) = 57%, varying from 47% to 65%.

Overall, this means that RH levels were good in 8 out of the 9 homes with data as follows:

- seven homes: 47–55% average RH, with a BTS MouldRisk score of 'low' or 'very low'
- one home: 59.6% average RH (62% in the main bedroom), with a BTS MouldRisk score of 'low' (Princedale)
- one home: 55.6% average RH (63% in the bathroom), with a BTS MouldRisk score of 'medium' (Passfield).

In all of these homes, and in the one without data, residents reported that winter humidity was 'just right'.

The remaining home exhibited high RH levels: 65% average RH (62% to 69.8% across the different rooms), with a BTS MouldRisk score of 'high'. This is attributed to insufficient ventilation, with residents not using the hob extractor fan in the kitchen and boost function in the bathroom, due to concerns about energy costs. Interestingly, in this home the residents reported that winter conditions were 'too dry'. This discrepancy is surprising to some extent, as it is the one home with the highest humidity levels, but it is supported by other instances in the literature, which indicate that people are not good at sensing humidity and differentiating it from other factors (Wilmcote).

6.1.5 Cabon dioxide

In 7 out of the 8 homes that provided data, CO_2 levels were generally good, with the average in occupied hours <1250 ppm. Occurrences above that threshold, if any, only happened a few times in the course of the monitoring period (i.e. 3–4 weeks) and tended to be for short periods only (max. a few hours).

In the remaining home, CO_2 levels frequently exceeded 1250 ppm for extended periods, and the average across all hours (even including periods where the home would have been unoccupied), was recorded at around 1400 ppm. (Wilmcote)

Figure 6.6 Build Test Solution's ambient air humidity sensor equipment

The SOAP survey includes one question asking about air quality, but in the five homes where this was answered, the residents commented on temperature rather than air quality. The survey does not include a specific question about 'stuffiness', but it includes one about odours. Similar to CO_2 levels, odours in homes are often linked to human activities and can indicate inadequate ventilation. In the sample of homes, there was a good match between monitored CO_2 levels and residents' feedback on odours in the winter:

- In the eight homes showing good CO2 levels, winter conditions were reported as 'odourless' in three homes and as having 'minimal odours' in five homes.
- In the home showing high CO_2 levels, residents reported 'some odours'. Incidentally, it is also the home with higher humidity levels, in which residents had reported winter conditions as 'too dry', despite high RH levels. This indicates that while residents may not be able to point out the exact physical factor at play, their dissatisfaction is rightly linked with less than optimal indoor conditions. (Wilmcote)

Figure 6.7 Build Test Solution's ambient air humidity sensor equipment

6.1.6 Fungal and allergen testing

Fungal and allergen testing was carried out in five properties. Several factors are used to assess and analyse the results:

- ambient fungal levels, allergen levels, and the ratio of fungal-to-allergen: the levels are rated on a scale of A+ (best = lowest) to D, on a scale developed by Mycometer
- fungal swab tests on surfaces
- fungal species (i.e. DNA analysis): this can help indicate the likely sources
- in addition, testing before and after a depressurisation airtightness test can provide an indication of whether there may be a fungal source within the fabric as they are driven out of the walls and floors by wind pressure; this was carried out in three homes.

In short, none of the homes was found to raise health and safety concerns related to fungal or allergen levels. Two performed very well, while three other homes pointed to some issues (often localised in some rooms) and possible causes and remediation measures. The results are summarised below, and full details of the method and results are in the UCL report.

The ambient fungal and allergen level results at Grove Cottage, Hawthorn Road and Blaise Castle indicate that, in some rooms, there is a high risk of mould contamination and there is the need for further specialised fungal testing procedures to detect potential contamination sources and address the issues, if any. The results in the other rooms tested, and the results in the two other homes

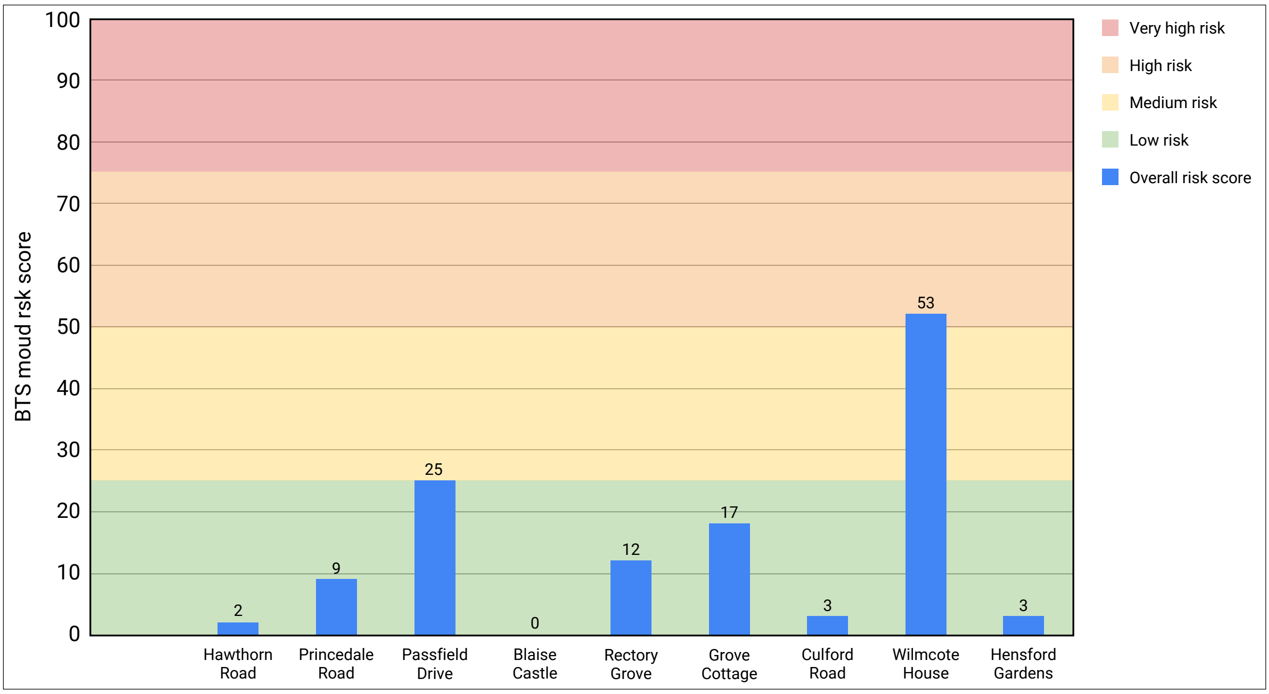


Figure 6.8 BTS mould risk score (March 2023)

(Culford and Shaftesbury), were found to be within the range typically found in rooms where a good cleaning standard has been followed and without visual growth or moisture-related issues.

In general, the swab tests showed that the tested surfaces have not been contaminated by fungi, and that the ambient levels are unlikely to be related to fungal activity on the surfaces. The exceptions are localised surface mould in the bathroom at Culford Rd, and in the loft at Blaise Castle. At Culford Road, this was attributed to a past (now resolved) plumbing leak. This has not affected ambient levels, which are good. At Blaise Castle, observed fungal levels in the bedroom might be associated with high fungal activity in the loft space (but we were unable to test the air activity in the loft, since doing so would have blown away the insulation). While mould was found in the rafters, no mould was found in the loft insulation, which had been treated with fungicides.

At Hawthorn Road, the results of the DNA analysis showed that the high number of species may indicate a combination of sources, some of them possibly related to occupants (e.g. cleaning regime, pets). In addition, given the observations about moisture-related fabric degradation in this property, other sources of fungi may also exist. Communication has been made with the housing association to recommend remedial actions to the fabric, and liaising with the resident on the actions that they could take; after this, re-testing could be carried out, and further specialised fungal testing procedures may be needed to eliminate potential fungal-related risks, if they remained.

At Grove Cottage, there was a significant difference in fungal levels before and after depressurisation, indicating a fungal contamination source within the fabric. This, together with the type of species found, could indicate an active hidden moisture issue which may require further investigation and opening-up works.

At Blaise Castle, the dominant species were the same in the swab tests in the loft and ambient tests in the bedroom, supporting the hypothesis that the fungal levels found in both rooms are related. However, the low number of fungal species, combined with high fungal and allergen levels in the bedroom, suggest that there might be other species present in the environment outside those targeted in the analysis, or that that high fungal and allergen levels may be due to an indoor occupant-related source (e.g. pets, soil, plants); further tests would be required to determine this with certainty.

6.1.7 Comments on ventilation

Issues with mould, RH and CO_2 can all indicate insufficient ventilation. As noted above, in most homes the conditions are satisfactory, indicating good operation of the ventilation systems. However, in some homes, issues were noted with the ventilation:

- *Grove*: the MVHR operated in extract mode; there was no negative user feedback, and the RH and CO_2 levels are within acceptable ranges.
- *Passfield*: while on average within recommended ranges (except in the bathroom, where RH is around 65%), the RH and CO_2 levels are relatively high. This could be due to high occupancy patterns (e.g. extensive cooking periods were noted), but would probably still warrant a check on the ventilation system; the evaluator noted that new filters had been provided, but the system may need to be checked for potential blockages, re-balancing etc.
- *Princedale*: the MVHR failed around the time of the start of the Retrofit Revisit, for the first time since its installation. IEQ monitoring started afterwards, but the monitoring does show relatively high RH (59.6%).
- *Hawthorn*: the MVHR was noted during the site visits as being noisy, with dirty filters, and notably in need of re-balancing. The RH and CO_2 levels are within acceptable ranges.
- *Wilmcote*: in the monitored maisonette, residents did not use the kitchen extract fan and boost function in the bathroom, due to concerns about energy costs: see 6.1.4.

6.1.8 Variations/additional comments

While general observations can be made across the sample, for example in terms of the good feedback from the residents (especially for winter thermal comfort) and good levels of temperature and

RH in most homes, IEQ is to some extent subjective (for thermal comfort), seasonal, and tributary to equipment reliability. Some of the observations are the result of a complex interaction of several factors, and therefore the case studies and the UKCMB report (Appendix 5) are a much richer and useful source of information than this briefing to understand the IEQ performance of the homes in a more meaningful manner.

6.2 Lessons learnt and recommendations

6.2.1 Indoor environment

Most homes show good internal conditions, both through feedback and monitored conditions.

The findings also highlight the importance of gathering both physical measurements and residents feedback:

- The temperature data shows a wide range of conditions, and the same conditions cannot be assumed to be perceived in the same way across different homes.
- The humidity data shows good conditions in most homes, which aligns with ratings of 'just right' by residents. However, there are relatively high levels in one home (Wilmcote), and to a lesser extent in another two (Passfield and Princedale)
- The CO_2 data shows good conditions in most homes, which aligns with ratings of 'odourless' or 'minimum odours' by residents. However, there are high levels in one home, the same home which has high humidity levels. Residents rated it with 'some odours', which indicates that while residents may not be able to point out the exact physical factor at play, their dissatisfaction is rightly linked with less than optimal indoor conditions. Both the high humidity and CO_2 levels are explained in this case by insufficient ventilation — see case study CS8 on Wilmcote House for details.
- CO_2 levels were generally good in most homes, and levels only exceeded recommended thresholds for short periods, if they did at all. The exception is the same home as suffered from relatively high humidity levels and reported odours, all three elements pointing to insufficient ventilation. This is confirmed by the site visit, which noted that the extract functions in the kitchen and bathroom are not operated by the resident (due to concerns about costs).

While most properties were rated at very low risk of mould from their temperature and relative humidity levels (using the BTS Mould Risk indicator), the more detailed tests carried out on five homes did indicate that, in three homes, there were some high fungal and/or allergen levels, from a variety of possible sources, e.g. fabric degradation, past water damage, occupant-related sources (e.g. pets). See also Briefing 10, 'BPE techniques: thermal and moisture evaluation', for more detail.

While residents' feedback is essential for thermal comfort, since preferences vary (a wide range of preferred temperatures is illustrated even in this small sample), it should be treated with much caution on other topics, as the terminology around 'air quality' may not be well understood by non-technical people, and as some parameters such as humidity are not reliably perceived:

- It is notable that in the home with the highest humidity levels, the residents rated the conditions as 'too dry' (Wilmcote).
- In the five homes where residents answered the SOAP survey question about air quality, in their response the residents mentioned temperatures, not air quality.

6.2.2 Could it have been expected given the original BPE, including post-completion review?

The good thermal comfort was expected, given the fabric-first approach and satisfaction recorded at the original retrofit stage.

There had not been systematic evaluation of indoor air quality at the time, and the topic received less focus than it does now, so the good levels observed in the Retrofit Revisit are a positive finding and evidence, generally, of good ventilation.

Feedback on summer overheating is also relatively common, and the topic received less attention 10 years ago, so many homes prioritised reducing winter heat demand with less attention to protection against excessive summer gains and good summer ventilation. For example, many homes have reasonable proportions of glazing (as is common in heritage stock), but none have external shading; one has recently installed internal shading to some windows and interstitial shading to others (i.e. between the original and the secondary glazing (Rectory Grove). Even on this topic, the homes still perform better than the SOAP benchmarks.

6.3 Remaining areas of uncertainties/needs for further research

The detailed tests carried out by UCL proved valuable in identifying issues which were not visible from site visits, nor through the routine temperature and humidity monitoring — some of them related to past water-damage events now resolved but still possibly affecting indoor quality. However, this is clearly still a new, evolving and highly specialised area:

- In many cases the cause of the tested fungal and allergen levels and species is not fully ascertained, and further tests would be needed.
- What is 'acceptable', in terms of levels and species, is not yet fully established, so further research is needed to help these tests become a more routine and useful measure for practitioners.

Briefing 7: User experience

7.1 Trends across the case studies

7.1.1 Overall satisfaction

Resident feedback was collected in all homes through the SOAP survey, often supplemented by informal interviews with the residents. These results were analysed in conjunction with other findings, such as on-site observations and indoor environmental quality (IEQ) monitoring data.

For an in-depth commentary of the SOAP survey, see Briefing 1, 'BPE overall approach'.

As a sample, the homes scored very well against survey satisfaction benchmarks, and results showed only few areas of dissatisfaction. They score particularly well against benchmark in terms of:

- winter thermal comfort, both in terms of temperature and the stability of conditions
- energy use
- comfort in winter
- overall ventilation.

It is worth noting that the lowest survey scores recorded (and listed below) are still very much aligned with the benchmark average:

- internet provision (clearly independent from the retrofit of the homes)
- condition of shared areas (e.g. hallways)
- control of domestic hot water systems.

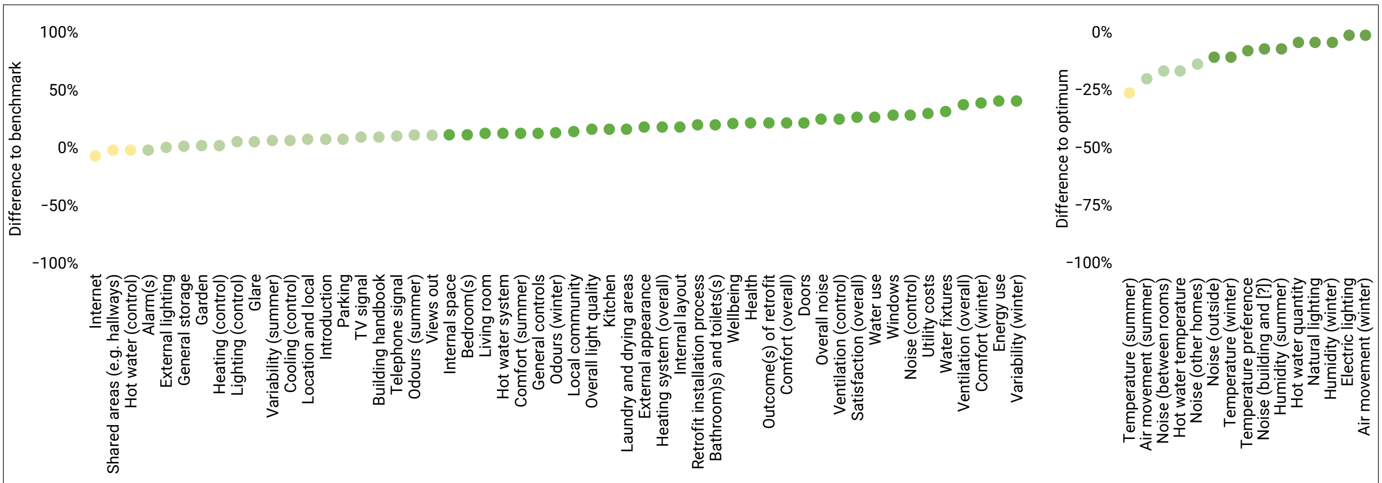


Figure 7.1 Results to SOAP survey questions across the Retrofit Revisit sample

The majority of homes were rated positively by residents: eight were rated 'excellent' (2), 'great' (5) or 'good' (1). Only one was rated 'average' and one 'poor'. None were rated 'very poor' or 'extremely poor'. This compares very well with the sample of homes within the SOAP database (over 200 homes).

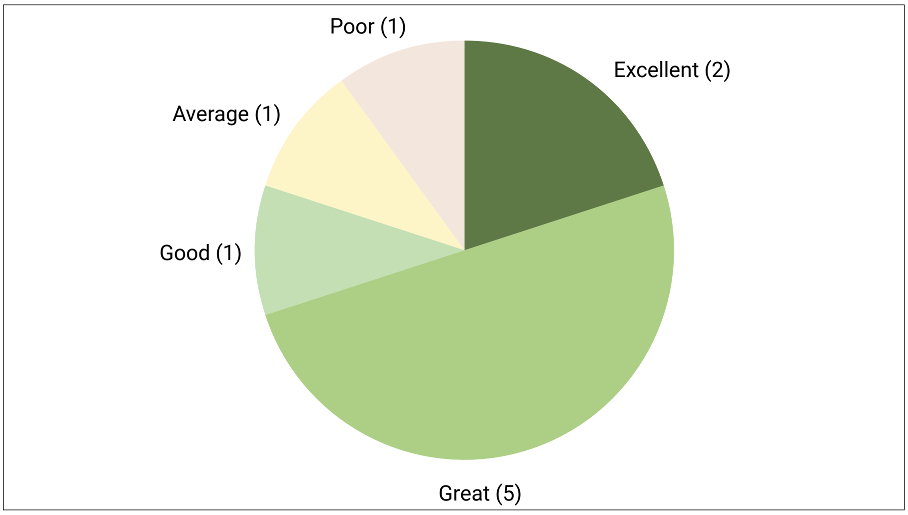


Figure 7.2 Repartition of SOAP survey: overall feedback scores across the Retrofit Revisit sample

A key point to note is that the SOAP survey lacks questions related to maintenance, which could be a valuable addition. Several properties have experienced issues with maintenance, see Briefing 8: Maintenance. There is no specific question on maintenance in the SOAP survey, but through informal feedback the residents in many of the case study homes reported issues with inappropriate maintenance or lack of (e.g. slow, not appropriate to the systems in their homes etc).

7.1.2 Tenure and relationship between the residents and the retrofit

The sample includes five tenanted homes, and five owner-occupied homes of which four whose owners were from the built environment industry and were very involved in the retrofit. The satisfaction scores are particularly high for homes with these involved and expert owner-occupiers (96% on average), followed by the other owner-occupier homes (81%). Scores in the tenanted homes are on average lower (68%), but they are varied: two homes are scored as 'average' or 'poor', but the others are scored similarly high as the owner-occupied homes. Because the sample is small, it is not possible to draw definite conclusions on whether the differences in score relate to tenure or are just incidental; however, a few of the tenanted homes did report finding it difficult to receive adequate maintenance and repair support, and this may have affected their overall satisfaction.

7.1.3 Satisfaction with energy costs

In the large majority of homes (9 out of 10), residents said they were 'very satisfied', 'satisfied' or 'somewhat satisfied' with their energy costs. The other home rated them 'neutral'. This is particularly notable given the current energy price situation, and as an overall sample the homes perform very well against benchmark. It aligns well with findings on energy use (see Briefing 2, 'Energy use: current use and evolution'), which shows average energy use well below the typical UK stock.

Figure 7.4 Hawthorn Road Rotex Gas Solar Combi Unit provides heating and DHW

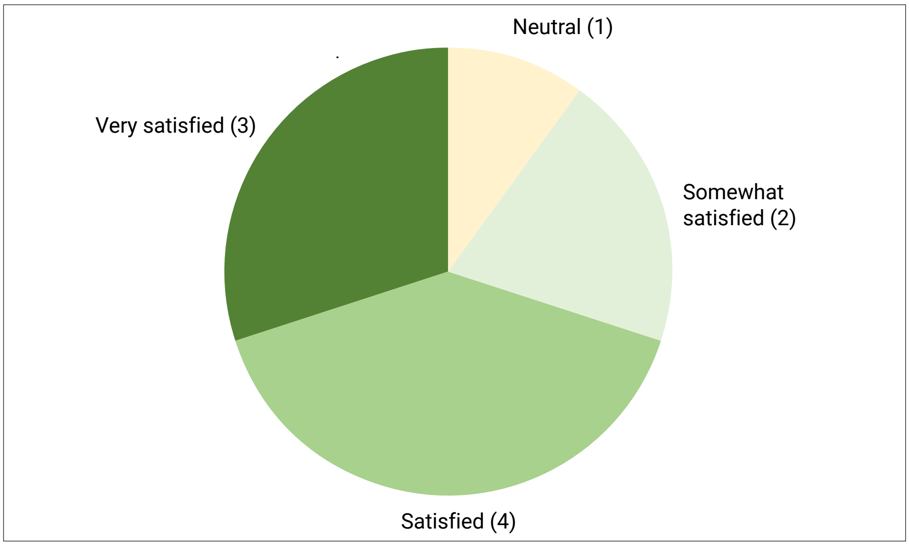


Figure 7.3 Repartition of SOAP survey: energy costs scores across the Retrofit Revisit sample

Figure 7.5 Hawthorn Road Rotex Gas Solar Combi Unit controls were more complex to operate than expected and lead to difficulty in operating the system for the tenant

7.1.4 Comfort (temperature, air quality, smells)

Residents generally rated indoor conditions well — for details, see Briefing 6, 'Indoor environmental quality'.

7.1.5 Systems

Generally, the most negative feedback revolved around systems and their controls, with a specific focus on heating and hot water systems. Users often found these controls too complicated, not giving them enough control, and sometimes failing to provide the right amount or temperature of water.

Figure 7.6 Princedale Road GenvexCombi unit controls with easy icons but quite complex to operate

In several homes it is likely to be compounded by poor maintenance as discussed in Briefing 8: Maintenance. However, it is noteworthy that even some homeowners who were actively engaged in the retrofit of their homes expressed dissatisfaction with certain systems and their controls:

- Controls for hot water were rated 'somewhat difficult' in two homes, and residents in three homes stated that they wanted more control

- Controls for space heating were rated 'somewhat' or 'very' difficult in three homes, and residents in four homes stated that they wanted more control.

7.1.6 Handover

Residents often did not answer these questions in the survey and, when they did, the answers did not always match what is known to have been provided (e.g. a user guide) or happened (e.g. a house tour, a training session). This may indicate that residents forgot or that the information was lost. On the other hand, some residents did comment positively on the guidance available to them — see Briefing 8: Maintenance, and the example of a user guide provided for Passfield House.

7.2 Lessons learnt and recommendations

The overarching message is that the vast majority of occupants continue to hold very positive views of their homes, even long after the initial retrofit.Their very good performance against the SOAP benchmarks (with no issue scoring below the benchmark) indicates how well they meet the needs of residents.As these retrofit projects were whole-house and substantial (rather than piecemeal, elemental measures), they probably offered opportunities for general improvements beyond energy and carbon reduction alone.

While energy costs must have increased compared to 10 years ago (even if energy use had not), the retrofits are still viewed positively, and much better than against the SOAP benchmark: residents must therefore have a good awareness of how they compare with their previous homes and/or that of people around them.

The lesson about avoiding complex systems and offering straightforward user controls is not a novel one; it is a recurring theme in BPE, especially in homes featuring relatively innovative systems like some within this sample. Simple user guides (e.g. one or two sides of A4), visually illustrated, do help, even if additional information is provided through other means, e.g. QR-codes linking to relevant, more detailed documentation.

7.2.1 Could it have been expected given the original BPE, including post-completion review?

Challenges in operating systems and controls of relatively innovative and sometimes complex/bespoke systems has led to some negative feedback. This could certainly have been expected as the original Retrofit for the Future programme did not include an ongoing maintenance plan and homeowners (in particular housing associations) did not have the resources to make specific maintenance plans for these unusual properties.

7.3 Remaining areas of uncertainties/needs for further research

7.3.1 Database

Carrying out occupant surveys is often disruptive for the people involved and can feel intrusive. However, data being of prime importance in BPE studies, careful attention to format and medium needs to be developed further. An open-source database would be interesting to help inform the whole industry and provide transparent, regular and accurate feedback on these properties.

7.3.2 Maintenance questions

With reference to the specific SOAP survey, it would be useful to add to it a question (or several) on the ease of maintenance, and on the quality and responsiveness of maintenance teams (where relevant). *Note*: this also applies to the BUS methodology, not just SOAP.

Briefing 8: Maintenance

8.1 Trends across the case studies

8.1.1 Methodology

All assessors were required to document repair and maintenance concerns uncovered during the retrofit projects in all 10 houses, in addition to any notable issues that may have arisen since the initial retrofit and of which they had become aware.

It is worth noting that 4 out of the 10 properties were owner-occupied and the occupants were mostly from the retrofit industry with a keen interest in achieving a good performance. This resulted in lesser maintenance issues in those particular properties.

The resulting log of repair and maintenance issues reported in all homes is shown in Table 8.1 below, summarising the issues found with:

- envelope
- water services
- ventilation systems
- heating and hot water systems (excluding solar thermal)
- solar thermal systems
- PVs.

Figure 8.1 Hawthorn Road: moss on brick wall by leaky gutter

8.1.2 Overview of findings

Maintenance concerns were noticed in the majority of residences, impacting various aspects of the homes. While some were of a minor nature or had been previously addressed (i.e. in the period between the original retrofit and the Retrofit Revisit), in some cases, they were substantial, with either ongoing issues or resulting in systems being non-operational during the study and for an extended duration.

It is worth noting that a considerable number of issues are not directly connected to the retrofit project; rather, they are of a general nature and indicative of the broader housing stock situation in the UK. For instance, a common issue is the widespread neglect of roofing and gutter maintenance.

MEP: Some issues are related to the relatively complex MEP systems installed, and competence (or otherwise) of the organisations looking after them.

Fabric: Most properties reported minor issues with the envelope, sometimes from minor degradation over time (e.g. windows and doors, seals or hinges, some window cills, and some minor material degradation such as phenolic EWI). Issues resulted mostly in unintended airpath or water ingress. In one severe case (Hawthorn), a leaky gutter and cement pointing resulted in significant brickwork

Figure 8.2 Princedale Road: MVHR fan and filters, left hand fan has been replaced after functioning for 11years

Figure 8.3 Princedale Road: GenvexCombi providing hot water and fresh air supply throughout the house; set behind acoustic doors

damage, although this did not seem to have affected the internal surfaces and comfort. In another case (Princedale), the butterfly roof gutter leak was minor but entered the property in a way that could not be traced (possibly within layers of the retrofitted materials). The potential damage is not visible internally but may be present nevertheless in the hidden layers forming the IWI (namely the OSB board).

Ventilation: Most properties (8 out of 10) have MVHR. Five of them reported some issues (e.g. noisy, seemingly not supplying or extracting as it should), including one home where it failed for the first time since its installation, just before the start of the Retrofit Revisit study, but has since been repaired (Princedale). Air quality is generally good in most homes (see Briefing 6: Indoor environmental quality), and, given how innovative MVHR systems were at the time they were installed in these homes, this is generally better than expected. Several tenanted homes with MVHR reported little maintenance taking place, and/or little replacement of filters.

Combined systems: Three homes had combined systems which were relatively complex or bespoke. The three reported severe failures:

- One was a combined exhaust heat pump and MVHR unit; one fan from the MVHR failed just before the Retrofit Revisit visit (after 12 years of operation) and has since been replaced (but still needs re-commissioning) (Princedale).
- One was a combined gas boiler and solar thermal system, from abroad. The solar thermal element stopped working several years ago, and it proved too difficult to find replacement parts and the skills to repair it (Hawthorn).
- One was a combined solar thermal and an exhaust air heat pump system. It proved too complex to operate and maintain, and stopped working several years ago. The home is now using electric heaters for heating, and a gas boiler for hot water; even the boiler proved difficult to maintain, as it was of foreign manufacture, unusual in the UK, with difficult access to the required skills and replacement parts (Shaftesbury).

Renewables: Five homes had solar thermal systems; there are no reported issues in one of them, beyond adjustments and rectifications in the first year of operation (Rectory); in another there were issues a few years ago, since rectified (Princedale); in the three others the systems have stopped working (two of these are part of combined systems, as noted above). While these systems were relatively uncommon at the time of the original retrofits, they were not completely new either, and better performance may possibly have been expected.

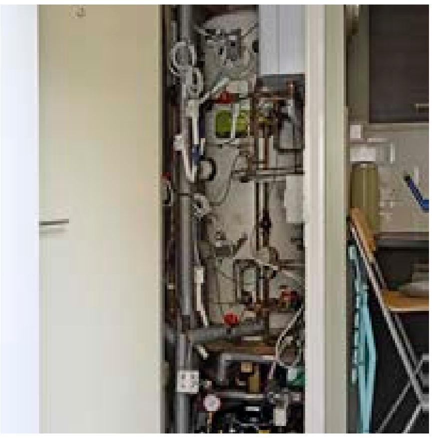


Figure 8.4 Shaftesbury Park: ventilation and hot water production system. The installation was an experiment and unfortunately did not pass the test of time and failed, mostly due to lack of maintenance

Two homes have PVs: one installed as part of the original retrofit (Culford) and one in the period since (Grove). No issues were reported.

8.1.3 Quality of maintenance services

In a few cases, it seems that maintenance efforts were either ineffective or inappropriate. To some extent this can probably be explained by the lack of familiarity and training to maintain the systems installed (e.g. bespoke heating system at Shaftesbury, 'combi' unit in Princedale). However, this also happened with systems which were relatively uncommon at the time of the original retrofit but should by now have become more familiar with, at least, large landlords (e.g. MVHR fans at Princedale Road). In some instances, residents reported that the team sent to look after the issue had no familiarity with the system, and had made the wrong recommendation or taken no action. For example, sending a gas engineer to resolve a space heating issue in a house with an air source heat pump (Princedale); recommending replacing the glazed doors with non-Passivhaus ones when re-calibration of hinges would have sufficed (Passfield).

As often found, there seems to be an issue of handover and organisational memory and staff turnover (sometimes due to companies changing hands). In most cases, the maintenance teams are not the ones originally involved and they may have little familiarity and expertise with the systems in these specific homes. This should be addressed with good documentation and training processes.

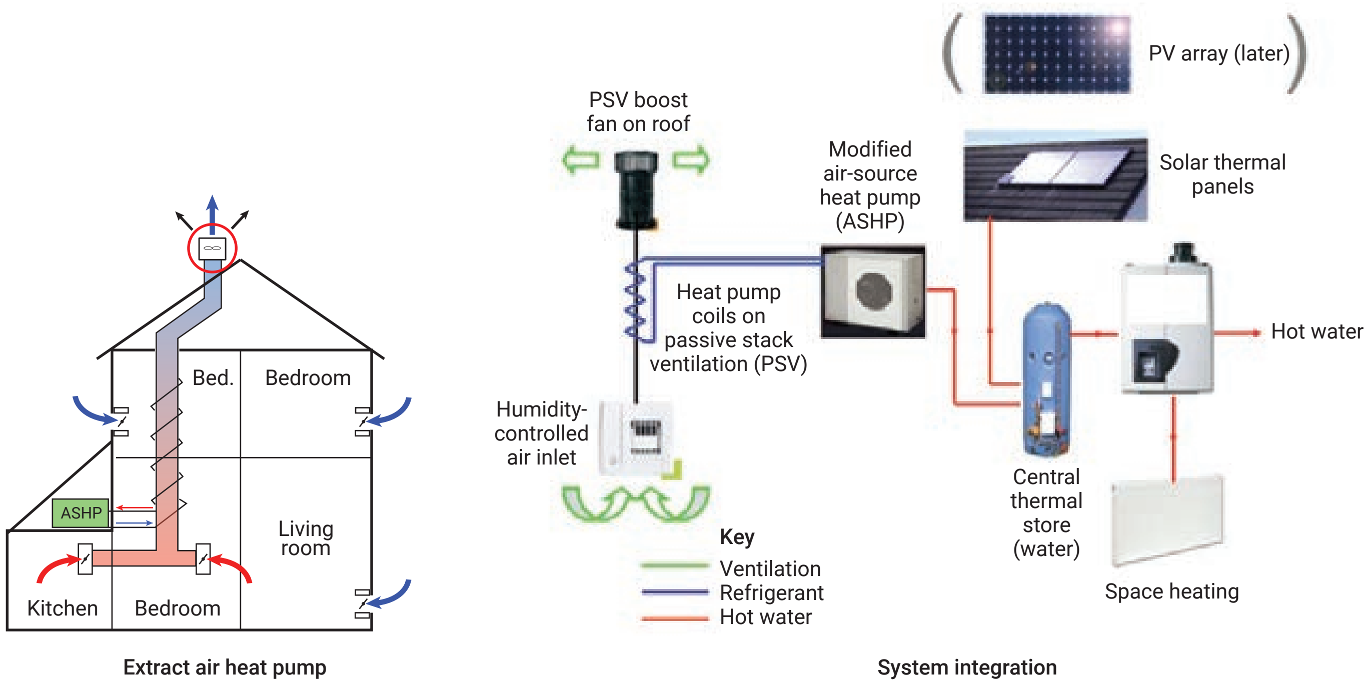


Figure 8.5 Shaftesbury Park: ventilation and hot water production system schematic

Figure 8.6 Princedale Road: solar thermal panel on the roof

Figure 8.7 Princedale Road: maintenance of MVHR fan within the Genvex combined unit (MVHR hot water cylinder and air source heat pump)

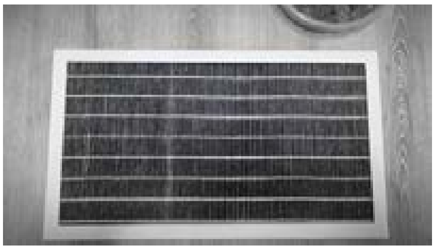


Figure 8.8 Princedale Road: MVHR filter clogged up with particles and pollution

8.1.4 Value of the BPE exercise

The BPE exercise helped uncover several issues (MVHR not supplying fresh air in Grove Cottage and not correctly balanced in Hawthorn (i.e. probably not extracting sufficiently/at all) which residents were not aware of, and in another instance (a faulty MVHR fan) it helped resolve the issue by providing additional resources and liaison with the housing association. It is unclear how long the issues would have remained otherwise (Princedale).

More generally, in many homes, the evaluator noted that the MVHR units probably needed some attention (e.g. rebalancing, changing of filters), for example by noticing it was noisy or seemed to be supplying too much/too little fresh air in some rooms. While under-performance or failure of other systems may already have been noticed by residents, it is possible that this is less the case for MVHR units. Routine maintenance of such units should be integrated into home maintenance routines, similar to the way annual boiler inspections are scheduled.

8.1.5 Observations on tenure

Most of the maintenance issues seem to have been reported in the rented homes rather than in the owner-occupied homes. In a few tenanted homes, residents reported finding it difficult to get repairs or maintenance carried out, with residents repeatedly raising issues and some systems simply remaining switched off (e.g. heating system at Shaftesbury).

It is possible that in the owner-occupied homes, especially because in this sample they are often occupied by building professionals, issues were spotted and/or acted upon more quickly. However, tenanted homes in this sample also have a tendency for more complex systems (e.g. the three combined systems mentioned above are all in tenanted homes), so this could be the explanation as much as the maintenance arrangements themselves.

8.1.6 User guide

Six of the ten homes reported that the handbook and/or introduction they had received at handover was 'somewhat good', 'good', or 'very good'. The others did not respond to these questions in the survey.

Only one house (Passfield Drive) had a user-friendly guide in the form of a poster pinned to the back of the utility door. This has worked well and, together with the recurring request for easier and simpler controls, it is a key take-away of this project, although it will only help with day to day operation and basic maintenance, not specialist needs.

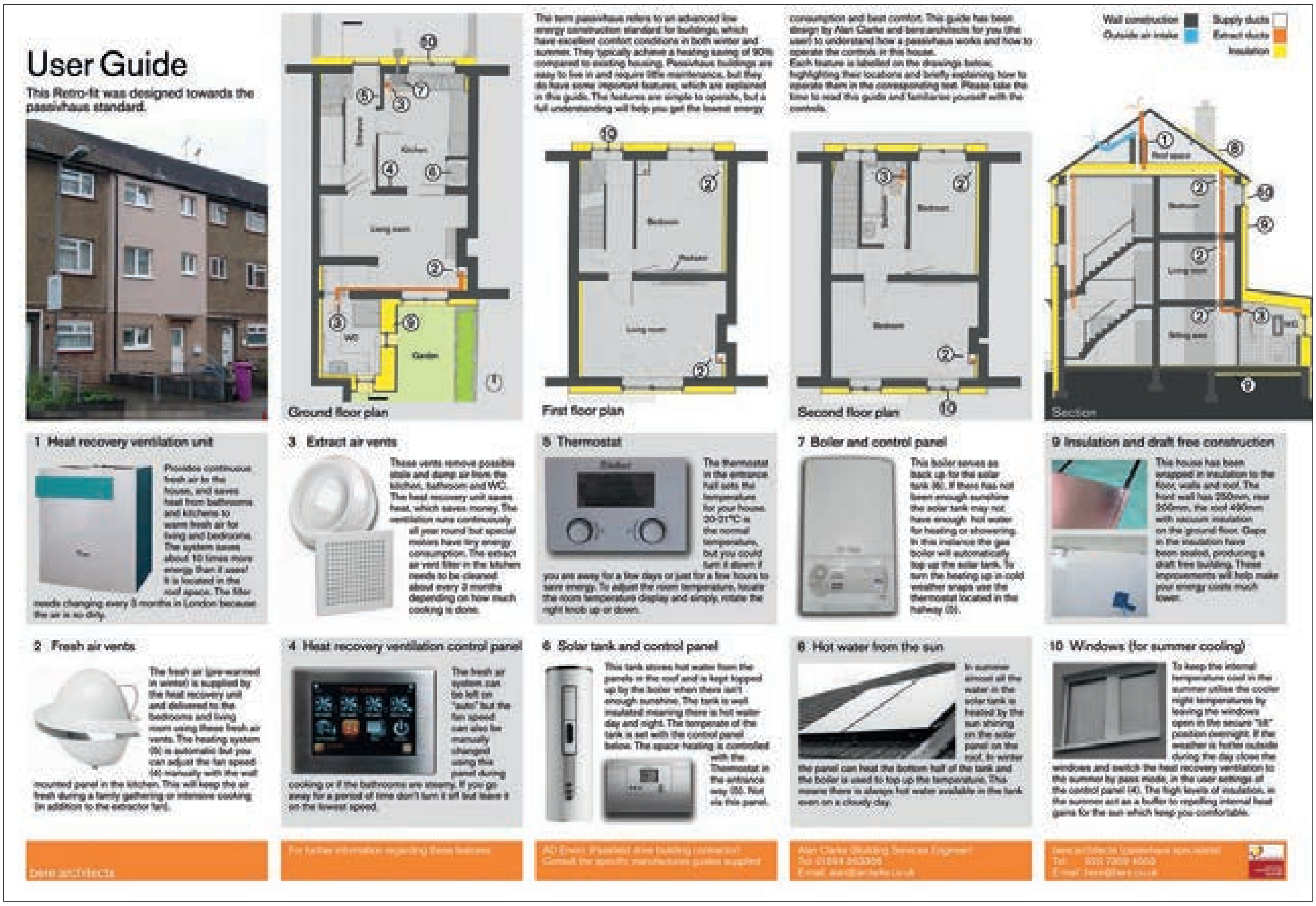


Figure 8.9 User Guide for Passfield Drive (Bere Architects)

8.2 Lessons learnt and recommendations

Most homes have performed rather well with minimal maintenance. Several have had very little repairs to their MEP systems in 10 years, which is remarkable.

This is of course to be balanced with some which have had partially failing systems, mostly when they were unusual in the UK or even bespoke, with difficult maintenance (e.g. Shaftesbury, Hawthorn).

No significant issues with water ingress or installation quality were noted in the original retrofit. Therefore, the widespread reporting of issues related to water ingress during the Retrofit Revisit (e.g. from gutters/roofs or small envelope issues) really stresses the importance of regular checks, to spot and act on issues before they become severe.

In future building performance evaluations (BPEs), it is advisable to consider the possibility of revisiting the properties at six-monthly and one year intervals to help address any issues that may have been identified at the time of the BPE, and to have a strategy for immediate rectification of issues when found during the BPE. In the properties where significant issues were found during the Revisit BPE, meetings were held with the housing association to help with immediate resolution and rectification, and to highlight the need for maintenance in the future.

8.2.1 Could it have been expected given the original BPE, including post-completion review?

Unfortunately it is well known that complex systems are often difficult to operate and maintain. Insufficient attention to routine issues such as rainwater goods is also, unfortunately, common.

On balance, considering how relatively uncommon PVs and MVHR units were at the time, there are relatively few issues reported, or just what would be expected for systems after operating for about 10 years.

Most of the issues identified in this revisit project seem to be rooted in insufficient or inappropriate maintenance, which is unfortunately common. Many large-stock owners (several of which are in this BPE study) provide only reactive maintenance (i.e. in response to defects reported by tenants) and they do not provide the routine, preventative maintenance (or even inspections) that supports timely intervention. These maintenance issues are known and could have been expected and its impact better mitigated perhaps.

8.3 Remaining areas of uncertainties/needs for further research

Maintenance should be combined with training where maintenance teams can assist tenants/owners to better operate and maintain their services and building fabric with clear explanation of what can be done by the occupant (changing the MVHR filters) and what cannot (e.g. repairing failing solar thermal equipment).

8.4 Reported repair and maintenance issues

In the table below, the symbols '+', '++' and '+++' are (loose) indicators of increased levels of complexity or innovation at the time of installation.

Key to colours:

- *Orange*: not working at all: broken, switched off, severe reported issue.
- *Yellow*: signs it's not working well, but doesn't seem to be major; or has been an issue in the past but was resolved by the time of Retrofit Revisit.
- *Green*: no reported issue.

Table 8.1 Reported repair and maintenance issues across the Retrofit Revisit sample

Property	Envelope	Internal and external water service (e.g. gutter)	Ventilation	Heating and hot water (boiler, heat pump and system)	Solar thermal	PVs
Owner-occupied homes: residents in charge of maintenance arrangements						
Culford Road (RftF)	Common repair issues, not related to the retrofit: water ingress to the top of the front parapet wall where the rendered top of the wall had cracked (repair and lead flashing have since been recommended). Apart from that, walls appear in good condition. Windows are in good condition. The folding sliding triple glazed doors appear to be leaking slightly.	Common repair issue, not related to retrofit: small water leak from the mains feed to WC cistern, which has since been replaced	++ MVHR. Appears to be functioning well and quietly, with no changes since installation 13 years ago	+ Boiler and tank for hot water, no reported issues. ++ Wireless heating control with an internet app has not worked well, causing small dis-satisfaction with resident but no significant operational issue.	N/A	++ PV – no reported issue
Grove Cottage (RftF)	In the years following the retrofit, some of the suspended floor insulation (where this abuts the external wall) was removed to reduce risks (moisture levels) in areas of sheep's wool/ joist timber adjacent to exterior brickwork. Remediation measures, and there have not been any reported issues since.	No reported issue	++ MVHR. The evaluator found that the unit has stopped supplying fresh air but was still extracting as expected; investigations are ongoing to discover the cause. The occupants were not aware of the issue and there was no indoor air quality monitoring before the RR, so it is unclear how long this has been the case.	+ Boiler and storage tank. The expansion vessel burst and caused a small flood a few years ago, resulting in remedial works to the hallway and bathroom areas and part of the suspended ground floor edges. This has long been resolved, but may be related to measured elevated mould levels. No reported issues since.	N/A	++ PV – no reported issue
Blaise Castle Estate	Generally good, but some emerging concerns about the stability of the phenolic EWI system, where outer panels have bowed slightly. It is suspected to be caused by solar gains, as inner panels are unaffected. Some wear on external door seals, particularly to tilt/slide doors and minor misalignment on bi-folding door sections. A hole had been made in the new flat roof membrane, probably at the time of the retrofit, but associated water ingress had been concealed due to a high performing VCL. A recent investigation (Jan 2023) revealed this had caused substantive damage, resulting in the replacement of the roof and timbers above the VCL (May 2023)	No reported issue	++ MVHR. No reported issue	+ Boiler and hot water cylinder; no reported issue to the boiler; cylinder was replaced under warranty due to premature failure in 2019.	N/A	N/A
Hensford Gardens	Small (flat) roof leak at two junctions in 2020/1, now resolved	No reported issue	++ MVHR – no reported issue	+ Combi boiler. No reported issue, though efficiency seems a bit low.	N/A	N/A

Table continues

Table 8.1 Reported repair and maintenance issues across the Retrofit Revisit sample (*continued*)

<table>
<tr><th>Property</th><th>Envelope</th><th>Internal and external water service (e.g. gutter)</th><th>Ventilation</th><th>Heating and hot water (boiler, heat pump and system)</th><th>Solar thermal</th><th>PVs</th></tr>
<tr><td colspan="7">Tenanted homes: housing association in charge of maintenance for envelope, and for all or most systems</td></tr>
<tr><td>Rectory</td><td>Minor maintenance and repair works needed (window seals)</td><td>No reported issue</td><td>+ Continuous extract ventilation, operating quietly; no reported issue</td><td>++ Controls reported as too complex and unclear</td><td>++ Solar thermal – no reported issue (following adjustments in the 1st year to rectify installation)</td><td>N/A</td></tr>
<tr><td>Princedale</td><td>Fabric, windows and loft hatches remain in good condition.
Roof issue related to gutter — see water services</td><td>Blocked roof gutter, leading to water penetration through the insulated roof/ceiling build-up. Full access to roof void is difficult so it is hard to ascertain whether the OSB layer has been affected</td><td colspan="2">+++ Combined MVHR & heat pump unit. MVHR had worked well since the original retrofit, but the fans stopped working around the start of the RR project. Now resolved but recommissioning, including control settings & sensors (e.g. possible fault in supply air sensor), would be beneficial following repairs.
Maintenance has become more reactive in recent years, with evidence that filters are not changed regularly.
Controls have proven to be complex and difficult to understand and operate efficiently as a result</td><td>++ Solar hot water collectors (drainback system) and storage. An issue was reported several years ago, which was promptly resolved. The system appears to have performed well since, with minimal maintenance. This was unexpected as this was a relatively unusual system</td><td>N/A</td></tr>
<tr><td>Hawthorn</td><td>Deterioration of fabric due to cement pointing, as well as leaky gutter and at the interface with solid floor (see Water services).
Roof void dry with sheep's wool insulation intact, but some roof membrane linings have come loose from rafters.
Small daylight holes noted near eaves but not unusual for unheated roof space. Evidence of small cracks in bedroom</td><td>Ongoing poor repairs and maintenance of guttering to North bay window, leading to build-up of moisture, moss growth and severe brick deterioration on the wall</td><td>++ MVHR, in need of rebalancing and cleaning: it is noisy in the bathroom and sounding as if on boost setting while very low flows are felt in other areas .
Responsibility for filters replacement has never been clarified between tenant and Housing Association. They are changed annually or on study visits by UCL; on first visit the evaluator noted they looked over-soiled.</td><td colspan="2">+++ Gas – solar thermal combi: the solar thermal element of stopped working at least 2 years ago. The tenant and Housing Association reported difficulty getting replacement parts and suitable engineer. This may be due to unusual manufacturer for the UK market.
Controls on Rotex Gas Solar Combi Unit appear complex but the house tends to run at comfort levels so resident does not interact with them</td><td>N/A</td></tr>
<tr><td>Shaftesbury Park Terrace</td><td>Good wall conditions, no signs of damage of maintenance issues.
Glazing showed the most wear and tear, with seals between sash window panes worn or missing. The bathroom window did not shut fully (this has since been adjusted)</td><td>No reported issue</td><td>+ Passive stack system – no reported issue</td><td colspan="2">+++ Bespoke hybrid solar thermal and an exhaust air heat pump acting as lead heating system, with gas boiler topping up the thermal store. In practice, and despite a responsive maintenance team, this proved too complex for effective operation and maintenance. This has not operated for several years. Boiler maintenance also proved a challenge, as it was an unusual unit from Germany, with little access to information and spares. The boiler is now used for hot water only, and local direct electric heaters for space heating.</td><td>N/A</td></tr>
</table>

Table continues

Table 8.1 Reported repair and maintenance issues across the Retrofit Revisit sample (*continued*)

Property	Envelope	Internal and external water service (e.g. gutter)	Ventilation	Heating and hot water (boiler, heat pump and system)	Solar thermal	PVs
Passfield Drive (RftF)	The rear garden door requires recalibration of one hinge. When the tenants raised the issue the Housing Association first suggested a window specialist who recommended replacing the entire door with a non-Passive House door. This was averted, with the architect and the tenant working together to programme a small maintenance intervention to adjust the door instead	No reported issue	++ MVHR. No reported issue, but CO_2 and RH levels are high in some rooms, indicating possible under-performance of the MVHR. The tenant has had difficulty getting the Housing Association to change filters. Over the years, they have sometimes been provided by the architect.	+ Gas boiler. No reported issue.	++ The solar thermal system has not been functioning since 2012	N/A
Wilmcote House	Small weathering signs on external façade. Access control to communal corridor doors, which are part of the thermal envelope, is reported to be regularly failing due to abuse. Some window restrictors appeared to have been disengaged, presumably to help with purge ventilation.	No reported issue	++ MVHR. The resident does not engage with the unit. It is maintained every 6 months by the landlord's service provider, including cleaning of the heat exchanger and filter replacement. However, there is likely under-ventilation, indicated by elevated CO_2 and RH levels; it is not known whether the installation has degraded over time, or there was an issue originally. In response to antisocial behaviour, on some floors windows in the communal corridors have had handles removed and are now operated by the landlord by request and in response to the seasons. The windows were not part of purge ventilation strategy so this is unlikely to have a major impact.	+ Electric heating and electric immersion heater for hot water. No reported issues.	N/A	N/A

Briefing 9: BPE techniques: airtightness testing

9.1 Trends across the case studies

9.1.1 Comparison of results from two testing techniques

Both blower door (BDT) and low pressure pulse (LPP, or 'Pulse') airtightness testing methods were applied to all 10 homes.

The aim of using both techniques was chiefly to compare results with the current body of data on both methods, including the formula for conversion of results at 4 Pa to results at 50 Pa. This holds relatively well on average.

The average absolute difference was of 14% between the BDT-tested q50 (i.e. air permeability ($m^3/h{\cdot}m^2$) at 50 Pa), and the calculated q50 using the Pulse-tested q4 (i.e. air permeability at 4 Pa). This is within the combined margin of uncertainty of 15% (CIBSE TM23 (2022) states 15% on the basis of a ±10% uncertainty, as per BS EN ISO 9972:2015 for the fan pressurisation method, and a ±5% uncertainty as stated by BTS for the LPP method).

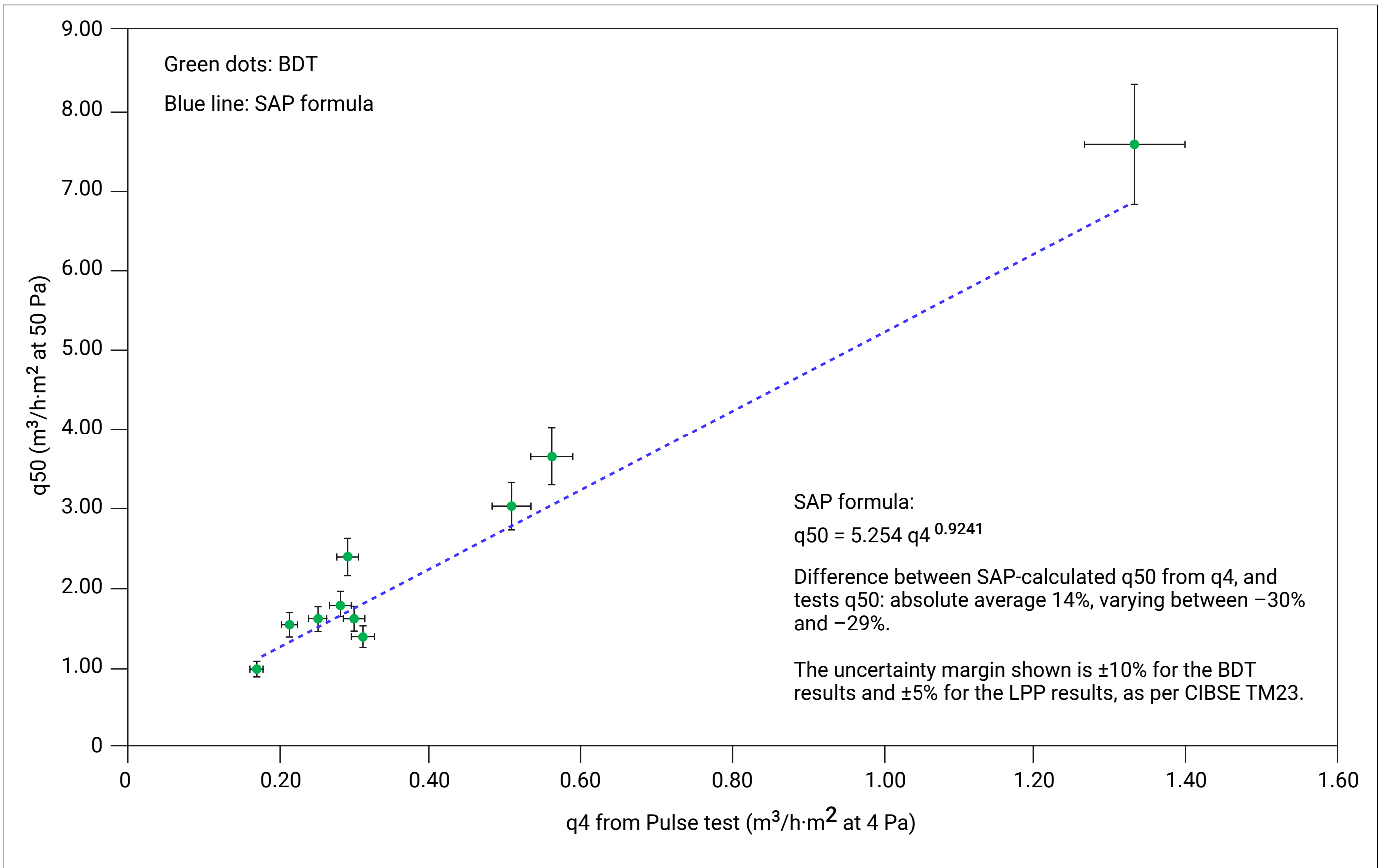


Figure 9.1 Relationship between q50 and q4: BDT q50 and SAP-calculated q50 against Pulse q4

The difference varied between –30% and +29%. This could have potentially important implications if results are used, for example, to discharge contractual obligations or in regulatory energy calculations. The homes with the largest difference between both methods are Grove Cottage (30%), which was only tested in depressure, and Blaise Castle, where there were difficulties mounting the blower door equipment in the door. Nonetheless, the range is very similar to the one available from literature (–35% to 27%, stated in CIBSE TM23 section 5.2). The BDT-tested q50 is on average higher than the calculated Pulse q50, and this is the case in 7 out of 10 homes.

It should be noted that, because air leakage values are low in this sample of homes, the relative error will be higher than on the average building stock (but similar to that in new-build homes): the absolute difference between calculated and tested values at 50 Pa is on average 0.33 $m^3/h{\cdot}m^2$ @ 50 Pa, varying from –0.41 to +0.74 $m^3/h{\cdot}m^2$ @ 50 Pa. The influence of individual elements is also likely to be more pronounced in this sample than on homes which are generally more leaky. This will influence the comparison between both methods, since the Pulse test takes account of the whole envelope (because the kit is located inside the home), while the blower door is placed in, typically, one of the doors, i.e. in effect, not testing leakage through that element.

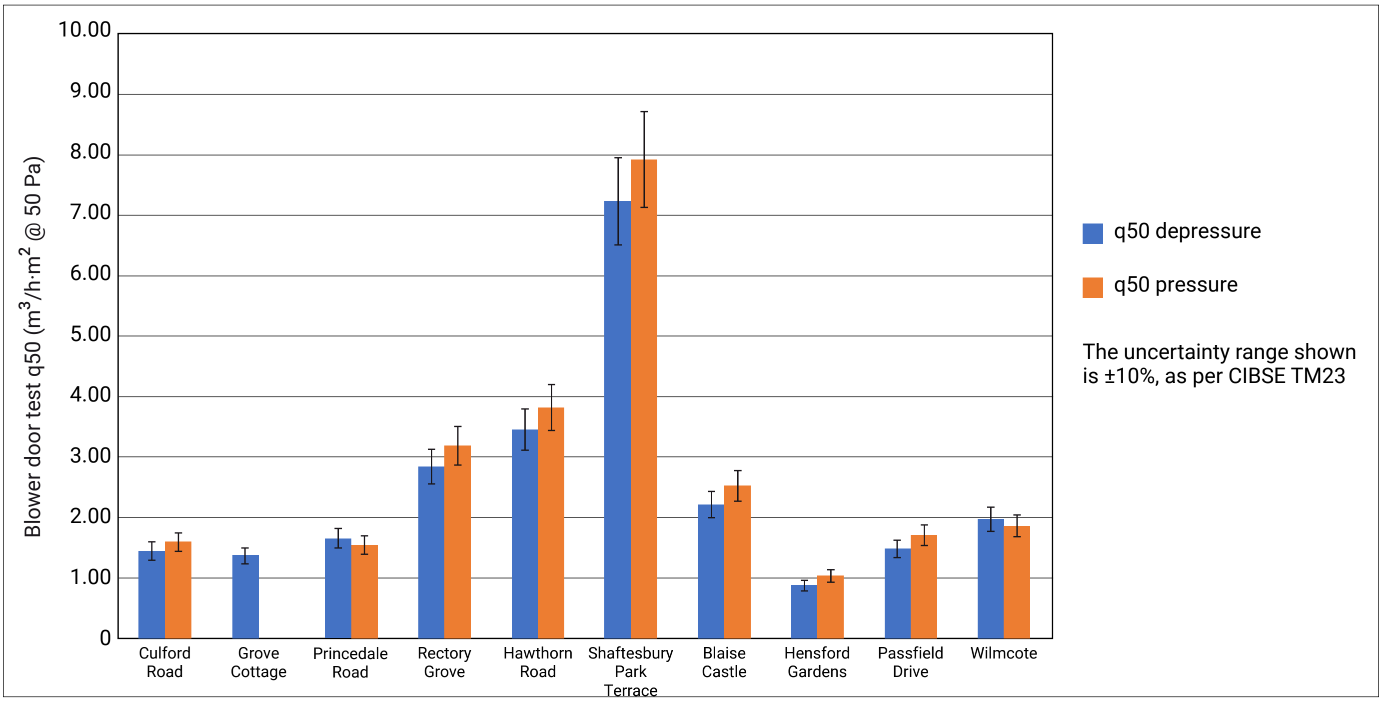


Figure 9.2 Pressurisation and depressurisation results

9.1.2 BDT: pressurisation and depressurisation results

During the BDT, 9 out of 10 homes were tested under both pressurisation and depressurisation. The stated BDT result in these reports is the average, as required for Passivhaus certification and as recommended by CIBSE TM23. The only exception is Grove Cottage, where only the depressurisation mode was used due to concern by the owner that a pressurisation test could damage the airtightness membrane (see details in case study CS3).

The average (absolute) difference in q50 between both modes is 9.3%, i.e. within the 10% uncertainty margin of the BDT method, varying between –15.4% and +6.6%. Results are generally higher (i.e. more leaky) in pressurisation mode: this was the case in 8 out of 9 homes. Only at Princedale Road and Wilmcote were the results in depressurisation mode higher than that in pressurisation; no obvious explanation was found as to why, e.g. at Princedale Road, the loft hatch, which did not fasten very tight, may have performed better in depressurisation, though this may also be the case in other homes (e.g. Shaftesbury Park).

9.1.3 Observations on testing methodology and practice

An independent airtightness expert (Paul Jennings) was involved in the testing of all homes except Grove Cottage. The purpose was to provide an independent oversight of the results, and observations on testing practice. At the time of the tests, the airtightness tester from BTS was experienced but not formally qualified (they now are), and the expert intervened on detailed aspects of implementation of the CIBSE TM23 methodology such as using an internal pressure tube, positioning of the internal and external tubes, and how many static pressure readings were required. In some cases he also provided advice, for example in the case of Wilmcote House which is somewhat complicated to test (see case study CS9 for details).

BTS carried out independent volume and area measurements as part of the testing, and these sometimes vary from the original sign-off measurements: in envelope area 1.9% as absolute average, up to –7%; and in volume 2.1% as absolute average, up to 6%. For comparison, between air leakage values, the original measurements were used in the Retrofit Revisit values, except where they are not available (i.e. in four homes for volume, and in three homes for envelope area). It is important to note that this uncertainty in measurement does not affect the conclusions: in all homes, the uncertainty in n50 and q50 related to volume or envelope area measurement, is smaller than the observed change in air leakage.

9.1.4 BDT and Pulse: comparative advantages and practical implications

One advantage of the BDT is its potential to be combined with or add value to other tests, in particular smoke tests and thermal imaging during pressurisation/depressurisation to identify sources of leakage.

It had been expected that some smoke tests may be carried out by the evaluator and tester, but they were not specifically requested and were not carried out. See section 9.2 below on lessons for future projects.

Thermal imaging was carried out during the blower-door air pressure tests in five properties. The fan in pressurisation mode creates a pressure difference between inside and outside, which makes the outside air rush into the building through the cracks that are present in the building envelope (floor, walls and/or ceiling). The outside air will quickly cool the location where an air leakage crack is present. This temperature difference will clearly show up in the thermal image as a cold spot or cold area, allowing the thermal imaging to accurately locate and map the air infiltration pathway.

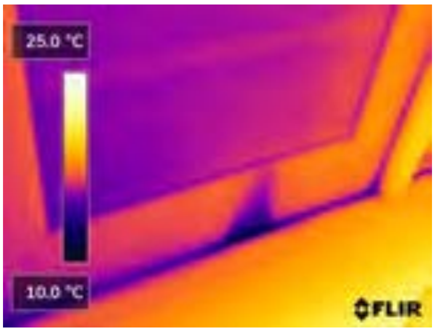


Figure 9.3 Princedale Road: air path under door due to failing door seal revealed by thermal imaging

Thermal imaging was used in five properties. In Princedale Road, the images showed a clear air gap in the door frame. Likely due to a loose door seal. In Grove Cottage, the images identified a wet area colder than the rest of the wall, hence visible in the infrared image. The camera also highlighted minor thermal bridges around the roof hatch and the junctions between ceiling and walls on the top floor. In Culford Road, the camera captured an area of dampness in the living room wall, an investigation resulted in the finding that a wc cistern had leaked very slowly into the fabric, something that was not previously visible to the naked eye. Thermal imaging can be a very powerful tool in investigating changes in surface temperature of air paths through the fabric, which might not always be visible. This helps in further assessing the state of the building fabric and allows planning remediation.

This has been identified in Princedale Road, for example, as shown in Figure 9.3.

To note, the relatively limited temperature difference (mild March) limited the observations somewhat.

9.1.5 Thermal images

The BDT tests also contributed to fungal and allergen testing, with ambient air sampling carried out before and after depressurisation, see details in Briefing 6 and Appendix 5.

A key objective in the development of the Pulse method is to provide results at 4 Pa, i.e. closer to ambient conditions and therefore expected to provide a better indication of infiltration. This could not be evaluated in this sample, as it would rely on additional methods such as tracer gas to estimate infiltration rates.

One advantage of the Pulse method is that it allows testing of the whole envelope, while with the BDT an element (typically the door, sometimes a window) is replaced by the fan installation. This may be particularly valuable in airtight homes, as in this sample, where the impact of a single element can be significant. Blower door installations are likely to be less airtight than a best practice window or door, and may therefore give a worse performing result than actual; as noted above, q50 results from the BDT test are higher than results from the Pulse test in 6 out of 10 homes (and on average across the sample), although this may also be due to the extrapolation formula to derive the q50 value.

Despite some time needed for charging the compressed air cylinders (unless compressed air tanks were brought to site), the Pulse test itself is faster. However, much of the time spent for a test is the preparation, which is the same in both methods.

In this sample, the blower 'door' was installed on doors in all cases. It proved a little difficult to install at Hawthorn Road, which has a narrow door and where the evaluator concluded that Pulse was better suited. It is unclear, however, whether in this case it had a significant impact on the results, as the difference between both test results is similar to the average across the sample (15.7%).

9.2 Lessons learnt and recommendations

9.2.1 BDT and Pulse

The differences between q50 from both methods are similar to that recorded in the literature, including CIBSE TM23 (2022), i.e. within 15% on average.

However, these differences are not insignificant (±30% on two homes), see section 9.3 on the need for further research.

9.2.2 Methodology

Despite available guidance, more detailed guidance and regular checks on implementation are useful, as well as good records of the testing methodology and dimensional measurements (areas and volumes), to ensure test results are robust, comparable, and can be interrogated in the future.

9.2.3 Air leakage investigation

One of the advantages of BDT is to use smoke testing or thermal imaging alongside, to identify sources of leakage. Smoke testing was not carried out systematically in this study, due to a weakness in the scope, which did not explicitly ask for it nor identify the responsible party (i.e. evaluator or airtightness tester). Retrospectively, this should have been made more explicit in the brief, particularly where differences in results were observed compared to the original test. This omission is partially due to the relatively short preparation period from start of the project to the tests being carried out. It is also partially explained by the relatively short increases in air leakage, which evaluators in many cases attributed to increased leakage from doors and windows, without the need for more investigations. This explanation does seem likely, due to physical observations (e.g. seals missing, movement on doors or windows), but nonetheless the absence of smoke tests could have confirmed it or find additional sources of leakage — an additional measure which could have been interesting would have been to test with sealing around windows and doors, to check that hypothesis.

In addition, thermal imaging is a great tool to identify air gaps in the fabric that are not always visible to the naked eye.

Based on these observations, the independent expert recommends that a specification for implementing CIBSE TM23 (2022) should be produced, to improve the comparability between airtightness tests, particularly when they are carried out by different testers.

Additional recommendations, including those based on observations from the evaluators (who had to coordinate the tests with residents include):

- Make sure that the airtightness tester is always equipped with something to identify the location of leaks, e.g. smoke pens in a blower door test, a fan or leak checker in the case of Pulse tests, or a thermal camera (if temperature differences with the outside allow).
- Make sure that the thermal line is adequately understood by the tester in advance of the visit. It is particularly critical in a large development where the outline can comprise of private and common parts.
- Make sure that the tester discusses the practicalities of the test before getting to the property by way of reviewing photos and speaking with the occupant/relevant consultants/contractors.
- Make sure that the tester comes equipped with all required tools adapted to the condition of the property so that vents can be sealed as necessary (high levels etc).
- Note that in existing, occupied, homes, it can be much more difficult than in new build ones to investigate the source of leaks, due to the presence of furniture etc.

9.2.4 Liaising with residents

- It is easier to carry out an air pressure test on the back of a retrofit building project than on occupied homes, especially if the property was vacant during the works and still is for the air pressure test. Accommodating these tests in occupied properties demands more planning and consideration for the occupants.
- It is important to clearly explain to the building occupant what an air pressure test entails. In particular:
  - the requirement to seal the primary ducts on the outside
  - closing all external doors and windows
  - turning-off purpose ventilation, e.g. MVHRs, extract fans etc.
  - the need to use some electricity to power the blower door fan and approximately how much, so that the energy cost may be estimated to reassure the occupant
  - the need to use a few tools
  - the duration of the test and investigations if the measured performance raises concerns or questions.

9.3 Remaining areas of uncertainties/needs for further research

One of the reasons for the interest in testing at low pressure is to obtain results closer to ambient conditions: the expectation is that the results are more representative of infiltration in 'normal conditions', providing another angle on building performance compared to the 'stress test' at 50 Pa. A better understanding of infiltration rates at ambient conditions would be very beneficial, both from a heat loss and air quality perspective, alongside a investigation of how Pulse results, at 4 Pa, relate to ambient infiltration. This could not be explored in this study, but a next step could be to carry out further tests such as tracer gas testing.

Continued and more widespread side by side testing using blower door testing and Pulse testing would be beneficial to better understand the sources of the differences, whether it is related to the techniques themselves, their application in practice in a wide range of conditions and housing typologies (including margin of uncertainty), or the SAP formula used to convert q4 results to q50. As airtightness testing becomes more common in existing properties, through an understanding of its importance in retrofit and encouraged by the new air permeability input in RdSAP, it could become useful to have a national register of properties that have been tested across the country. Making this data available and accessible could be instrumental for the industry forward learning curve as well as for researchers policy makers, and could be aligned with the plans for digitalisation of the EPC register.

Briefing 10: BPE techniques: thermal and moisture evaluation techniques

Figure 10.1 Evaluator installing monitoring equipment in Princedale Road

10.1 Trends across the case studies

10.1.1 Techniques applied to all houses

A number of thermal and moisture investigations techniques were applied across all homes in the sample:

- *Visual inspections*: for signs of moisture-related fabric degradation, internal condensation and mould.
- *SmartHTC*: a method developed by BTS to estimate the heat transfer coefficient (HTC) of a home, based on measurement of energy use and temperature data over a relatively short period of time (ideally at least three weeks). This was deployed across all Retrofit Revisit homes. The results are available in all homes except one, where sensor data was not logged. This method is part of a series of innovative techniques (many tested as part of the SMETER trial[5]) aiming to determine HTC without the need for co-heating tests, which are more expensive, disruptive and time-consuming.
- *Mould risk score*: a method developed by BTS, working with SOAP and Loughborough University and based on measurement of temperature data (over at least three weeks).
- *SOAP survey*: while qualitative and indicative only, the survey includes two questions to residents, about whether there is the presence of mould and of condensation in the home.

10.1.2 Additional tests to five houses

While levels provide an indication of the severity (or not) of ambient fungal and allergen presence in the home, the species analysis can provide an indication into the likely causes, e.g. fabric degradation, internal sources such as pets.

Five homes were subjected to an additional series of tests; the homes were selected on a combination of criteria including:

- the presence of features or details which were deemed of interest for industry, in discussion between evaluators, the Steering Group and experts e.g. insulation which was or not vapour permeable, insulation applied with or without cavity, insulation to underside of timber joists
- accessibility of the features
- approval of residents.

10.1.3 Detailed techniques

These included:

- Heat3D (method developed by BTS) and heat flux plate *U*-value measurements; Heat3D is intended to be simpler to deploy at scale than heat flux plate methods

[5] https://www.gov.uk/government/publications/smart-meter-enabled-thermal-efficiency-ratings-smeter-technologies-project-technical-evaluation (accessed 22.04.24)

- fabric moisture content tests, and associated hygrothermal modelling (2D)*
- 'mould' tests*, i.e. fungal and allergen levels and species analysis (i.e. DNA analysis), in ambient air (before and after depressurisation) and on surfaces (i.e. swab tests). While levels provide an indication of the severity (or not) of ambient fungal and allergen presence in the home, the species analysis can provide an indication into the likely causes e.g. fabric degradation, internal sources such as pets.

It must be noted that 'moisture' issues include a wide ranging, complex and interlinked number of issues, hence the need to apply a range of techniques if the topic is to be examined in depth, with issues identified where they occur, and likely causes put forward. This is illustrated in the following figure, showing the range of techniques available if a comprehensive integrated approach is deployed; most were applied to the homes subject to detailed tests, but not all, and only over a relatively limited tests.

* For details on the fabric moisture tests, fungal and allergen tests, and hygrothermal modelling, see separate report by UCL on the methodology, techniques, and findings.

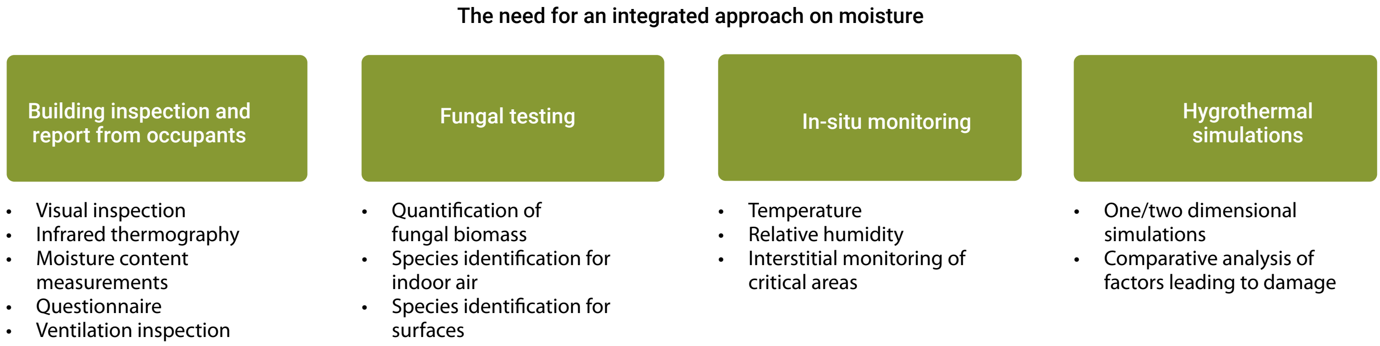


Figure 10.2 Need for an integrated appoach on moisture

10.1.4 Additional observations

The following observations on the building performance evaluation techniques can be made. The performance results from all these techniques are detailed in the following briefings:

- Briefing 4: Thermal layer — for moisture content and degradation of insulation
- Briefing 5: Construction details
- Briefing 6: Indoor environmental quality — on ambient mould.

10.1.5 Ambient mould

Most of the homes performed very well against the BTS mould risk indicator, with internal conditions generally within the recommended temperature and RH ranges: see details in Briefing 6 on IEQ. However, the more detailed tests carried out by UCL on ambient mould (including levels and species analysis) revealed potential issues in some homes. Some of these issues seem unrelated to the building fabric and ventilation (e.g. presence of pets); others were attributed to past issues which would have could fabric damage at the time and may still result in mould in ambient air or within the fabric (e.g. water penetration from the outside, or damage from internal water leak).

The methods therefore seem complementary, with the BTS mould risk score more suited to routine monitoring, focusing on ambient mould risk related to internal moisture generation and ventilation, and the UCL set of techniques more suited to deeper investigations, if an issue is found or for a more thorough assessment of mould risk from a number of possible reasons, including fabric degradation due to water damage or moisture transfer through the fabric.

10.1.6 Fabric moisture

In some cases, fabric deterioration was visible (e.g. mostly Hawthorn, and localised issues in other homes, e.g. Blaise Castle). The detailed techniques therefore added to the analysis.

In others, the detailed techniques were essential to evaluate the performance, which could not be done by visual inspection only, e.g. moisture content in joists, moisture content in cavities.

The detailed techniques themselves were not always sufficient to determine with certainty the absence of problems, or the cause of the issues found: in those cases, more intrusive tests would have been required e.g. lifting of floor boards, physical samples of the fabric.

At Hawthorn, while the physical observations and modelling led to some conclusions about performance issues and risks of fabric deterioration, the modelling and its conclusions relied on assumptions about the brick properties. On site measurement of brick porosity would greatly help (Karsten tube test), as the assessment risk is dependent on these assumptions.

Carrying out ambient mould tests before and after depressurisation was also useful: in 1 of the 3 homes where this was carried out, mould levels are much higher after depressurisation, which indicates mould growth within the fabric layers, 'sucked' into the room’s ambient air through the depressurisation. Species analysis supports this, with the sample showing more species typically linked to fabric degradation (Grove).

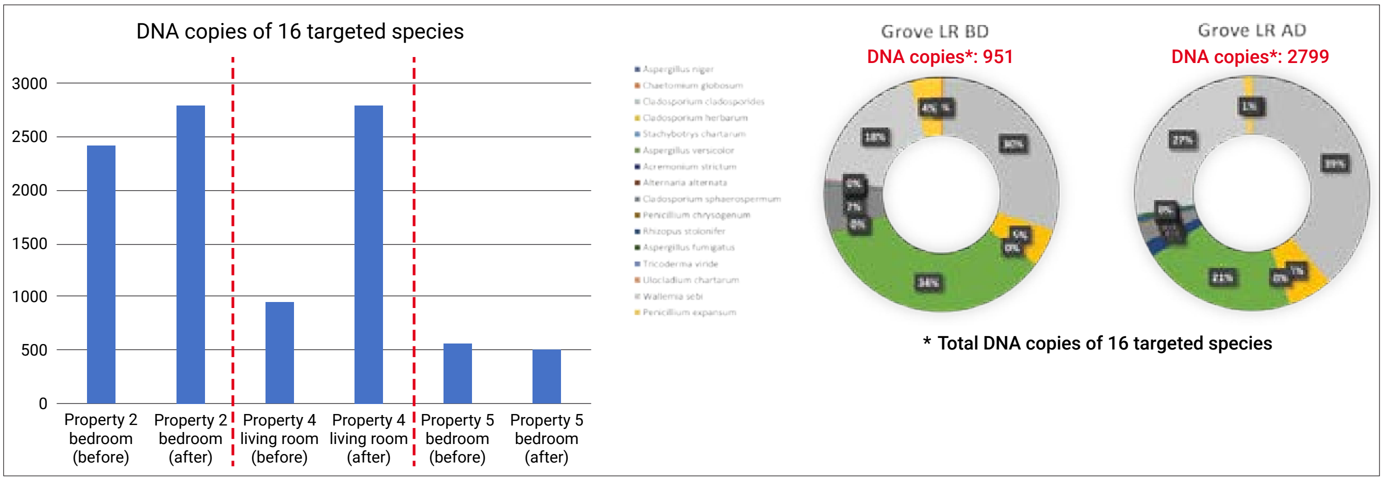


Figure 10.3 Comparison of air sampling before and after depressurisation

10.1.7 SmartHTC

The SmartHTC values were compared with the design values (from PHPP or SAP calculations): see Briefing 4: Thermal layer. No comparison is possible with tested HTC values from co-heating tests, as this was not carried out as part of this project (due to costs, timescale and disruption to residents), nor at the time of the original retrofit. However, the SmartHTC method was evaluated independently through the SMETER programme; there is reasonably good agreement of measured HTC with design values across most homes, and likely explanations in 3 of the 4 homes showing large differences between design and measured HTC values: see Briefing 4: Thermal layer. Only in one home (Grove Cottage) is the difference unexplained, and may be due to either a yet unidentified fabric performance issue, or the testing methodology.

10.1.8 Fabric *U*-value

Details of the *U*-values obtained through both methods are shown in Briefing 4, 'Thermal layer'. *U*-values were obtained for seven elements across four homes, of which two elements were tested using both methods. The following observations can be made:

- The sample of tests does not allow a conclusive comparison between both methods.
- The uncertainty range (±0.1 W/m^2·K) of the Heat3D method may limit its usefulness when it is applied to very well insulated elements (e.g. within 0.1–0.15 W/m^2·K, i.e. well within the range of uncertainty). However, it is useful as it indicates the uniformity (or otherwise) of insulation.
- Across the tested elements, there are non-negligible differences between the tested *U*-values (whether with the Heat3D or heat flux plate method) and the design *U*-values. Unfortunately, as there were

no similar tests at the time of the original retrofit, deviations cannot therefore be attributed to degradation, or installation. However, the other tests carried out (e.g. moisture content) do not indicate fabric degradation, and the uniformity found in Heat3D also indicates a good installation and no subsequent degradation.

10.2 Lessons learnt and recommendations

As some of the techniques used in this study are themselves innovative, conclusions are sometimes limited on the performance results they show, since there is a margin of uncertainty. This was expected, with the intention that this study adds to the body of evidence on the testing techniques, as well as on building performance itself.

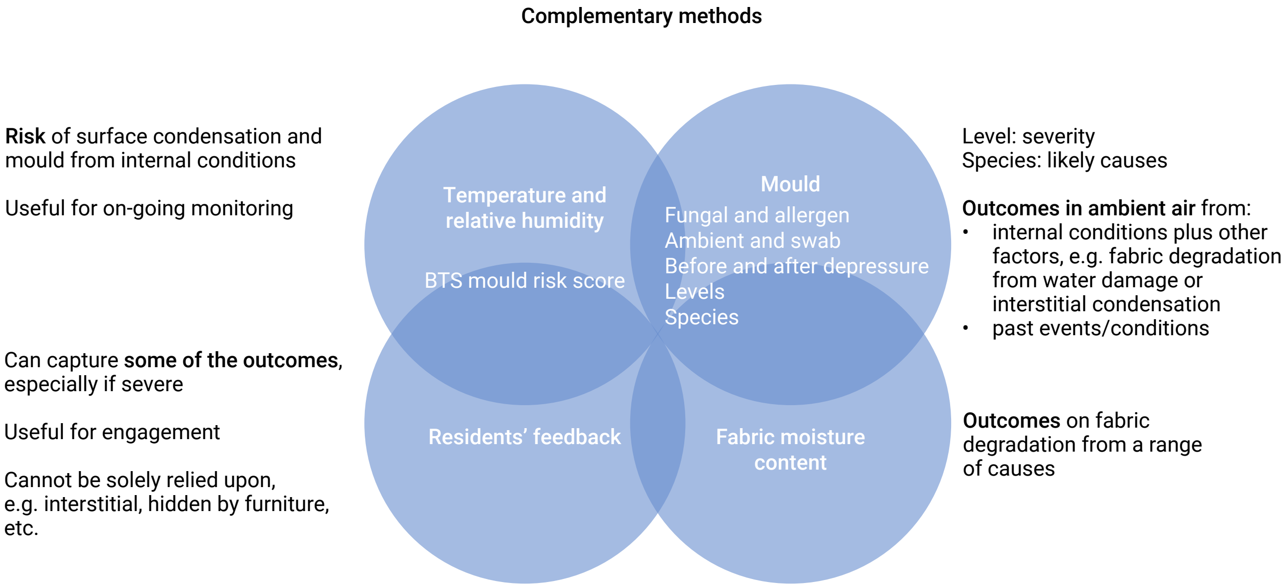


Figure 10.4 Moisture and mould: testing and risk techniques

The techniques applied showed good complementarity on the issue of ambient and fabric moisture, and can add value in different contexts, i.e. routine monitoring versus detailed investigations. Systematic testing of the ventilation systems may have been useful, especially where high RH levels were found, to identify whether underperforming systems (e.g. unbalanced or blocked) were the cause.

The application of *U*-value testing was inconclusive, in part due to the relatively small sample, the absence of comparators (e.g. past heat flux plate data) and the uncertainty margin of the Heat3D method. The uncertainty range of the Heat3D method may make it more suited to poorly insulated elements e.g. to understand the baseline performance pre retrofit or where retrofit U-values are not expected to be below

0.2 W/m^2·K, or those where a qualitative assessment is needed, for example to assess and visualise the continuity of insulation across an element.

10.2.1 Could it have been expected given the original BPE, including post completion review?

Not applicable — this is a briefing on the evaluation techniques, not building performance

10.3 Remaining areas of uncertainties/needs for further research

As in 10.2 above, further studies should be carried out to add to the body of evidence about the various techniques used in this study, and their comparative advantages.

In addition, in the case of mould levels and species, as a relatively new technique it is expected that future developments will add to the usefulness of the technique, especially for practitioners. In particular, it would be useful to build a better understanding of possible impacts on health e.g. threshold levels, and clear recommendations when certain species are found.

Case studies

CS1 Blaise Castle

Blaise Castle

Companies involved in the 2023 BPE

Four Walls Consultants
Original designer and evaluator

UKCMB
Ambient and surface mould sampling and analysis

Build Test Solutions
Pulse and blower door test, SmartHTC and mould risk indicator

Original retrofit designer
Ian Mawdit

Property age
Post 1919 (1962)

GIA area
202 m^2 (post-retrofit) 154 m^2 (pre-retrofit)

Typology
Detached

Occupancy
Family. Owner-occupier; two adults

One-off property retrofit; date of completion: June 2013

Overview of the original retrofit

Fabric strategy

Insulation strategy: Hybrid approach: cavity walls infilled with EPS with phenolic EWI over and XPS below ground to foundations. IWI used where EWI was not possible. Solid ground floor either replaced with insulated slab or Aerogel-backed board applied to retained slab. Existing roof filled with cellulose insulation; flat/warm roofs treated with PIR insulation.

Thermal bridges: EWI extends and abuts with ground floor/foundation insulation. Original Finlock concrete gutters removed (Figure CS1.2), allowing roof eaves and insulation to extend and abut with EWI. Original concrete balcony removed and replaced with ground-supported balcony. The existing porch was insulated to bring it within the thermal envelope.

Airtightness: The air permeability was reduced during the retrofit through targeted measures, such as: a sand/cement render slurry coat prior to EWI; air-sealing tapes around openings and junctions (Figure CS1.2); grommets to any services penetrations; air-sealing foam around original intermediate floor joists that penetrated the cavity.

Services

Heating and hot water: Original gas boiler (<2 years old at time of retrofit) was retained. A new multi-zone heating system replaced the original system, along with the installation of a new 210 litre vacuum-insulated hot water cylinder.

Ventilation: A 300 m^3/h, MVHR system was installed as part of the retrofit, connected to rigid steel ducting throughout.

Publication of reference

'LEBD – Bristol Retrofit' *Passive House+* Issue 14

Fabric improvement description and values

Walls: 2 × 60 mm staggered EWI panels to existing and new walls (Figure CS1.3) with *U*-value range between 0.14 and 0.12 W/m^2·K.

Floors: Rebuilt floor slab with 100 mm phenolic beneath screed with a *U*-value of 0.13 W/m^2.K. Aerogel to retained slab achieves a *U*-value of 0.25 W/m^2·K.

Roofs: Main roof (cold loft) infilled with 400 mm cellulose to *U*-value of 0.10 W/m^2·K. Flat roofs applied 2 × 60 mm PIR to achieve 0.14 W/m^2·K.

Windows and doors: New triple-glazing windows throughout (*U*-value 0.8 W/m^2·K) and composite doors (*U*-value 0.9 W/m^2·K) installed within EWI layer.

Insulation properties: Mainly vapour-closed. IWI is used in the utility room, which is wood fibre/diffuse open.

Overview of the revisited retrofit

Figure CS1.1 Front elevation prior to render or cladding

Figure CS1.2 Original Finlock gutter; gutter being cut off; eaves extended with insulation between rafters; EWI interface with roof insulation in new soffit zone

Figure CS1.3 Recent exposure of EWI (April 2023) above balcony section undergoing repairs

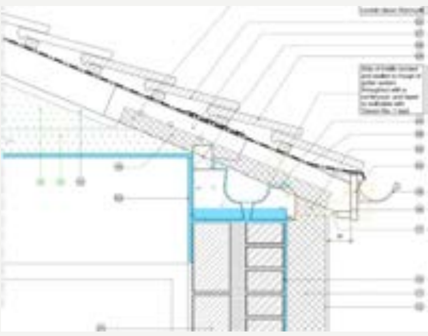


Figure CS1.4 Retrofit treatment

Significant changes since the original retrofit

Occupancy: No change

Building: Hot water cylinder replaced in 2019 (see below). Flat roof repairs carried out in 2023 (see below).

Envelope

Overall performance: The fabric still performs well despite some emerging concerns about the stability of the phenolic EWI system (see rectifications). The HTC measured was approximately equivalent to the design (SAP) value. *U*-value found to perform similar to design calculations.

Airtightness integrity: There is a small increase since original retrofit of 0.52 $m^3/h{\cdot}m^2$ @ 50 Pa, which is due mainly to wear on external door seals, particularly to tilt/slide doors and minor misalignment on bi-folding door sections (see IR images).

Further investigations: Some degradation has occurred to the EWI, where outer panels have bowed slightly (Figure CS1.3). It is suspected to be caused by solar gains as inner panels are unaffected. The impact on performance has not been evaluated. The thickness of the roof/loft insulation results in a low *U*-value. However, this also results in a cold loft with high RH in winter (RH is above 85% during colder periods). Swab tests taken by UCL from the rafters within the loft void confirm a high concentration of mould spores present (*Aspergillus versicolor*). This finding will trigger an intervention to increase the level of ventilation in the loft.

Rectifications needed: A small hole had been made in the new flat-roof membrane, probably at the time of the retrofit, but the associated water ingress had been concealed due to a high performing VCL.

A recent investigation (January 2023) revealed this has caused substantive damage, resulting in the replacement of the roof and timbers above the VCL (May 2023).

Key lessons learned: Check performance and stability specifications when using phenolic insulation material for EWI applications.

Be cautious when specifying thermal specifications too low, where there will be a cold void.

Figure CS1.5 Cellulose roof insulation covering the MVHR ducts

Services

Heating: There have been no modifications since the original retrofit. The system delivers the desired comfort levels, although efficiency is slightly compromised due to under-sized radiators. ASHP planned for 2024, which may require some radiator sizes to be increased.

Hot water: The domestic hot water cylinder was replaced under warranty due to premature failure in 2019. The replacement cylinder is vacuum insulated and has a single coil (the original solar hot water option now abandoned). Interventions were made in 2022 to improve efficiency, see 'Services strategy' below (p98).

Ventilation: The MVHR system was originally commissioned in December 2013, and further fine-tuned in April 2015. There have been no adjustments since then and the system has been maintained in continuous operation since installation, including during unoccupied periods as the property is in a radon area (radon accumulates if MVHR is off).

Figure CS1.6 MVHR unit and related ducts

Energy performance (2022 values):

- EUI: 45.3 kW·h/m^2 per year
- Gas: 5910 kW·h per year
- Electricity: 3244 kW·h per year
- Space heating demand: 22.1 kW·h/m^2 per year

Indoor environment: Conditions monitored through Feb and March 2023 in three rooms: main bedroom, living room and kitchen. No issues found with temperature, RH or CO_2 — see also (see Briefing 6).

User feed-back: The owner/occupier/evaluator purchased the property to demonstrate the potential for a fabric-first deep retrofit. By living in the property both pre- and post-retrofit, they appreciate the challenges in undertaking such a project, but have detailed knowledge about the building and how to optimise its performance.

Description of the BPE approach: Core BPE tasks undertaken with some additional tests and measurements performed, which included thermography; MVHR measurements, ambient and surface mould testing.

Table CS1.1 2023 BPE findings: details

	Pre-retrofit (2011)	Original retrofit (2014)	Retrofit revisit (2022)
Annual energy use	Gas: 19349 kW·h/year Elec: 4120 kW·h/year	Gas: 4437 kW·h/year Elec: 3181 kW·h/year	Gas: 5910 kW·h/year Elec: 3244 kW·h/year
Airtightness levels	18.4 $m^3/h{\cdot}m^2$ @ 50 Pa	1.85 $m^3/h{\cdot}m^2$ @ 50 Pa	Blower door test: 2.37 $m^3/h{\cdot}m^2$ @ 50 Pa Pulse test: 0.29 $m^3/h{\cdot}m^2$ @ 4 Pa (estimated 1.67 $m^3/h{\cdot}m^2$ @ 50 Pa)
Fabric moisture tests	None performed		
Thermography			See pictures at the end of the report, with relevant observations throughout this briefing
HTC	SAP-predicted (calculated) HTC of 839 W/K	SAP-predicted (calculated) HTC of 169 W/K	SmartHTC (measured HTC) was 166 W/K (–30/+33) (remarkably close to the original retrofit calculated SAP prediction ~2% difference)
Mould risk			Zero risk in all rooms evaluated according to BTS mould risk indicator. However, UCL samples found a high level of fungal contamination (*Aspergillus versicolor*) on the roof rafters. This is backed-up with RH monitoring conducted during March/April 2023, which showed higher-than-expected RH, with a mean of 69%, and exceeding 85% on colder days.
Walls	1.4 $W/m^2{\cdot}K$	0.14 to 0.12 $W/m^2{\cdot}K$	0.14 $W/m^2{\cdot}K$ (measured 2019)
Floors	0.57 $W/m^2{\cdot}K$	0.13 $W/m^2{\cdot}K$ (re-built) or 0.25 $W/m^2{\cdot}K$ (existing improved)	Not measured
Roofs	0.7 $W/m^2{\cdot}K$ (pitched) 4.65 $W/m^2{\cdot}K$ (flat)	0.10 $W/m^2{\cdot}K$ (pitched) 0.14 $W/m^2{\cdot}K$ (flat)	0.11 $W/m^2{\cdot}K$ (pitched, measured 2019)
Windows and doors	2.4 to 3.2 $W/m^2.K$	0.8 $W/m^2.K$ (windows)	

Indoor environmental performance

(See also Table CS1.1 and Figure CS1.8.)

Temperature (March 2023): Mean internal temperature (MIT) was maintained above set point temperature (18 °C) during daytime occupied periods. At night (23:00 to 07:00) the heating sets back to 16.5 °C. The MIT fell below the 18 °C threshold during these periods for 10% of the time, with a minimum MIT of 17.2 °C.

Relative humidity (March 2023): The mean %RH values ranged between 48 and 51% for the bedroom and living room, respectively, and 57% for the kitchen. The max. RH recorded was in the kitchen at 63.2%. The performance criteria (Approved Document F) for a 24-hour rolling mean below 85% and a weekly rolling mean below 75% were not exceeded in any room at any time.

CO_2 concentration: The 8-hour rolling mean (applied to the bedroom CO_2 data for occupied hours) was 898 ppm during March 2023. This is within the threshold applied for bedrooms of 1240 ppm based on a steady-state CO_2 concentration whilst sleeping in a room with a ventilation rate of 3.5 litres per second per person (this being the background ventilation rate in dwellings — Approved Document F). The ventilation rate in the bedroom during the occupied period was measured at just over 6 l/s (3 l/s per person). The exceedance above the threshold was for 5.5% of the occupied hours, or 14 hours in total. In summary, the CO_2 concentration is within thresholds, and within expectations for the ventilation rate and level of occupancy.

Commentary on physical findings versus user feedback: The conditions in the home are considered by the occupants to be comfortable. Temperature in winter is maintained to their desired comfort setting, and the application of EWI and use of TG windows has helped to reduce the pre-retrofit overheating conditions.

Figure CS1.7 Rear elevation with external wall insulation and balcony

Services strategy

Hot water: The gas energy used for hot water was 1811 kW·h/year in 2014. The cylinder was replaced in 2019 with a more efficient unit, which reduced the hot water energy to 1563 kW·h/year in 2022. In June 2022 the cylinder thermostat was reduced to 50 °C (with a weekly one hour at 60 °C for sterilisation), arising from the rising energy cost crisis. This intervention will also be reflected in the reduced energy between 2014 and 2022 (see also Figures CS1.9 and 1.10). *Note*: hot water energy demand is estimated by applying the average gas energy use during the summer months (minus the metered data for gas hob use) across the 12-month calendar year.

Space heating: The gas energy for space heating for the first year post retrofit (2014) was 2254 kW·h/year[1], equivalent to 12.5 kW·h/year (accounting for boiler efficiency), and is slightly less than the SAP-calculated space heating prediction of 13 kW·h/year. The energy used for space heating has increased over the last few years and, in 2022, was 3983 kW·h per year (22.1 kW·h/m^2 per year).

Electricity: The electrical installation is fully sub-metered. The highest consumption circuits are non-regulatory socket circuits, with the ground floor being the highest consumer. The two occupants work from home full time, so there will be atypical IT energy patterns compared to other homes. Interventions were made during 2022 to reduce energy use for this circuit. It was found that the standby power for IT equipment and other electronics on the same circuit amounted to 430 kW·h/year. These savings, made by fitting simple plug-in timers, are approximately equivalent to the annual energy use for operating the MVHR system, which typically uses 330 kW·h per year, and the boiler pump/ancillary circuit which typically uses 115 kW·h per year.

Ventilation: Measurements of the MVHR flow rates and specific fan power performed during March 2023 were found to match or better the performance values from either the design or the manufacturer's declared values. Air flow rates for the normal use setting were measured to be 175 m^3/h and for other, higher occupancy, settings, 235 m^3/h and 275 m^3/h. The imbalance between intake and exhaust is 5.7%, which is within the recommended 10%. The specific fan power in normal setting was found to be 0.77 W/l·s^{-1}, which is the same value declared by the manufacturer.

Renewables: No renewables at present. There was a plan to install solar thermal, but this has since been abandoned owing to technological advances with solar PV. There is a plan to install a 5.7 kWp PV array, connected to a 10 kW·h battery store.

User feedback

Questionnaire findings

Score was 96%, so the house scores very well[2]. Comfort conditions in winter reported as excellent. In summer, the responses suggest an average benchmark score for temperature and air movement. Some drawbacks were:

- Location to amenities and local transport.
- Utility costs due to recent £/kWh increases.
- Temperatures in bedrooms can be high on hot summer days.

BPE techniques: lessons learned

Airtightness testing (blower door and Pulse): The values tested on this property are close between fan method and pulse. Further cases are needed to demonstrate robustness of the pulse method in low leakage buildings.

Views on methodology: This case study was the only one where ventilation air flow rates were measured. In conjunction with CO_2 measurements, judgements can be made about the performance of the ventilation for maintaining the intended IEQ conditions. The CO_2 measurements in this case study are higher than those found in other case studies. However, as the evaluator resides in this case study property, there was much more context to enable the evaluator to assess, e.g. window opening patterns in the CO_2 analysis. More rigour is needed for consistency for CO_2 measurements (placement of sensors, occupancy density/behaviour/patterns, and analysis of data, e.g. using occupied periods only and applying rolling 8-hour averages.

Roof monitoring: This has proved to be valuable, particularly in conjunction with UCL swab samples. The spores present and the higher RH will now trigger an intervention for this property, e.g. to increase ventilation in the roof space.

[1] Note weather-adjustment has been applied to the 2014 energy use to 2022 weather data (using heating degree days, which suggests that the heating demand would be very similar between these years, with 2022 being slightly milder). However, even allowing for the increase over the years, the 2022 heating demand still represents a 75% reduction compared to the pre-retrofit heating requirement of 18043 kW·h per year (120.1 kW·h/m^2 peryear) in 2011 (see Figures CS1.9 and 1.10).

[2] Note the survey was completed by the evaluator who is a resident of this property.

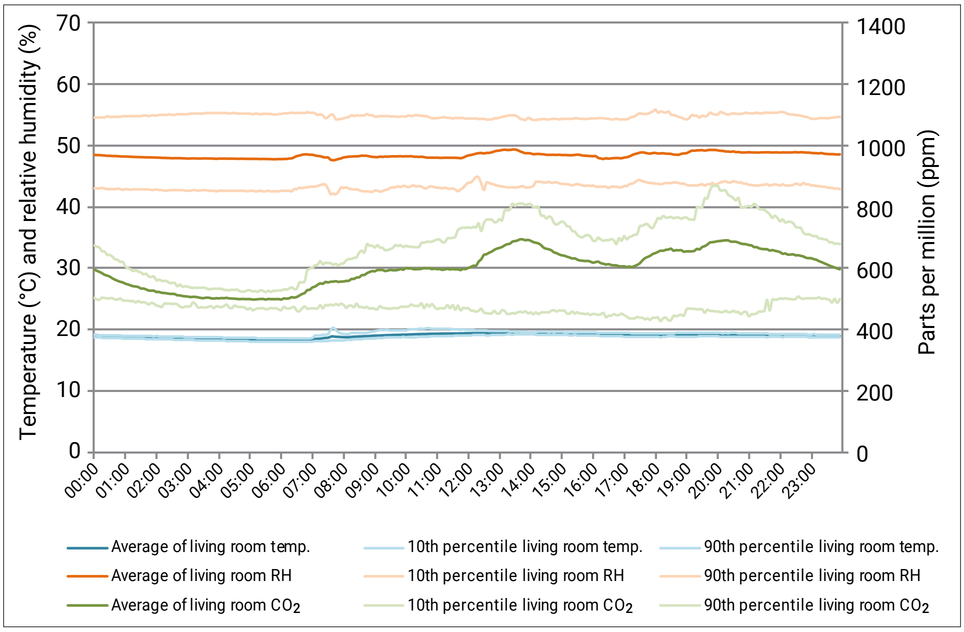


Figure CS1.8 Blaise Castle: hourly profiles (living room)

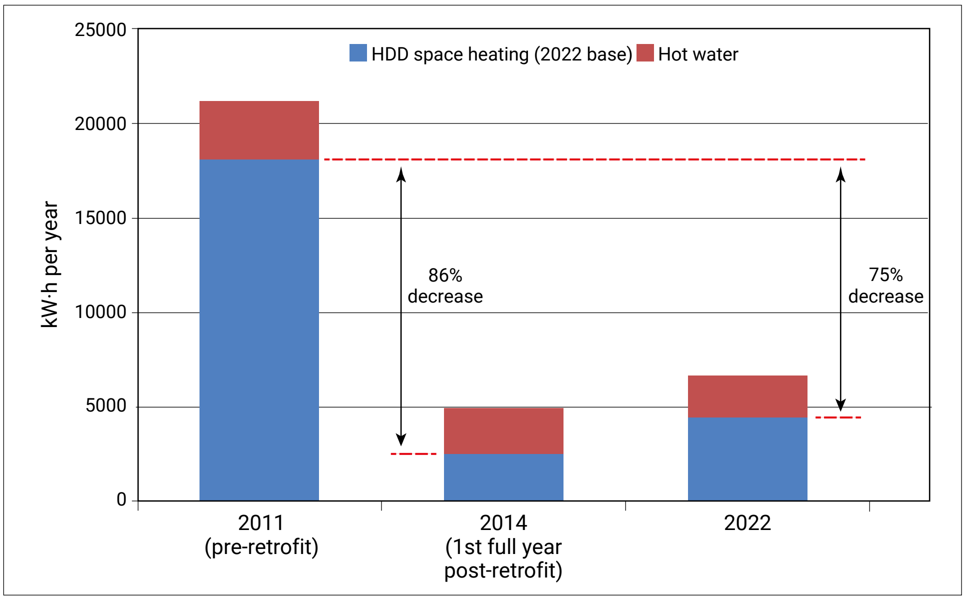


Figure CS1.9 Delivered energy for domestic hot water and space heating (HDD adjusted) between pre- and post-retrofit, and 8-years post-retrofit

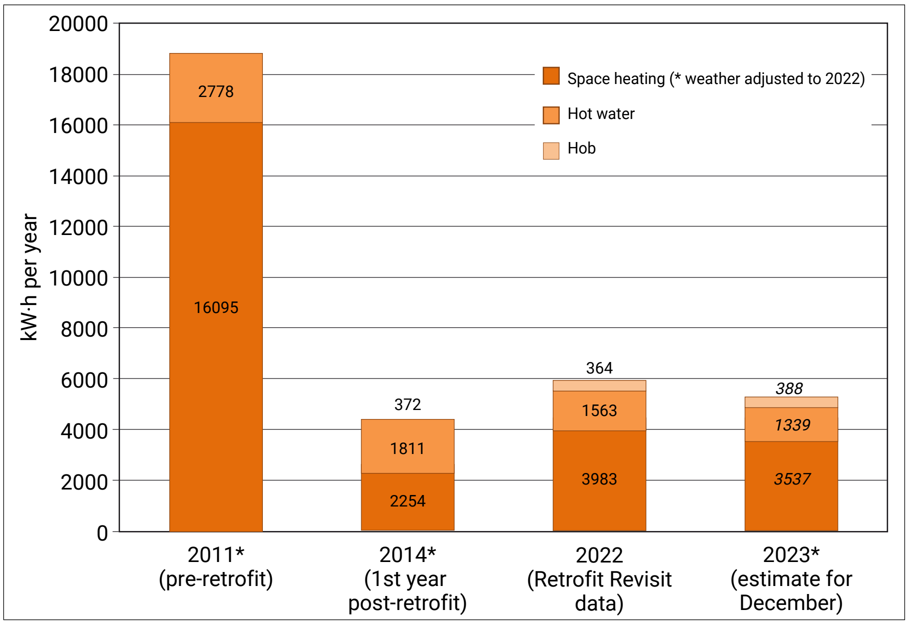


Figure CS1.10 Gas energy consumption (kW·h per year)

Notes to Figure CS1.10

(1) Space heating: energy reduced by over 85% in the first-year post-retrofit but has crept up since until end 2022.

(2) Specific heating demand equivalent values: 2010:120 kW·h/m^2 p.a., 2014:12 kW·h/m^2 p.a., 2022: 22 kW·h/m^2 p.a., 2023: 19 kW·h/m^2 p.a.

(3) Space heating energy use for 2023 predicted to be around 11% improvement against that used in 2022.

(4) Hot water: energy use reduced by around 50% compared to pre-retrofit levels

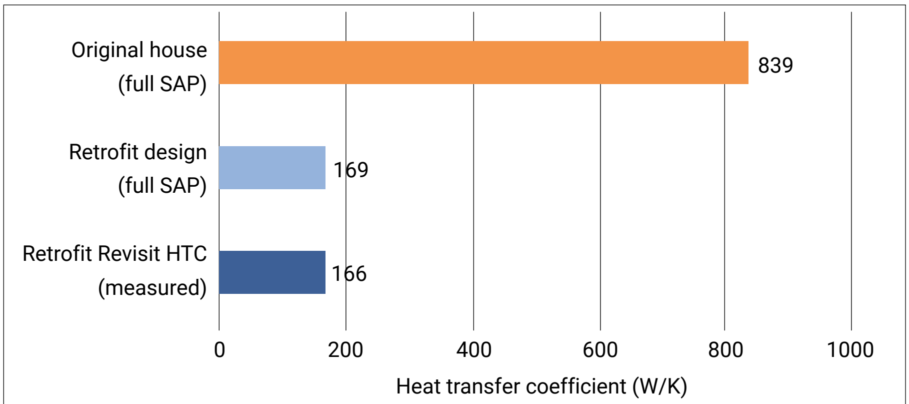


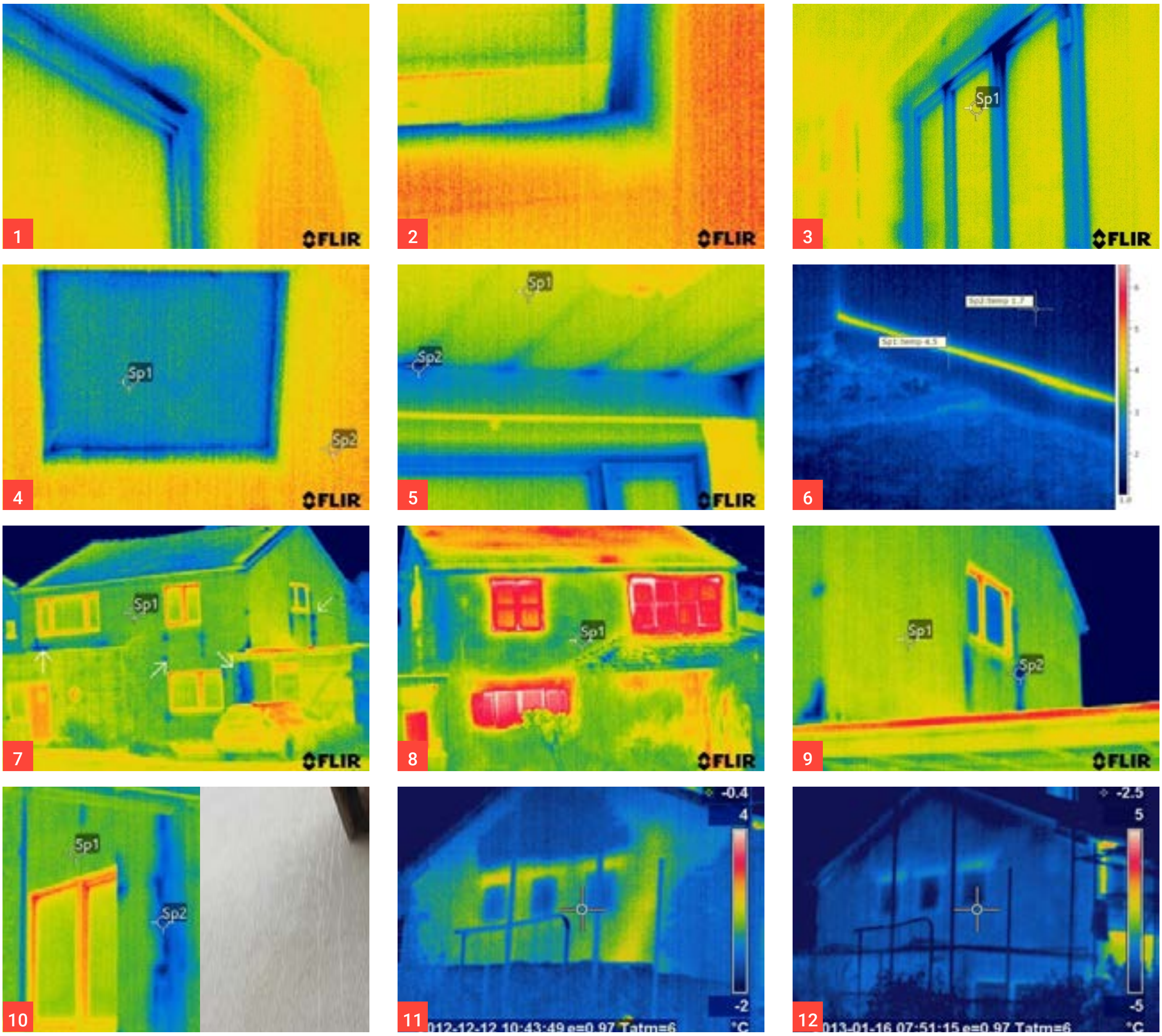
Figure CS1.11 Heat transfer coefficient (HTC) (W·K)

Notes to Figure CS1.11

(1) Pre-retrofit (original house): SAP calculation resulted in an inefficient thermal envelope with an HTC of 839 W/K (HLP of 5.42 W/m^2·K).

(2) Retrofit design: SAP calculation predicted an 80% reduction with the extent of thermal improvements planned. Revised HTC of 169 W/K (HLP of 0.75 W/m^2·K).

(3) Retrofit Revisit measured HTC: Measured temperature, relative humidity and space heating energy consumption data uploaded to the BTS SmartHTC portal, resulted in a HTC almost identical to that predicted by SAP.



1: Air leakage through top seal on tilt/slide door during depressurisation

2: Air leakage through bottom seal on tilt/slide door during depressurisation

3: Air leakage between bi-folding door panels during depressurisation

4: Minimal leakage around loft hatch. Insulation to the hatch could be improved (and has been since this image was captured).

5: Cellulose insulation in loft above. Air flow at eaves is causing an amount of insulation cooling at outer edge of ceiling.

6: A thermal image from 2014 showing thermal bridge associated with steel carrier plate for EWI.

7: IR of front (west) and side (south) elevations. Arrows indicate surface condensation with run-off from aluminium sills and interface with car port roof. This finding is subject to further investigations to confirm cause.

8: Neighbour's house (not retrofitted) for comparison.

9: Bathroom window over car port roof, showing similar surface condensation. Further checks need to be made to confirm water run off is not passing behind render/EWI.

10: Closer view of surface condensation on EWI render at car port roof interface — photo shows surface wetness. This condition tends to occur on colder mornings, arising from clear sky radiation.

11a and 11b: Images from 2013 showing (left) heat loss via cavity into gable/roof zone (image captured just prior to CWI fill). Right image shows heat loss is via gable has been eliminated after CWI infill. This will also result in minimal bypass around EWI fitted later on. Note for both images: the three square windows have been removed and block infilled/insulated. Lintels can be still just be seen in the right image.

Figure CS1.12 Blaise Castle: thermal images

CS2 Hawthorn Road

Hawthorn Road

Companies involved in the 2023 BPE
CIBSE
UKRI
Metropolitan Housing Partnership
UCL
QODA
BTS
Aeldas

Original retrofit architect
Anne Thorn Architects

Property age
Pre-1919

GIA area
122 m^2 SAP EPC (PHPP = 109 m^2 TFA)

Typology
Mid-terrace

Occupancy
Tenant (housing association); two adults and one child (baby)

One-off retrofit. Completed January 2011

Overview of the original retrofit

Description of the original retrofit strategy: Retrofit for the Future Project, including 80% CO_2 reduction agenda. De-conversion: two flats returned to single family three-bedroom home. Semi-derelict property (fire damaged). The property was empty, so it gave the opportunity for a deep retrofit. The strategy consisted in 'fabric-first' and whole house approach, applying the Passivhaus principles with excellent levels of airtightness, insulation and ventilation, windows and doors improvements. Gas boiler upgrade with solar thermal for hot water. MVHR system throughout. Aiming for ease of use in occupation, and low running costs for tenant benefit.

Fabric strategy

Insulation strategy: EWI to rear façade and IWI to front. Natural insulation materials where possible. Front walls fitted with two layers of sheep's wool insulation within timber frame structure, lined with wood fibre insulation board to reduce thermal bridges. Sheep's wool also to roof/ceiling, expanded polystyrene to solid floors. Substantial thicknesses of EPS to rear façades.

Thermal bridges: TB reductions analysis, modelled in THERM. Use of PHPP.

Airtightness: Walls and roof with airtight membrane. EnerPHit target of 1 $m^3/h{\cdot}m^2$ @ 50 Pa unachievable economically or in practice as would have required removing and replacing staircase. MVHR ducts and Rotex flues were challenging to install with airtightness compromised. Internal walls finished with lime plaster applied to wood fibre insulation boards.

Services

Heating and hot water: Rotex Gas Solar Combi Unit provides heating and DHW, but controls more complex than planned.

Ventilation: Maico Aeronom WS250 MVHR, requiring periodic cleaning and changes of air filters. *Note*: Unclear who is responsible for maintenance. It provides 300 m^3/h and is connected to rigid steel ducting throughout.

Publications of reference

Residential Retrofit: Twenty Case Studies (Baeli, 2013)

Retrofit for the Future Project Final Report:The Haringey PassivTerrace report for TSB by Metropolitan Housing Partnership (2011).

Fabric improvement description and *U*-values

Walls: IWI at front: 0.20 $W/m^2{\cdot}K$; EWI at rear: 0.15 $W/m^2{\cdot}K$.

Floors: Concrete floor slab with rigid insulation: 0.12 $W/m^2{\cdot}K$; existing floor to kitchen and plant room areas: 0.18 $W/m^2{\cdot}K$.

Roofs: New with overhang extensions for deep EWI. Sheep's wool insulation: 0.10 $W/m^2{\cdot}K$.

Windows and doors: New triple glazed windows in existing openings 0.8 $W/m^2{\cdot}K$; insulated doors with good seals for airtightness.

Insulation properties: two layers of 100 mm vapour-open sheep's wool fitted between two layers of 50 mm × 100 mm timber battens; airtight Intello membrane to internal side of party and front facade walls protected behind 60 mm wood fibre insulation to minimise cold bridging of timber battens. Lime plaster finish. EPS insulation vapour-closed on EWI. OSB floor over 200 mm EPS floor insulation over new concrete floor replacing existing suspended timber floor. 100 mm sheep's wool between existing intermediate floor joist for sound insulation. 250 mm cellulose and sheep's wool insulation between and above joists and MVHR ducting in cold roof void.

Overview of the revisited retrofit

Significant changes since the original retrofit

Occupancy: Essentially same residents have been in continual occupation over the past 12 years. A new family member arrived about a year ago with consequent lifestyle and clothes washing changes!

Building: No significant changes but deterioration of fabric on north facade, ad hoc repair failures to guttering and brickwork; breakdown of solar thermal element for the Rotex Gas Solar Combi Unit requiring spare part and maintenance.

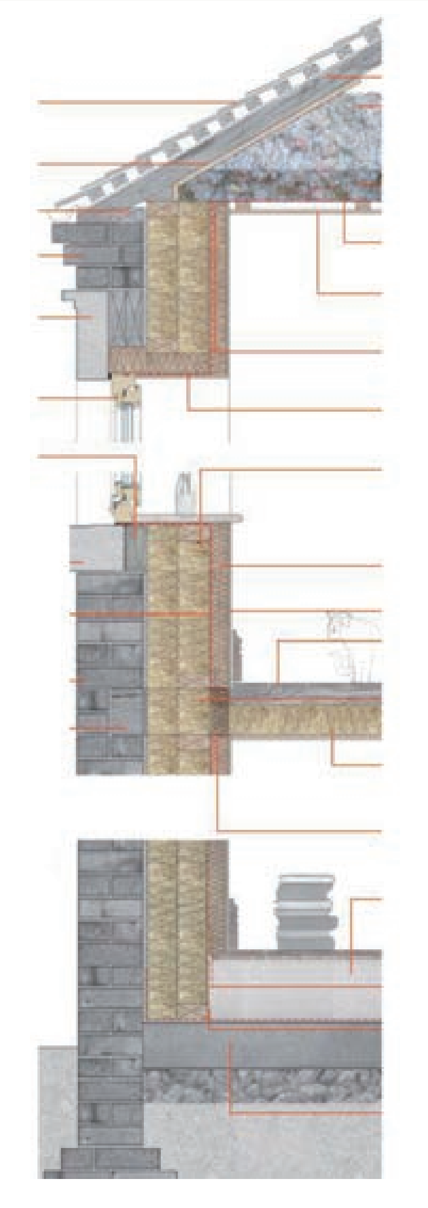


Figure CS2.1 Front elevation section illustrating the wood fibre airtight membrane and sheeps' wool internal wall insulation.

Envelope:

Overall performance: EWI to south side (rear) elevation generally in good condition, albeit signs of hairline cracks at junctions. Brick mortar joint repairs to the north side where cement rather than lime has been used with consequent evidence of deterioration of north facing brickwork. Ongoing poor repairs and maintenance of guttering to north bay window has resulted in build-up of moisture and moss growth, severe brick deterioration and also salt efflorescence at the wall-floor interface. This may be further exacerbated by levels of IWI preventing timely drying out of bricks. Many hairline cracks in mortar generally to the North façade requiring re-pointing.

Airtightness integrity: Blower door (BD) test demonstrates that the airtightness has been compromised compared to original test, although difficulty of installing BD in door frame may have had some impact on results.

Further investigations: Smoke tests may have helped identify more clearly where air leakage occurred. Thermography to check integrity of wall, roof and floor insulation. 2D hygrothermal modelling is being used to assess whether levels of internal insulation are contributing to cold and damp brick deterioration on north-west facing walls.

Rectifications needed: Guttering and mortar repairs to brickwork need urgent attention to prevent further deterioration. MVHR in need of re-balancing.

Figure CS2.2 The MVHR filter is being replaced, revealing an abundance of particulate matter and dust accumulated over an extended period since the last replacement

Figure CS2.3 MVHR unit with primary ducts insulated

Services

Heating: Rotex Gas Solar Unit powering small radiators to top up space heating on coldest days. No change or maintenance schedule (see next item).

Hot water: The solar thermal circuit stopped working 2+ years ago, after parts failure. (Spare parts and a maintenance engineer have proved difficult to arrange.) As a result, there has been no renewable energy contribution to the home's needs for over two years.

Ventilation: The MVHR is in need of re-balancing and cleaning: it is noisy in the bathroom and sounding as if on boost setting while very low flows are felt in other areas. A volume flowmeter test would be useful here.

Energy performance: Refer to Table CS2.1 below.

Indoor environment: The average temperature from bottom to top of the house ranges from 20.97 to 18.76 °C. Min. temperature recorded: 17.2 °C. Max. temperature recorded: 26.5 °C. The average relative humidity (RH %) from bottom to top of house ranges from 50.20% to 53.37%. Min. RH recorded: 34.0%. Max. RH recorded: 73.5%. Average CO_2 over 27 days in the sitting room: 613 ppm (7 am–11 pm) with Min: 418 ppm and Max: 1854 recorded. Max. night time (11 pm–7 am) recorded 1068 ppm.

User feedback: The property has very few issues and the whole house (deep retrofit) is generally regarded as performing well. It is rated 'Great' at 82% compared to benchmark scores, with little negative feedback from the residents.

Description of the BPE approach: A fabric-first approach had been adopted in the original specification to ensure a warm, comfortable home that is easy to operate. To check comfort levels and risks of mould growth, humidity and temperature readings were needed over a winter month. Relative humidity and internal temperature sensors were installed at the beginning of March 2023 to establish some benchmark performance data. A CO_2 data logger was installed in the sitting room, to determine indoor air quality. Anonymous user feedback helped to provide context and user satisfaction levels. Blower door and Pulse tests helped determine the relative airtightness/leakage of the building over time and therefore the quality of the build or to highlight defects in performance or building maintenance. Internal and external inspection of fabric. Mould and damp testing was additionally performed by a specialised unit from UCL.

Table CS2.1 2023 BPE findings: details

	Pre-retrofit 2020	Original retrofit 2021	Retrofit revisit 2023
Annual energy use	73061 kW·h (LEB database) This is acknowledged to be very high, but was checked against the original reports.	6344 kW·h	9783 kW·h (2020) 12890 kW·h (2021)
EUI (kW·h/m² per year)	599	52	80 (2020) 106 (2021)
Gas (kW·h)	70164	3418	4810 (2020) 7406 (2021)
Electricity (kW·h)	2897	2925	4973 (2020) 5484 (2021)
Airtightness levels	17 $m^3/h{\cdot}m^2$ @ 50 Pa	2.53 $m^3/h{\cdot}m^2$ @ 50 Pa (2.37 ach^{-1} @ 50 Pa)	Blower door test: 3.64 $m^3/h{\cdot}m^2$ @ 50 Pa (4.07 ach^{-1} @ 50 Pa) Pulse test: 0.56 $m^3/h{\cdot}m^2$ @ 4 Pa (estimated: 3.07 $m^3/h{\cdot}m^2$ @ 50 Pa)
Fabric moisture tests			Detailed ambient air and fabric testing, see Appendices 5, 8 and 9.
Thermography			
		Retrofit Revisit only	
HTC		SAP-calculated HTC of 80 W/K	SmartHTC -measured results: heat transfer coefficient (HTC) of 154 W/K [−85/+39] and heat loss parameter (HLP) of 1.3 W/m^2 K giving a 'Good' rating.
Mould risk			BTS mould risk score is 2/100 , or 1 on 0–4 scale, which gives the property a 'low risk' rating. See reports on the detailed testing in Appendices 5, 8 and 9, which incorporate overall outcomes from a wider range of factors than the BTS mould risk score, which reflects ambient temperatures and humidity levels.
Walls	225 mm solid brick walls, no insulation	Generally appear in good condition with new paintwork from the photos taken at the time. 100–200 mm EPS EWI adhered to wall at rear façade. IWI with natural vapour open insulation to front façade.	North-west wall in bad repair with moss growing. Gutter junctions dripping combined with prevailing wind from west blowing water onto wall. Repairs with cement rather than lime mortar have caused further deterioration of brickwork so it is crumbling away. General state of mortar joints in poor repair with much cracking in evidence for further moisture penetration. Needs re-pointing overhaul with lime mortar to all of north (street side) façade and returns. South walls with EWI seem in good repair but with signs of cracks emerging that will need maintenance programme.
Floors	Suspended timber	New floors with engineered timber laminate and EPS insulation on new concrete slab at ground floor.	Engineered timber floors are difficult to lift so inspection limited to surfaces. The presence of the new solid floor has a negative effect on north wall and sleeper wall.

Table continues

Table CS2.1 2023 BPE findings: details (*continued*)

	Pre-retrofit 2020	Original retrofit 2021	Retrofit revisit 2023
Roofs	Pitched slate roof no insulation	New roof with sheep's wool. Membrane linings to underside of slate roof tiles (re-used).	Roof void dry with sheep's wool insulation intact. Some membrane linings have come loose from rafters. Small daylight holes noted near eaves but not unusual for unheated roof space. Evidence of small cracks in bedroom ceilings below through shrinkage will require maintenance programme. Given that the well sealed insulated roof hatch provides access for storage in the roof space, the insulation is prone to be disturbed so boarding out of this area would provide safety (danger of walking between joist and damaging ceilings below) and easier inspection of rafters and roofing internally as well as provision of additional storage.
Windows and doors	UPVC windows, double hung sash windows. Edwardian panelled timber doors.	PH-certified EcoPassiv triple glazed timber windows; insulated triple sealed timber doors. *U*-value to 0.8.	Generally in good condition but will need maintenance programme. Cills and thresholds need attention and repainting/sealing where necessary.

Indoor environmental performance

Temperature: Generally comfortable and even temperatures. Average 20.1 ºC, which is also the occupant's stated preferred temperature in the SOAP survey; with average minimum: 18.0 ºC and average maximum: 23.3 ºC.

Hottest temperature recorded during the month of March was in the ground floor WC which is shared with the plant room cupboard at 27.1 ºC. In terms of more generally occupied space the kitchen was the next hottest with a recorded maximum of 26.5 ºC. Average temp differences across the house of 2.21 ºC.

Relative humidity: Generally stable humidity levels with average across the house of 50.7% RH. Average minimum recorded: 48.35% and average maximum: 53.37%. Highest RH recorded during the month of March was in the kitchen at 73.5 %. Average RH differences across the house of 3.17%.

CO_2 concentration: The CO_2 sensor in the sitting room gave an average daytime (7 am–11 pm) level of 613 ppm over a period of 27 days. This level is regarded as generally good and within the recommended range suggesting that the MVHR strategy is working well.

Commentary on physical findings versus user feedback: Occupants are generally happy with property but maintenance is a serious issue. Degradation in airtightness may be down to hairline cracking in mortar and brickwork as more obvious declines are through doors and windows but these retain good seals or are rarely opened. Possible additional heat losses as smokers leave doors open while outside. Controls on Rotex Gas Solar Combi Unit appear complex but the house tends to run at comfort levels so no need to fiddle with them. Occupant of bedroom 2 finds the bedroom often very hot but evidence suggests that bedroom 1 gets warmer being on the south side more prominently but with no complaints from the occupant. In both cases internal venetian blinds appear to be down most of the day reducing solar heat gains (even in winter month).

Although the house is comfortable, there is great concern by the tenant and evaluator at increasing deterioration of North façade brickwork and contributing drips from the poorly maintained gutter above.

While the overall running costs are deemed reasonable and keep the house at a comfortable 18–20 ºC as designed, the loss of contribution from the solar thermal array is unfortunate as it would appear to be a simple replacement of a faulty part.

Results of annual energy use would suggest higher running costs than previously achieved but increased internal temperature requirements may be at play here.

A tumble dryer is used in winter to stay on top of household laundry but otherwise drying rack outdoors in garden. Moths are reported as an issue throughout the property with evidence around the MVHR filter inlet/plant room cupboard. No moths were observed in sheep's wool insulation in roof space.

Services strategy

Space heating: Rotex Gas Solar Combi unit has been reliable (unfamiliar/complex controls means less fiddling!). However, the solar elements and servicing of the unit has proved difficult as apparently an unusual item in this country.

Heating booster in line with MVHR ducting was used in early days but proved expensive to run and generally unnecessary so advice was to turn off the switch operating this element.

Electricity: On meter. Power cut recently experienced temporarily (10 minutes) as insufficient funds in account. Issue of fuel poverty raised by this — mostly counteracted by low energy usage fabric first building strategy but important to maintain solar (free energy) too.

Ventilation: MVHR filters are changed annually or when UCL's Prof. Ben Croxford visits with student study groups. This may be a cost issue or not seen as the responsibility of the tenant. Responsibility has never been clarified between Housing Association and tenant.

On first visit the evaluator witnessed existing filters which looked over-soiled and therefore not working as effectively as they could in keeping air quality to high standard.

The MVHR is noisy in the bathroom and overall seems out of balance and needs cleaning and performance overhaul. However, the ventilation function still maintains stable humidity levels with average across the house with 50.7% RH.

Renewables: Solar connection has been faulty for some two years. The tenant and Housing Association have reported difficulty getting replacement parts and suitable engineer. This may be due to unusual manufacturer for the UK market.

User feedback

SOAP questionnaire findings:
The property has very few issues and the whole house (deep retrofit) is generally performing well. It is rated 'great' at 82% compared to benchmark scores, with little negative feedback from the residents.

Very satisfied with comfort levels generally although can overheat in summer. User guide was provided along with an introduction to the various aspects of running the home. Showers estimated at 20 per week and seven baths per week. Energy costs for the past year stated as £1700 and water costs at £400. No visible signs of condensation or mould internally.

BPE techniques: lessons learned

The original building analysis and implementation work has generally stood the test of time but a lack of maintenance schedule has eroded some of the performance with cracking in mortar courses evident and where tackled, poorly re-done. Long term, this leads to higher overall remedial costs than a few essential repairs done regularly and with correctly specified materials.

Airtightness testing (blower door and Pulse): There was a technical difficulty of securing the blower door inside the narrow door frame elements. The Pulse test was more practical to execute in this location.

Views on methodology: Some concern that there was insufficient analysis of insulation thicknesses around the cold north-west wall area which may be contributing to the brick deterioration. UCL monitoring of this area may give further information not yet received . Also WUFI analysis would be useful.

Figure CS2.4 Light moss and weathering on external wall insulation render

Figure CS2.5 Rear elevation external wall insulation in good condition with very few hairline cracks in render

Figure CS2.6 Front elevation showing impact of leaky gutter on brickwork

Figure CS2.7 Freeze–thaw damage at high level as a result of faulty rainwater goods, primarily exacerbated by inappropriate cement pointing. Cryptofloresence visible. The IWI may be increasing the risk, but to a lesser degree than the cement

Figure CS2.8 Moss growing on brickwork due to excessive moisture exposure

Figure CS2.9 Salt crystallisation damage near to ground level as a result of rising damp (likely linked to the floor treatment), primarily exacerbated by inappropriate use of cement (and possibly impermeable paint)

Table CS2.2 Indoor environmental monitoring during Retrofit Revisit period

Level	**Ground**	**Ground**	**Ground**	**Ground**	**Ground**	**First**	**First**
Room location	Kitchen	WC/plant room	South sitting room	North lounge	Stairwell	Main bedroom	Bedroom 2
Average temp. (°C)	20.97	21.97	19.99	20.2	19.71	18.76	18.81
Min. temp. (°C)	19.20	18.8	17.9	17.8	17.9	17.4	17.4
Max. temp. (°C)	26.50	27.1	22	23.1	22.9	21.1	20.3
Average RH (%)	50.2	48.35	50.01	49.68	51.33	52.05	53.37
Min. RH (%)	34	38.5	39.4	39.4	41.5	41.5	43.6
Max. RH (%)	73.5	60.1	60.7	59.8	65.4	65	64.7

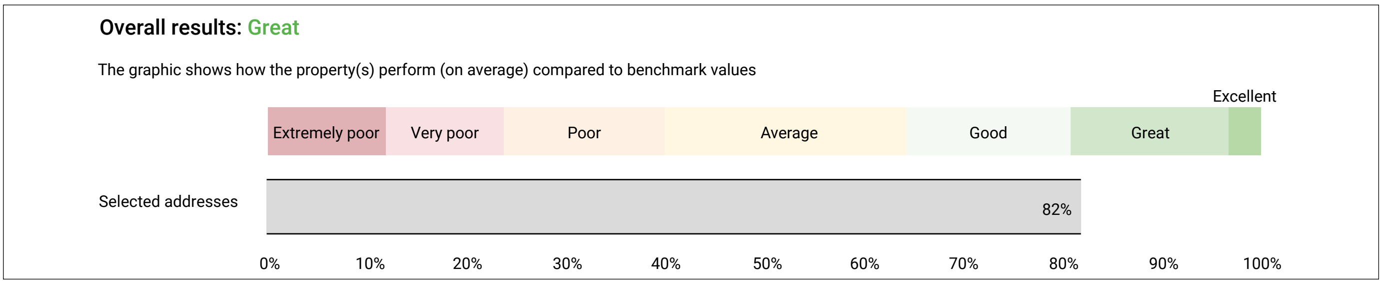


Figure CS2.10 Performance compared to benchmark values

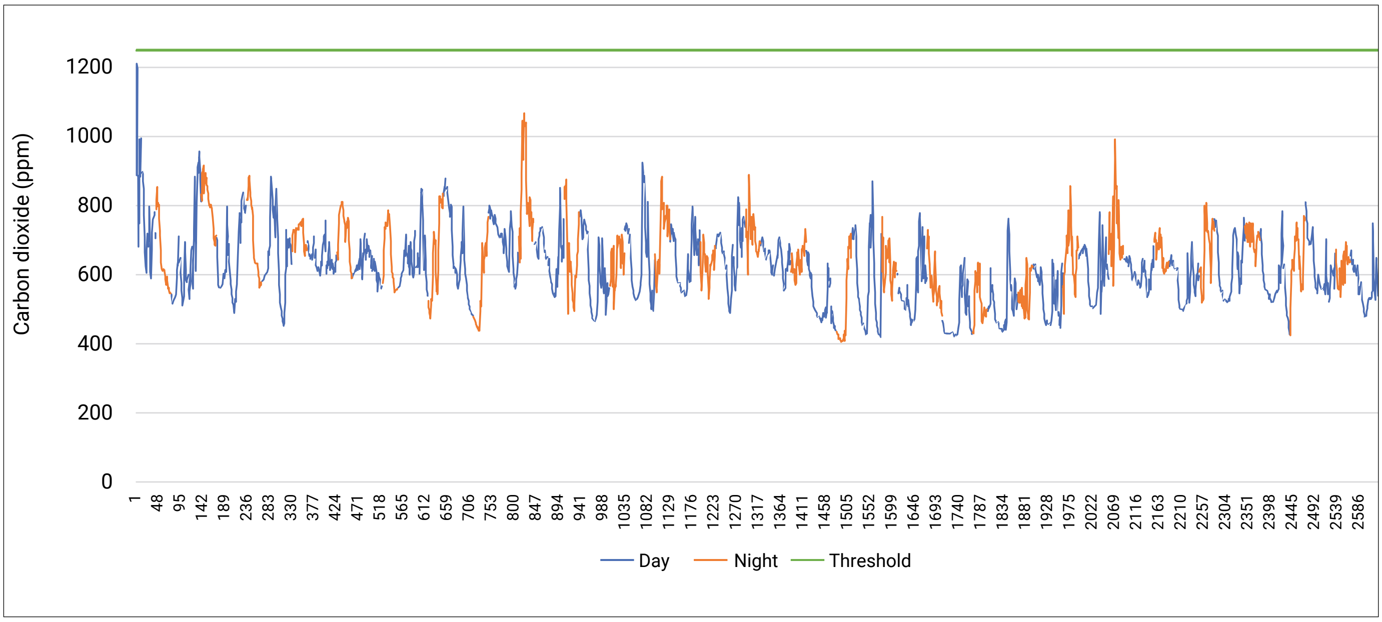


Figure CS2.11 Hawthorn Road carbon dioxide logger results for March 2023

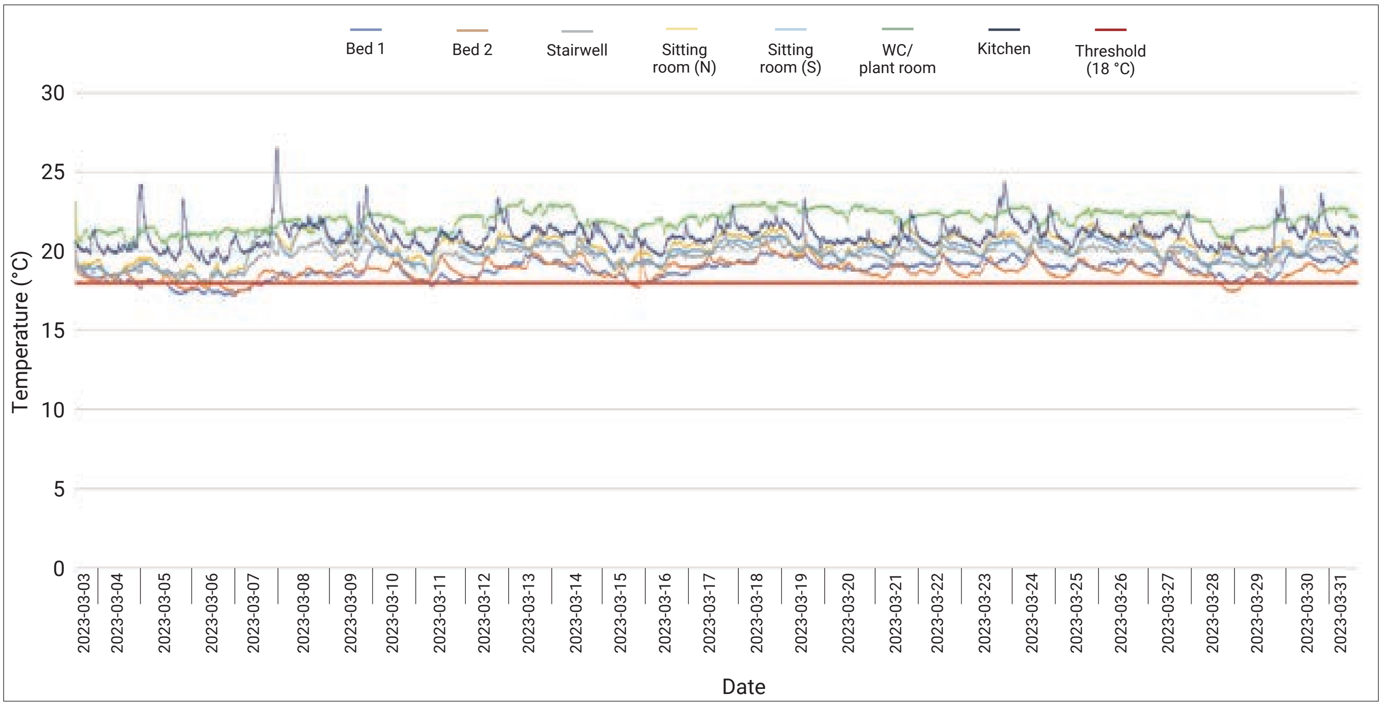


Figure CS2.12 Hawthorn Road internal temperatures (°C) during March 2023

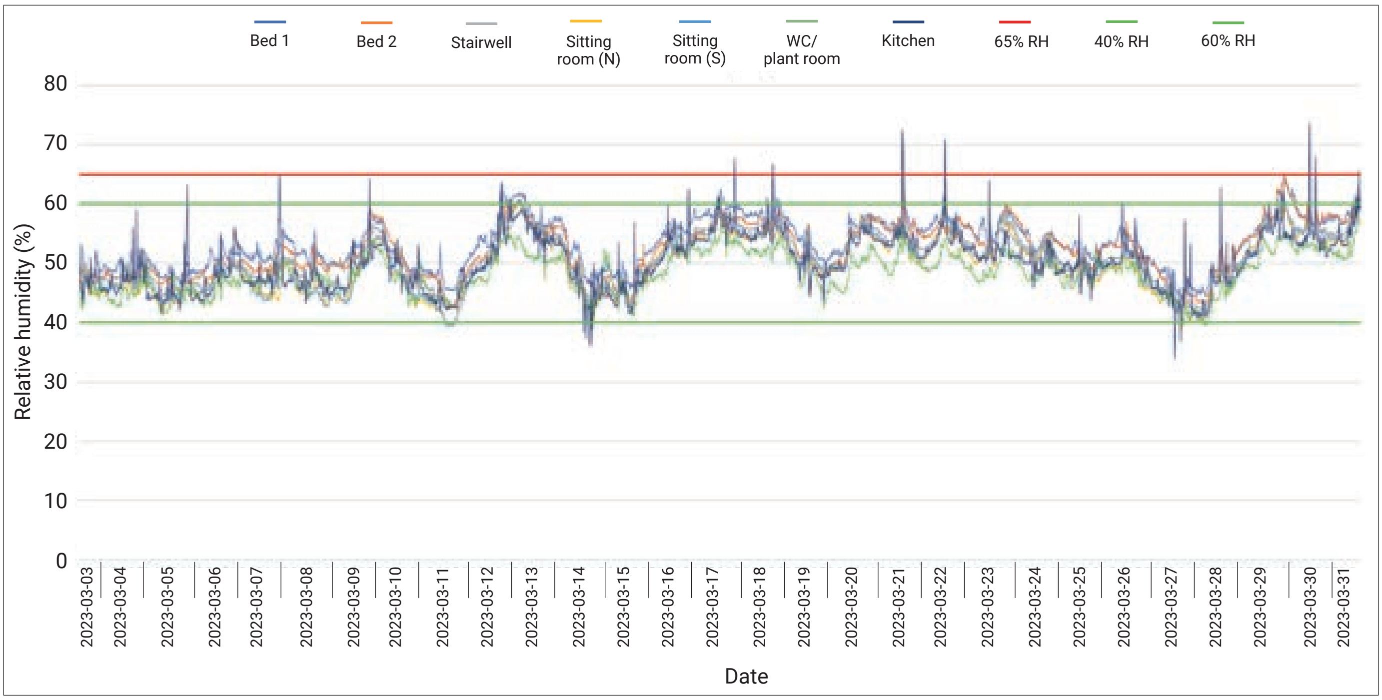


Figure CS2.13 Hawthorn Road relative humidity (%) during March 2023

CS3 Grove Cottage

Grove Cottage

Companies involved in the 2023 BPE
WARM
BTS
UCL
Simmonds Mills

Original retrofit architect
Simmonds Mills

Property age
Pre 1919 (1869)

Floor area
162 m^2 (post-retrofit)

Typology
Detached cottage

Occupancy
Owner occupier family house: five occupants

One-off retrofit and extension works between 2008–2009

Overview of the original retrofit

Prior to refurbishment, the majority of the property had a timber ground floor with a cellar space beneath. Because the cellar was damp and because funds did not allow for a conversion, the team decided to thermally separate it from the rest of the dwelling, while still allowing door access.

The modifications to the existing building fabric included an extensive remodelling of the ground floor structure with the insulation and airtightness elements installed between and underneath the floor joists in order to avoid disruption and cost related to existing partition walls and floor finishes.

Because of the unusual nature of the floor insulation layers and the inclusion of an insulated downstand at floor perimeters, some modelling was carried out to help ensure that the details were as free of cold bridges as possible and that the surface temperatures would be high enough to prevent and mould growth (THERM and WUFI software were used). This study indicated a small degree of risk, but the use of a vapour-variable membrane combined with continuous mechanical ventilation in the house meant that the project team felt the long-term risk was acceptable.

Fabric strategy

Insulation strategy: External wall insulation (EWI), a small area of internal wall insulation (IWI) used in the gable wall at attic level. Floor insulation: insulation between and underneath the timber joists (for existing ground floor over basement), insulation laid over existing slab and a raft foundation (in extension.)

Thermal bridges: The main thermal bridges being the connection to the roof and ground floor. The EWI extended to be in line with the roof insulation, resulting in a thermal-bridge free detail from the continuous insulation. The thermal bridges between ground floor and external wall were reduced using load bearing insulation blocks.

Airtightness: Air permeability post-retrofit was 0.82 m^3/h·m^2 @ 50 Pa based on an internal volume of 498 m^3.

Services

Heating and hot water: A Vaillant ecoTEC plus boiler with a 3000 litre insulated hot water cylinder was connected to radiators for space heating, and a 3000 litre cylinder was installed for hot water storage.

Ventilation: An MVHR ventilation system with 92% heat recovery efficiency.

Publication of reference

Passivehouse+, AECB

Fabric improvement description and values

Walls: Rendered walls: brick walls were wrapped with 250 mm EPS with render. Timber clad walls: timber Larsen trusses fixed to existing solid brick and filled with 350 mm of mineral wool. The north gable wall: 25–40 mm PU foam injected into the gap to the neighbouring dwelling. This reduces heat loss but there is a risk of reducing the drying area. Sensors indicate this did not cause moisture build up in walls but is not considered a robust solution to be copied without consideration of this issue. The gable wall at attic level has PU internal wall insulation. Average wall *U*-value: 0.113 W/m^2·K.

Floors: Existing timber floor 175 mm sheeps' wool installed between joists, variable-vapour resistance membrane, 50 mm sheep's wool insulation and 15 mm plasterboard. Existing solid floor: 100 mm PIR insulation on existing slab. New extension floor: concrete raft on DPM, 250 mm EPS. Average floor *U*-value: 0.187 W/m^2·K.

Roofs: Existing rafters with insulation, 400 mm deep timber I-beams filled with mineral wool Average roof *U*-value: 0.084 W/m^2·K

Windows and doors: Triple-glazed units. Average installed *U*-value: 0.99 W/m^2·K.

Insulation properties: Graphitised, expanded polystyrene EWI for masonry walls, mineral fibre batts for new timber Larsen truss and flat roof, sheep's wool for suspended floor, EPS for IWI for masonry walls , spray foam polyurethane (PU) for party walls. The sheep's wool provided capillary active and hygroscopic performance to help manage a healthy moisture balance in the more challenging situations, notably around floor joist ends on exterior walls.

Overview of the revisited retrofit

Figure CS3.1 Installation of air/vapour barrier during original retrofit

Significant changes since the original retrofit:

Occupancy: Occupancy the same as original retrofit.

Building: No significant changes reported, other than the remedial works described below.

Envelope:

Overall performance: The fabric still performs well and its performance in the Retrofit Revisit was similar to the design calculations.

In the years after the retrofit, a precautionary measure was taken to reduce moisture-related risks in two areas where sheep's wool and timber joist near the external wall. Specifically, some of sheep's wool fitted between joists on the suspended floor was removed where it meets the external wall. This decision followed the discovery of localised timber decay affecting a single joist parallel to the exterior south gable wall, which was set off from the masonry (without a damp-proof course) by less than 25 mm. It was also to allow injection of a hydrophobic brick cream DPC in the mortar joints of the solid wall, a measure the homeowner regrets not doing during the retrofit. The combination of basement wall condensation wetting, leading to vertical capillary movement of moisture ('rising damp') behind the airtightness membrane of the suspended floor, and the increased temperature resulting in one of the timber joists rotting. New insulation was installed with a tapered angle.

Airtightness integrity: The airtightness integrity has slightly reduced. This seems to be mainly associated with from several damaged exterior door seals/door adjustment issues.

Another factor may be the MVHR system having only one fan working before and during the investigation team's visit. The MVHR unit was running on extract only, the supply side fan having failed, pending a replacement fan being delivered (this was a long wait due to supply chain problems). Potentially the resulting depressurisation of the house over several months may have drawn some fungal spores from flood damaged areas or the basement up into the house during this period.

Further investigations: Fungal tests (air sampling) was carried out in one room with the suspended ground floor (living room) and one room under the roof (bedroom); The results of the fungal biomass quantification test indicate high fungal levels (according to UCL reports, see Appendix 5). This may be interstitial rather than surface mould and may be connected with water damage from a leak in a heating system expansion vessel.

Rectifications needed: Further drying of flood damaged areas, and repair of the MVHR fan.

Figure CS3.2 Insulated pipes throughout the property

Services

Heating and hot water: Some radiators have been removed from the original retrofit for aesthetic reasons and to accommodate a wardrobe. The boiler expansion vessel burst and caused a small flood, resulting in remedial works to the hallway and bathroom areas and part of the suspended ground floor edges.

Ventilation: The visit found that the unit had stopped supplying fresh air but was still extracting as expected; investigations subsequently discovered a failed fan unit.

Energy performance (2022 values):

- EUI The total EUI is 113 kW·h/m^2. Exported PV electricity is not metered so the actual energy used may be lower than this figure.
- Gas usage has increased from original retrofit, but this appears to be from significantly increased shower usage and the metered data supports this (based on the increase is summer gas consumption).
- Electricity: no significant changes reported.

Indoor environment: The monitored data indicates good indoor environment in terms of air temperatures, CO_2 levels and RH. Occupant feedback reflects this as feeling comfortable There were no complaints of stuffiness despite the MVHR fault.

User feedback: Survey feedback confirms that the house is performing well. The only issues reported are to do with the services and wanting more user control of room temperatures.

Description of the BPE approach: Core BPE scope plus Detailed BPE: This property was selected as the ground floor was of interest due to it having an insulated timber floor above a cold basement. The scope was to test the moisture content of the floor insulation between joists for risk for mould. Heat flux *U*-value measurements and thermal imaging were also completed.

Table CS3.1 2023 BPE findings: Details

	Pre-retrofit	Original retrofit	Retrofit revisit
Annual energy use	May 05–July 06: • Gas: 30614 kW·h • Electricity: 4954 kW·h Approximate apportionment to 12 months: • Gas: 29070 kW·h • Electricity: 3963 kW·h	Feb 2009–Feb 2010: • Gas 8167 kW·h • Electricity: 4771 kW·h 2009–2020: • Gas: 7889 kW·h • Electricity: 4037 kW·h (this is the average figure prior to PVs being installed in 2017)	10/05/2022–10/05/2023: • Gas: 11900 kW·h • Electricity: max total 6546 kW·h – grid import: 3061 kW·h – PV generation: 3485 kW·h (some of which may be exported; amount used by home unknown)
Airtightness levels	No information available.	Air change rate at 50 Pa: 0.79 h^{-1} Air permeability: 0.82 $m^3/h{\cdot}m^2$ @ 50 Pa	Blower door test: 1.37 $m^3/h{\cdot}m^2$ @ 50 Pa (depressurisation mode only) Pulse test: 0.31 $m^3/h{\cdot}m^2$ @ 4 Pa (estimated 1.78 $m^3/h{\cdot}m^2$ @ 50 Pa)
Fabric moisture tests	No visual signs of mould were present. The results of the fungal biomass quantification test indicate high fungal levels. This may be interstitial rather than surface mould. There are signs of water damage from a plumbing leak which may be the cause of high levels in the ground floor rooms.		
Thermography			See images (section 6)
HTC		SAP-calculated HTC of 84.6 W/K	Measured BTS Smart HTC of 175 W/K [−49/+36]. Differences with the calculated design HTC could be attributed to: • Differences or errors in the methods of calculation. • Overestimate of energy consumption (potentially the inclusion of electricity supplying the garden home office) • Accuracy of PHPP data used to generate the HTC design value. The floor *U*-value appears to have improved from the design *U*-value, which is unexpected. Further tests into this may be required. The wall *U*-value measured are higher than the design *U*-value.
Mould risk			BTS mould risk score: 17/100, or 1 on 0–4 scale, i.e. the building is at low risk for mould. The UCL fungal tests do indicate some mould is present but this is not thought to be related to the performance of the building fabric.
Walls (retrofit revisit)			Good condition, Heat flux measured *U*-value: 0.15 $W/m^2{\cdot}K$
Floors (retrofit revisit)	Remedial works were completed (some years before the Retrofit Revisit).		Floors are in good condition.
Roofs (retrofit revisit)	Minimal mould spots appearing on the window frame bathroom, but this is from user behaviour and not a material issue.		Good condition. There are no visible defects.
Windows and doors (retrofit revisit)	Mix of double and single glazing	New timber triple glazing units	Minimal mould spots appearing on the window frame bathroom, but this is from user behaviour and not a material issue.

Indoor environmental performance

Temperature: The mean internal temperature was above the set point temperature of 18 °C.

Relative humidity (March 2023): The mean relative humidity ranges from 58–61% for the bedrooms, 51% for upstairs bathroom, living room 51%, kitchen 55%.

CO_2 concentration: The CO_2 monitor was in the living room, which is the most consistently occupied space. The CO_2 levels seem to stay below 1250 ppm for most of the monitoring period, with a few dates rising above 2000 ppm.

Commentary on physical findings versus user feedback: The user feedback is consistent with the physical findings.

Internal temperatures and relative humidities were considered comfortable. No mould and condensation issues were identified by the occupants.

Hot water temperatures were considered too high.

Services strategy

Hot water: Provided by gas system boiler and storage tank. Boiler does legionella cycle once a day (assumption based on spike in gas usage between 10:30 am and 11:00 am).

Space heating: Three radiators supplied from gas boiler in the building. No reports of maintenance issues. There were more radiators, but they were removed due to heat rising upstairs and making it too uncomfortable.

Electricity: The average electricity use, post retrofit was slightly lower (4037 kW·h per annum) than the pre-retrofit usage (4954 kW·h per annum). In 2017 a PV installation was added but this did not meter the exported electricity. As a result it is difficult to compare more recent electrical consumption figures.

Ventilation: Mechanical ventilation system with heat recovery (MVHR). The MVHR unit is a Paul 200 Thermos. The unit was installed as a prototype originally and has worked reasonably well. Whilst checking the flow rates the supply air was not working properly due to a fan that had stopped working.

Renewables: PV was added after the retrofit in 2017. The total output of PVs is metered, but how much is used by the home is unknown: electricity export is not metered and instead is credited a set amount).

User feedback

Questionnaire findings: The occupants are knowledgeable professionals who designed the retrofit and have been very thorough in keeping the building maintained to a high quality. The SOAP score is 95% (rated as 'great').

Feedback is generally above benchmark values except for control of services and storage space. Energy use and comfort was rated highly. There are a few minor elements that the occupants would like to change, such as having a higher level of control for the heating, ventilation and lighting. The main areas that will need to be maintained are items are door seals and the ventilation system.

The ventilation system and boiler have worked well, with minimal maintenance required over the years. There was no correlation between occupant feedback and faults with the MVHR.

The new house (extension) is reported as being warmer compared to the retrofitted areas; this may be a result of fewer thermal bridges in the new-build compared to the retrofit. The extension includes the kitchen-dining room, a first-floor bedroom and the completely re-roofed first floor bathroom and hallway.

BPE techniques: lessons learned

We would attend site at the start of the monitoring period to set up, answer any questions the occupant may have, complete the building survey so we could determine which detailed tests should be carried out and where they were required. There also would have been greater control over where the sensors were placed and whether any additional meters could have been read.

Airtightness testing (blower door and Pulse): We could not conduct a pressurisation test at 50 Pa on the blower door test due to concerns by the homeowner that this could damage the airtightness membrane on the basement ceiling.

The amount of information to compile in one month has been great, and the contribution of everyone involved has made this possible in such a short period of time. We would have preferred to have longer to refine the methodology; have a clearer understanding of the project brief and what output was expected.

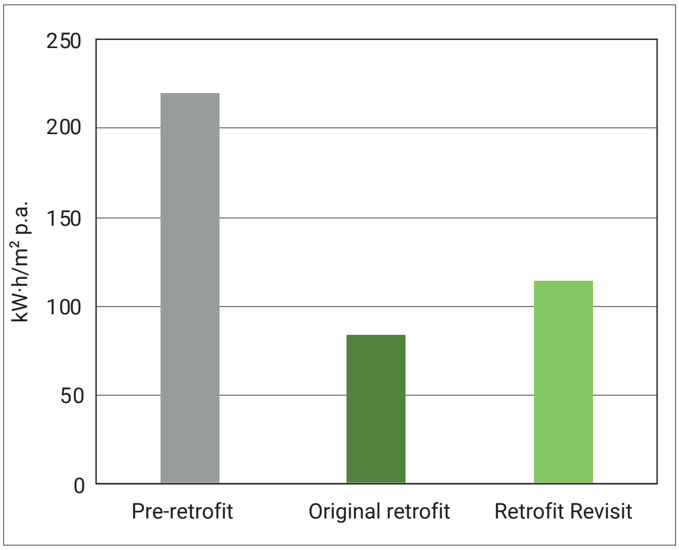


Figure CS3.3 Energy use intensity (kW·h/m^2 p.a.)

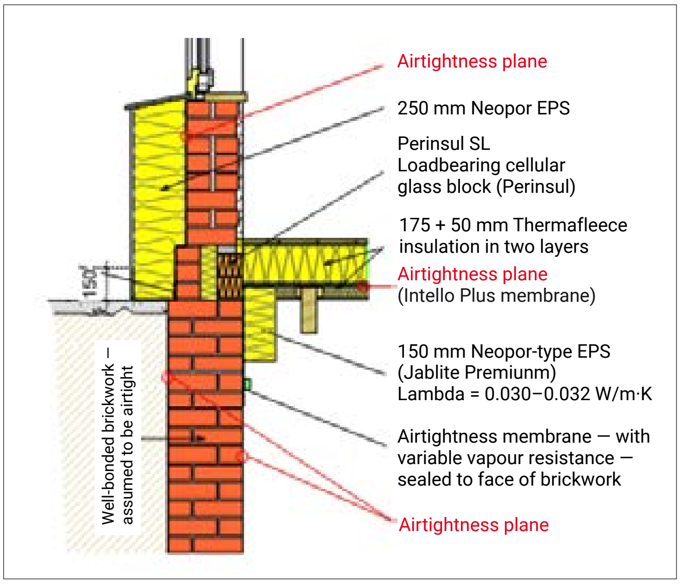


Figure CS3.4

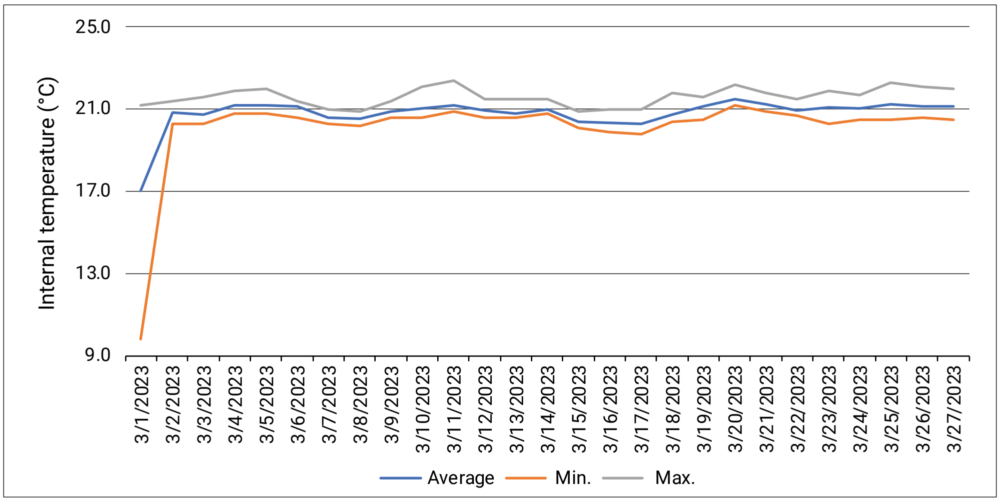


Figure CS3.5 Daily internal temperature (°C) in living room

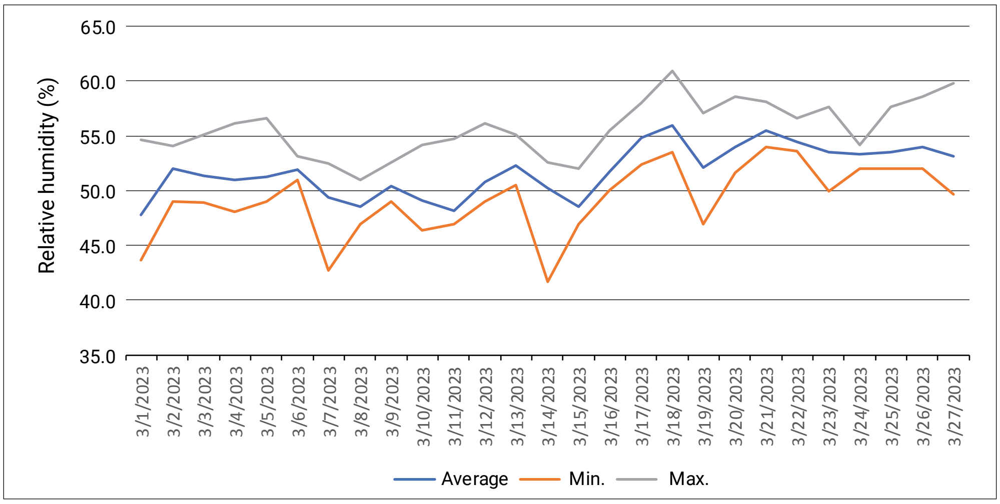


Figure CS3.6 Daily relative humidity (%) in living room

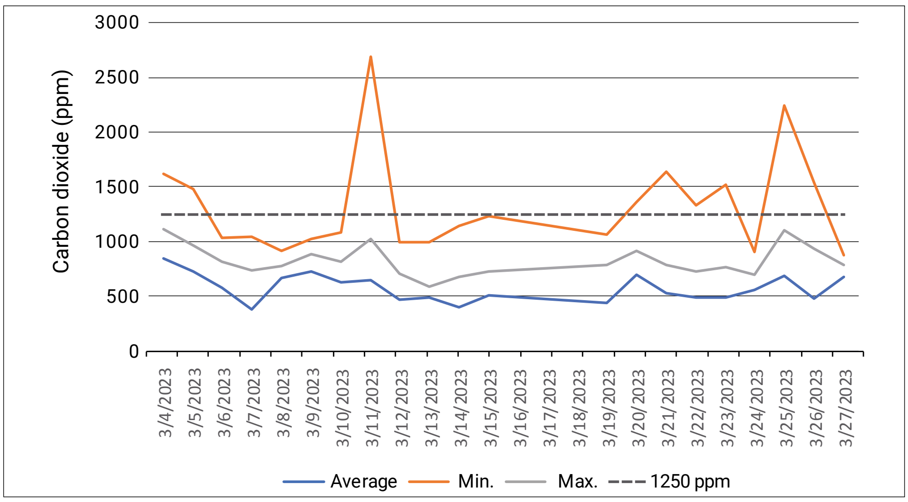


Figure CS3.7 Daily carbon dioxide levels (ppm) in living room

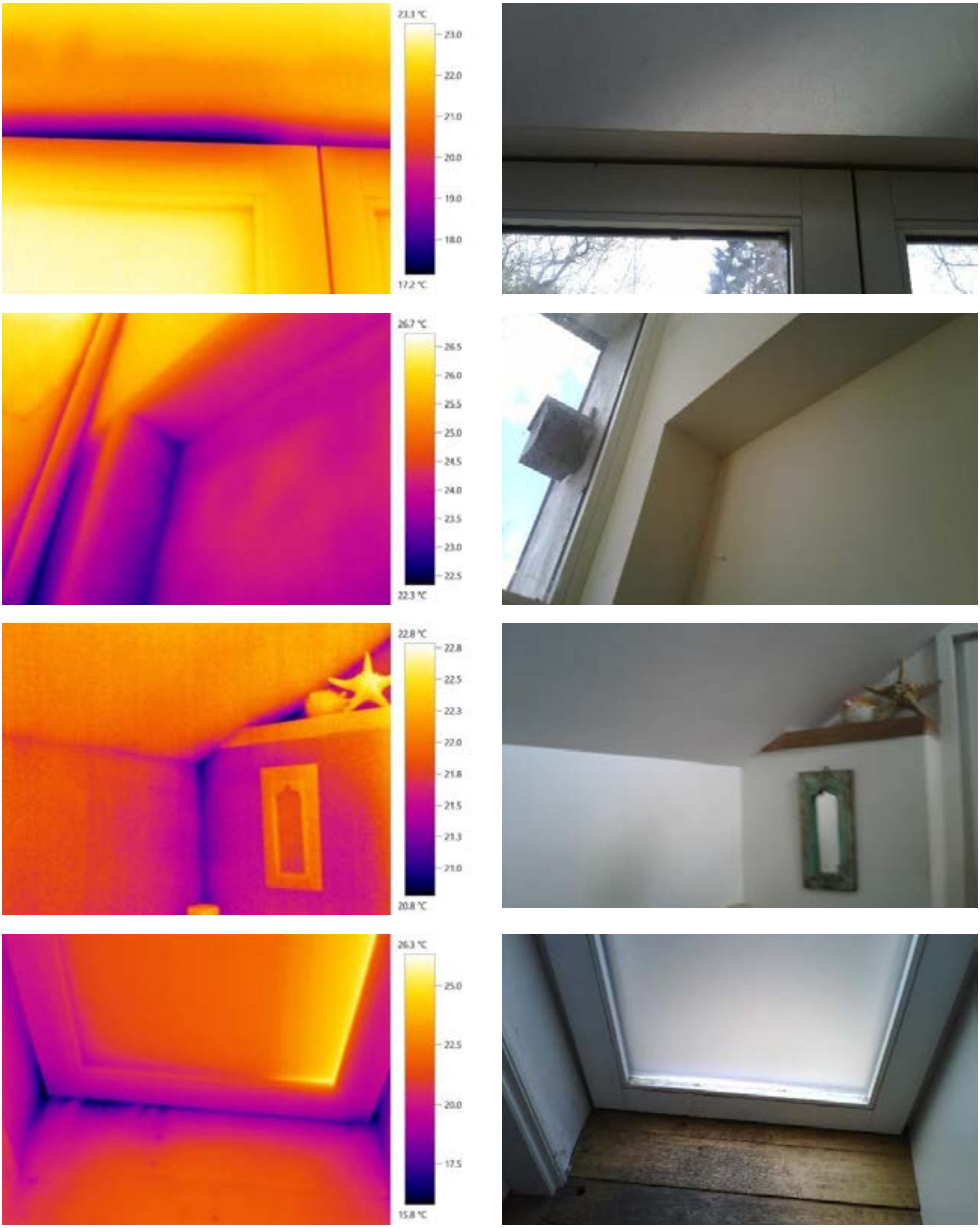


Figure CS3.8 Thermal Images

CS4 Culford Road

Culford Road

Companies involved in the 2023 BPE
Prewett Bizley
Aldas
Build Test Solutions
UKCMB
SOAP Retrofit.

Original retrofit architect
Prewett Bizley

Property age:
Pre 1919 (c.1835)

GIA area:
106 m^2 pre-retrofit
121m^2 post-retrofit

Typology:
Mid-terrace house

Occupancy:
Private homeowners; two adults.

Retrofit completed and occupied January 2010. (Design June 2007–8. Planning consent sought Dec 2007–Sept 2008. Construction 2009.)

Overview of the original retrofit

The client sought an 'extreme' retrofit, to see how far it was possible to take a leaky and poorly maintained mid-19th century house within a Conservation Area.

The solid brick front façade was deliberately left unchanged for streetscape reasons as well as planning/conservation restrictions, so was internally insulated. The rear elevation of the house was rebuilt with an insulated cavity wall, partly due to the extension at ground and first floor but also as it was discovered the original wall was disintegrating. The original butterfly roof has been replaced with a warm flat roof construction as part of a loft extension.

There was a deliberate intent to consider the design holistically and consciously a 'whole house approach' and a realisation that detailed coordination would be required for an optimal outcome on not just energy demand but also thermal comfort, daylight and health.

Fabric strategy

Insulation strategy: IWI on the protected front façade (see Figure CS4.2). Cavity wall insulation to new walls for extension/rebuilt wall at rear.

Thermal bridges: Mostly eliminated from IWI by cutting joist ends back and hanging from steelwork. Foam glass used within stepped cavity wall insulation.

Airtightness: Existing brickwork to party walls and new blockwork for the cavity wall at rear was either plastered/parged. Front wall lined with IWI (see Figure CS4.2) with taped OSB sheathing. Concrete slab on ground taped to wet plaster or IWI sheathing. Similar for plywood sheathing of the main roof to walls. Taped junctions between wet plastered walls and concrete ground slab/sheathing boards to IWI.

Services

Heating and hot water: Gas boiler with hot water tank

Ventilation: MVHR 88% efficiency and low specific fan power.

Publications of reference

- Lane TA 'Haus In Hackney', *Building* magazine, 22 January 2010.
- Chandler B 'It's Just a Lovely Place to Live', *House and Property*, 26 January 2011.
- Cohen RR and Prewett R, 'Measuring is Believing', *Proc. 16th International Passive House Conf., Hannover, May 2012*.
- Baeli M. *Residential Retrofit, 20 Case Studies*. Routledge. 2013.
- *Cheltenham Climate Change SPD* (p 29), Cheltenham Borough Council, 2021.
- 'Robert Cohen and Bronwen Manby', *SuperHomes* (website) (https://superhomes.org.uk/homes/robert-cohen-and-bronwen-manby)

Fabric improvement description and values

Front wall: Internally insulated with glass wool and insulated studs with three sheathing layers (see Figure CS4.2). *U*-value transformed from around 1.6 $W/m^2 \cdot K$ to 0.20 $W/m^2 \cdot K$. With vented cavity between brick and new insulation layer. This wall was subject to *U*-value analysis by BTS (see Briefing 4 and Figures CS4.2 and CS4.3).

Rear wall: Rebuilt as a fully-filled insulated cavity wall (Thermalite, 200 mm glass wool and reclaimed bricks as facings). *U*-value transformed from around 1.6 $W/m^2 \cdot K$ to 0.15 $W/m^2 \cdot K$.

Roofs: New flat roof with small loft extension executed fabricated as a 'warm' roof with single ply membrane. Timber framing and PIR insulation. *U*-value transformed from around 2.0 W/m²·K to 0.15 W/m²·K.

Front windows: In respect of conservation area and streetscape, replica sliding sashes with slim double glazing and warm edge spacer inset into timber frames with authentic glazing bars. Quadruple brush seals with very little measured air leakage. Overall *U*-value around 2.0 W/m²·K.

Insulation properties: Mainly vapour-closed. IWI is used in a bedroom, which is wood fibre/diffuse open.

Rear windows: Imported (German) inward-opening triple-glazed windows. *U*-value around 1.0 W/m²·K.

Front door: Bespoke insulated door with double edge seals. *U*-value 1.0 W/m²·K.

Ground floor: New slab on ground with 100 mm XPS insulation with UFH over. *U*-value around 0.15 W/m²·K.

The aim was to create a continuous all enveloping layer of insulation (see orange insulation line on Figure CS4.1 and CS4.3). This involved the use of foam glass blocks within the cavity wall construction to reduce thermal bridging. An internal lining to party walls using 50 mm of mineral wool (mainly for acoustic reasons) helped mitigate a number of other thermal bridges between party wall and external envelope.

Insulation properties: The glass wool insulation used in the front internal wall insulation and cavity wall is vapour open and non-combustible. It was preferred over rigid insulation as it can be fitted snugly into voids leaving little or no air gaps. The moisture safety of the front wall is founded on the ventilation gap between the existing masonry and the new internal layer.

The warm roof insulation and the insulated slab both contain plastic membranes (VCL and DPM) so are inherently vapour-closed constructions in their very nature.

Overview of the revisited retrofit

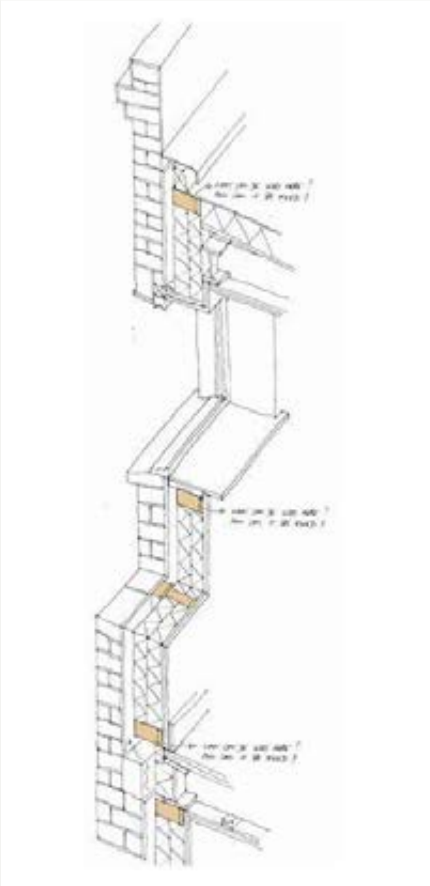


Figure CS4.1 Section through external wall showing IWI

Figure CS4.2 Internal wall installation drawing and site photos showing a series of layers built up in-situ. This wall was subsequently assessed for measured *U*-value by BTS during the March 2023 Revisit study.

Significant changes since the original retrofit

Occupancy: Normally two adults but only one for most of time during the internal environment monitoring period of the revisit.

Building: No significant change.

Envelope

Overall fabric performance: The very close correspondence between the PassivHaus PHPP model and measured gas use over 12 years (measured space heating demand of 25 kW·h/m^2 per annum, compared to a predicted demand of 26 kW·h/m^2 p.a.) suggests that the fabric and ventilation system are performing well. Performance very close to EnerPHit standard and well below LETI target.

Smart HTC measured assessment by BTS also very similar to HTC abstracted from PHPP, further corroborates correspondence between modelled and measured.

Airtightness integrity: Modest degradation over 13 years (q50 1.30 m^3/m^2·h to 1.52 m^3/m^2·h), which appears to be attributable to additional leakage associated with windows.

Further investigations: In-situ *U*-value measurement of front wall showed 0.18 W/m^2·K, slightly better than calculated 0.2 W/m^2·K, possibly due to partially ventilated brick façade contributing to resistance while modelling discounts this.

Fungal/mould test showed low spore count on the day of visit before and after depressurisation. The report confirmed this and did not indicate any likelihood that mould was present within the IWI material.

An RH sensor was mounted into the IWI air cavity from March 2023. The sensor data (see Figure CS4.9) shows that RH varies over the period between 70% and 90%, which appears to be simply following external ambient levels. The dew point is never reached indicating that interstitial condensation did not take place during the study period

Rectifications needed: Nothing significant except for common non-retrofit maintenance requirements such as repairs to cracked render to front parapet and a slow leak on a WC cistern.

Services

Heating: Underfloor heating on lower ground and two towel radiators in bathroom on the first floor were very effective and these rooms exhibit a stable temperature that follows the thermostat. Upper ground where no heat emitters is a little more variable and the temperature usually a degree or two lower. Wireless heating control with a first-generation internet application has not worked well.

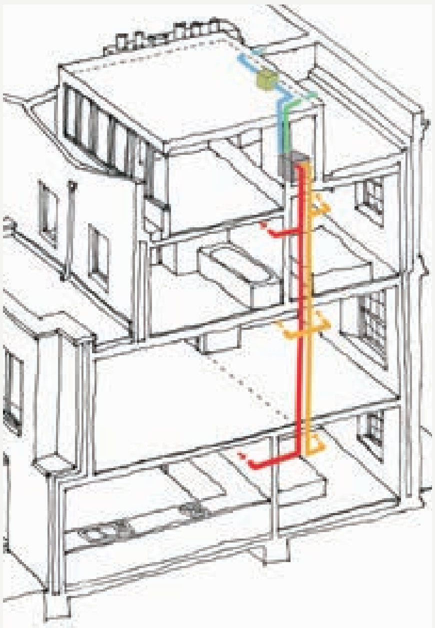


Figure CS4.3 MVHR ventilation distribution

Hot water: Simple boiler and tank working effectively without problems.

Ventilation: While homeowners run the MVHR throughout the heating season they switch it off in summer (relying on natural ventilation) to save electricity. The system appears to be functioning well and quietly with no changes since installation 13 years ago.

Energy performance (averages over 12-year measurement period):

- *EUI*: 51.9 kW·h/m^2 p.a. (meeting LETI target despite gas heating system with only 90% efficiency).
- *Heating demand*: 25 kW·h/m^2 p.a. (lower than LETI target of 50 kW·h/m^2 p.a.) at 18.7 °C.
- *Hot water demand*: 10 kW·h/m^2 p.a. (interpolated from measured summer gas use).
- *Flue losses*: assumed to be 10%: 4 kW·h/m^2 p.a.
- *Electricity (used on site excluding PV)*: 13 kW·h/m^2 p.a.
- *Electricity generated by PV*: 10 kW·h/m^2 p.a.

PHPP suggests that if the temperature during the heating season were 20 °C, an increase in the space heat demand of 4–5 kW·h/m^2 p.a. would be expected.

Indoor environment: Very good IAQ with excellent RH and CO_2 levels. Average temperature 18.7 °C during the heating season.

User feedback: User feedback (based on survey provided by Zack Gill of SOAP Retrofit).

The homeowner is generally very satisfied with the house, except for some reservations regarding the heating/hot water controls, some concerns with glare in respect to the large window expanse to the loft (though they love the view).

Description of the BPE approach: Building on previous data including 12 years' of energy data and several months of IAQ data, during March 2023 a series of additional BPE exercises were carried out including:

- SmartHTC measurement/calculations extending to mould risk assessment
- 3D Heat *U*-value testing
- fungal count in one room
- airtightness measurements and thermal imaging.

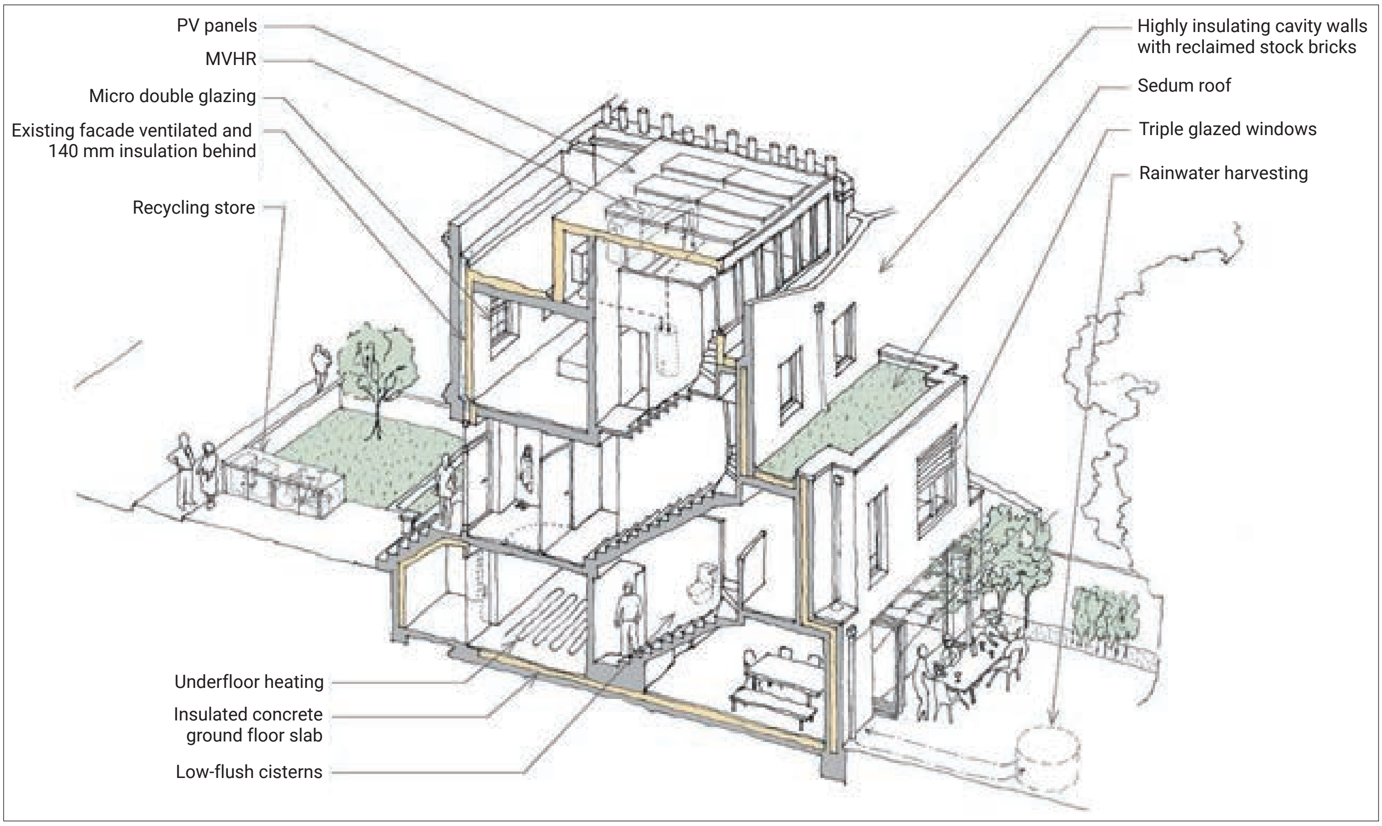


Figure CS4.4 Whole house strategy axonometric

Continuous insulation, high performance windows, shading, heat recovery ventilation, heating, renewable energy, rain water attenuation, biodiversity. *Note*: front wall insulated internally and rear wall rebuilt as a full fill cavity wall.

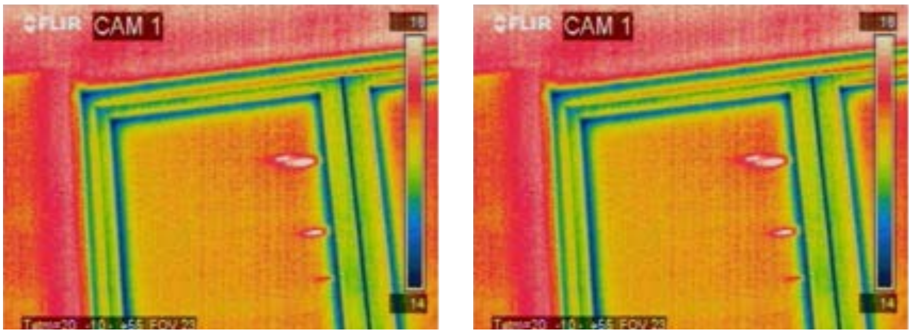


Figure CS4.5 Thermography of part of patio doors at rear lower ground.

Left hand image taken in 2010, just after completion, shows window frames with even temperature generally, only worsening at gaps and where glass meets frame. Right hand image taken in 2023 during the airtightness test. Note how the junction between the frame on the left appears to be sealing poorly at the upper RHS. This could probably be made good by adjusting the espagnolette locking mechanism on this door. Its possible that this was always a weak point as the original thermography was not carried out under depressurisation, though the very even appearance of the frames does indicate it was better than now.

Table CS4.1 2023 BPE findings: Details

	Pre-retrofit	Original retrofit	Retrofit revisit
Annual energy use	291 kW·h/m^2 p.a. (estimated)	51.3 kW·h/m^2 p.a. (in 2011) Gas: 3871 kW·h Electricity: • from grid: 0 kW·h • from PV: 1270 kW·h	51.2 kW·h/m^2 p.a. (average over 12 years) 42.5 kW·h/m^2 p.a. (2022) Gas: 4660 kW·h Electricity: • from grid: 326 kW·h • from PV: 1225 kW·h
Airtightness level	10–15 m^3/h·m^2 @ 50 Pa (estimated)	1.0 m^3/h·m^2 @ 50 Pa	Blower door test: 1.52 m^3/h·m^2 @ 50 Pa Pulse test: 0.21 m^3/h·m^2 @ 4 Pa (estimated 1.26 m^3/h·m^2 @ 50 Pa)
Fabric moisture tests			
Pre-retrofit	No measurements from pre-retrofit, but there were some signs of modest damp issues in lower ground and mould around windows.		
Original retrofit	There were no observable moisture issues immediately following the retrofit works. Measured RH average during winter 2016–17 was 55%.		
Retrofit revisit	A moisture sensor has been inserted into the cavity between the front wall and the IWI to record relative humidity levels of this notionally ventilated void (see Figure CS4.9 for initial data). Site visit in March 2023 showed that there some common repair issues that were not related to the retrofit work, including two moisture related issues within the building: 1. Some water ingress to the top of the front parapet wall where the rendered top of the wall had cracked (repair recommended and that area be capped with a lead flashing). 2. A small water leak from the mains feed to the WC cistern in the first floor bathroom. The cistern has now been replaced.		
Thermography	None	See Figure CS4.5	See Figure CS4.5
HTC	386 W/K Taken from SAP model	87 W/K Taken from PHP model	97 W/K [−35/+33] BTS Smart HTC
Mould risk	No data	No data	BTS mould risk score: 'very low' (3/100), or 1 on 0–4 scale)
Walls	Solid wall in London stock, front and back.	Front solid with IWI. Calculated *U*-value 0.2 W/m^2·K, see Figures CS4.2 and CS4.3. Rear rebuilt as cavity.	No change — all in good condition. IWI *U*-value measured by BTS: 0.18 W/m^2·K
Ground floor	Solid slab on ground, no DPM.	New insulated slab with UFH over.	All in good condition.
Roofs	Original roof with 50 mm glasswool. Poor condition.	New warm flat roof over loft extension. 200 mm insulation.	All in good condition.
Windows and doors	Single-glazed multi-pane sash circa 1980s with widespread rot.	Front: replacement sashes with hardwood cills with authentic replica 'slimlite' double glazed with robust draft stripping. Rear: large pane triple glazed casement in timber frame windows imported from Germany.	All windows in good condition. One minor rot issue to bottom of attic extension window frame to rear, which is being repaired. The sashes have been repainted once. Some paint has strayed onto the brush seals in places. The folding sliding triple glazed doors on the lower ground floor at rear appear to be leaking slightly under air pressure test.

Indoor environmental performance

Temperature: See Figure CS4.8. The March 2023 temperature record showed an average internal temperature of around 18.7 °C. Previous data collected over winter 2016–17 showed an 18.5 °C average, which was a period more representative in terms of occupancy and with an average of around 18.5 °C. See Figure CS4.8 for more detail and explanation. The living room and study on upper ground have no heat emitters and the temperature varies a little more and on cold days gets as low as 17.5 °C, though the occupant does not find this uncomfortable. If this becomes unconformable for the occupants in the coldest weather, the kitchen thermostat is turned up a little to boost the whole-house temperature.

Relative humidity: Average 55 %. Generally 40–60% for 93% during the measured period. This is seen as very good (see Figure CS4.9).

CO_2 concentration: The CO_2 levels during March remain constantly below 1000 ppm, indicating very good air quality. The monitoring done during Dec 2016 to March 2017, showed similar continuous low levels of CO_2.

Commentary on physical findings versus user feedback: The homeowner describes the house as always feeling 'fresh', which aligns with CO_2 monitoring; very low fungal spore level count and low mould risk score.

The rooms without heat emitters do tend to have greater amplitude of temperature variation than those rooms with radiators or underfloor heating. At the design stage, the architect believed that the MVHR might play a role in evenly redistributing the heat around the house. In fact the rooms without heat emitters tend to sit a degree or two lower in temperature than elsewhere (see Figure CS4.8) though it would be quite possible to add extras radiators to the existing system. The homeowners have not done this as they find the existing arrangement quite agreeable and do not regard it as a problem. The freedom from drafts and absence of cool internal surfaces may predicate a feeling of comfort even with slightly lower air temperatures. On cooler days the client chooses to wear a fleece.

Services strategy

Hot water: The hot water is delivered using a system boiler with a tank. This has performed well. The hot water consumption of 1200 kW·h has been inferred by measuring gas use in the summer when no space heating is required. 1200 kW·h/year for a two-adult house seems credible. Since the works, technology has evolved to allow excess electrical generation from PV to be directed towards hot water. In this instance, however, as the owners benefit from a 'feed-in tariff' for exported electricity, this has not been adopted.

Space heating: The space heating has heat emitters in only three spaces: kitchen UFH, lower front bedroom UFH and first-floor bathroom (two towel rail radiators).

The system is powered by a Vaillant ecoTEC 612 condensing gas boiler (with weather compensation) that has a power output of 4.9 to 12 kW (now over 13 years old, though not showing signs of decreased efficiency).

The PHPP model predicated heat demand of the house was around 30 kW·h/m² (assumed internal temperature 20C).
Over 13 years the average measured space heat demand is closer to 25 kW·h/m² p.a. Measurements have shown that the average temperature internally is closer to 18.5 °C. Adjusting the PHP model to account for this shows a predicted demand of 26 kW·h/m² p.a.

Electricity: Measured data shows an annual domestic electrical use of 1550 kW·h/a (13 kW·h/m² p.a.), which is quite low. This is partly due to occupancy of two adults only and their careful selection and use of appliances.

Ventilation: The house has an 'Itho' MVHR unit fitted in the loft extension with short insulated primary ducts. A rigid metal branch system of supply and extract ductwork has been fitted vertically between the historic chimney breasts. The PHPP calculation indicated a heat recovery performance of 88%. The electrical consumption does not appear to have varied and the unit has remained as quiet as when commissioned 13 years ago, indicating the fan motors and bearings have a long service life.

Air quality analysis (March 2023 and Dec 16–March17) looking at RH and CO_2 has shown consistently very good levels of air quality (see Figure CS4.9).

Renewables: In March 2010, shortly after occupation of the house, a 1.32 kWp PV array was fitted to the flat roof of the loft extension, oriented south-east, inclined from the horizontal at 10° (not more in order to limit its visibility from the street). Very little overshadowing from chimney stacks occurs. Six panels produce around 1200 kW·h annually (see Figures CS4.2 and CS4.3).

User feedback

Questionnaire findings: (SOAP and BUS used). The user is very satisfied with the home and the survey findings were rated 'excellent'. The only exceptions were with regard to the heating/hot water controls, which were hard to manage, and the lack of opening windows in the kitchen (leaving the external door open for ventilation invites the curiosity of cats and foxes). They noted that while the comfort level reduces at extremes of weather (hot and cold) it is generally still very good. During severe summer heatwaves, the large areas of west-facing glazing on both the upper ground and, particularly the top floor study, typically make it too hot from 3:00 pm onwards. When the temperature exceeds around 30 °C indoors, the cooler lower ground floor makes an attractive retreat. When the outdoor temperature is above 35 °C the good cross-ventilation provides little relief. In general, the users consider the overheating in hot weather to be more of an issue than underheating in cold weather, which is easily resolved by an extra layer of clothing and is never so severe as to make desk work unviable.

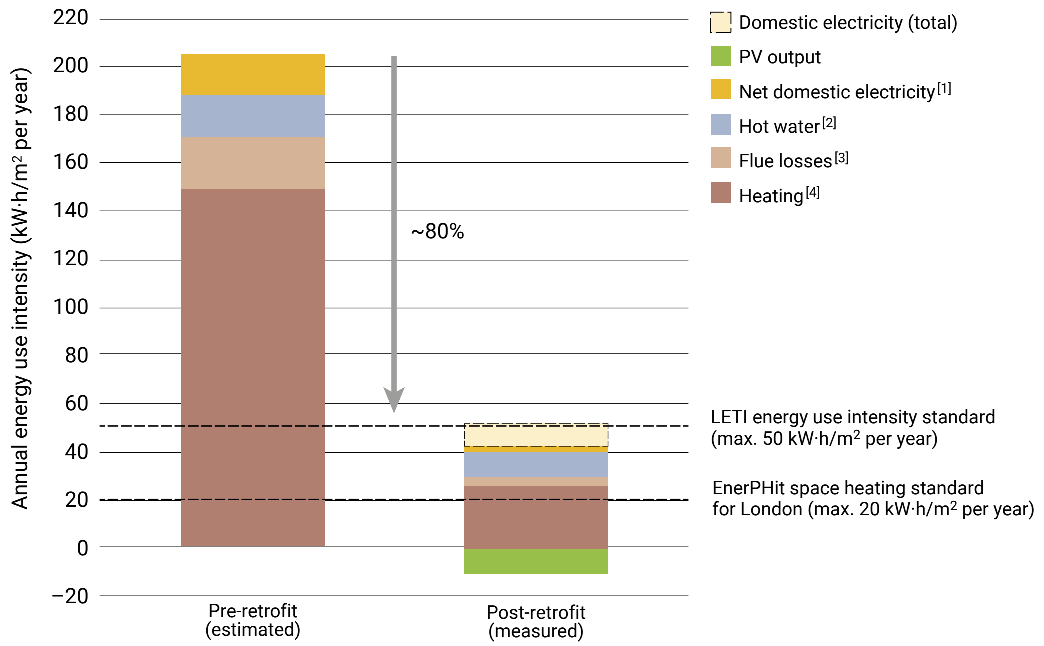
BPE techniques: lessons learned

The short time to plan the testing, combined with limited study period to carry out the tests, reduced the potential scope and value of some of the findings.

Airtightness testing (blower door and Pulse): Blower door test and Pulse results seemed to align quite well. However, Pulse provides no indication on where leakage points are. Even blower door testing on 'tight' buildings, such as this, requires great patience to find leaks or requires the use of thermography.

Views on methodology: The SmartHTC method seems to provide quite an accurate assessment at low cost or fuss. It would be good to see this become commonplace on a large scale for building assessment.

The Heat3D process seemed quite convincing and only required an hour of assessment time, which makes it very deployable and attractive. The confidence margins of around 0.1 W/m^2·K did not suit this assessment so well, but would be useful for assessing buildings with lower insulation levels (pre and post retrofit).



Notes:

[1] The net domestic electric energy use is calculated by subtracting the PV output from the total domestic electricity use.

[2] Annual hot water use is inferred as 10 kW·h/m^2 per year, based on recording gas use over one summer when heating was off.

[3] Overall gas use has not changed significantly, therefore it is assumed that boiler efficiency (and flue losses) have remained consistent. The boiler was assumed to be 90% efficient.

[4] Space heating demand is inferred having made the assumptions on energy use for hot water and flue losses.

Figure CS4.6 Culford Road; overall EUI comparison before and after retrofit.

The overall EUI reduction of 80% (not accounting for PV) has been shown to have met. The deep fabric strategy resulted in a space heat demand reduction of over 90%. Interestingly, the project exceeds the LETI standard for both EUI and SHD despite being in a Conservation Area, even without an ASHP.

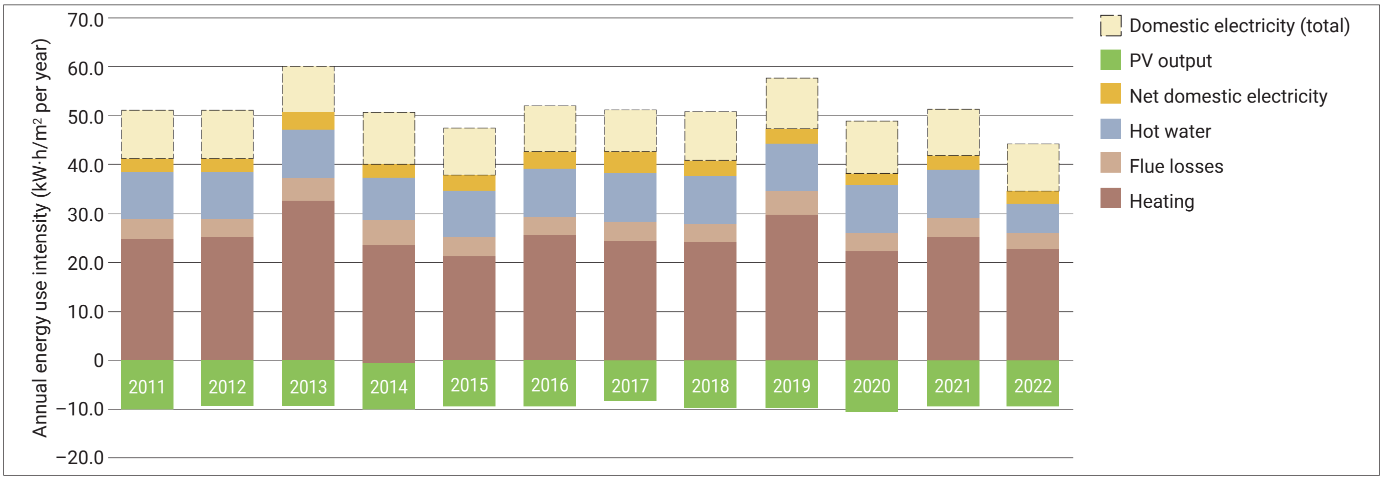


Figure CS4.7 Recorded annual energy consumption, post-retrofit; twelve years of measured EU

On the whole a very stable energy use profile suggesting that the fabric is performing very well. The 2022–23 data is the lowest to date and accords with the lower occupancy that year due the occupants being partially based elsewhere. The energy use of the house over 12 years is remarkably consistent from the perspective of both the total and the constituent parts. The consistency of the space heat demand suggests that the fabric of the house has not reduced in efficiency over that time.

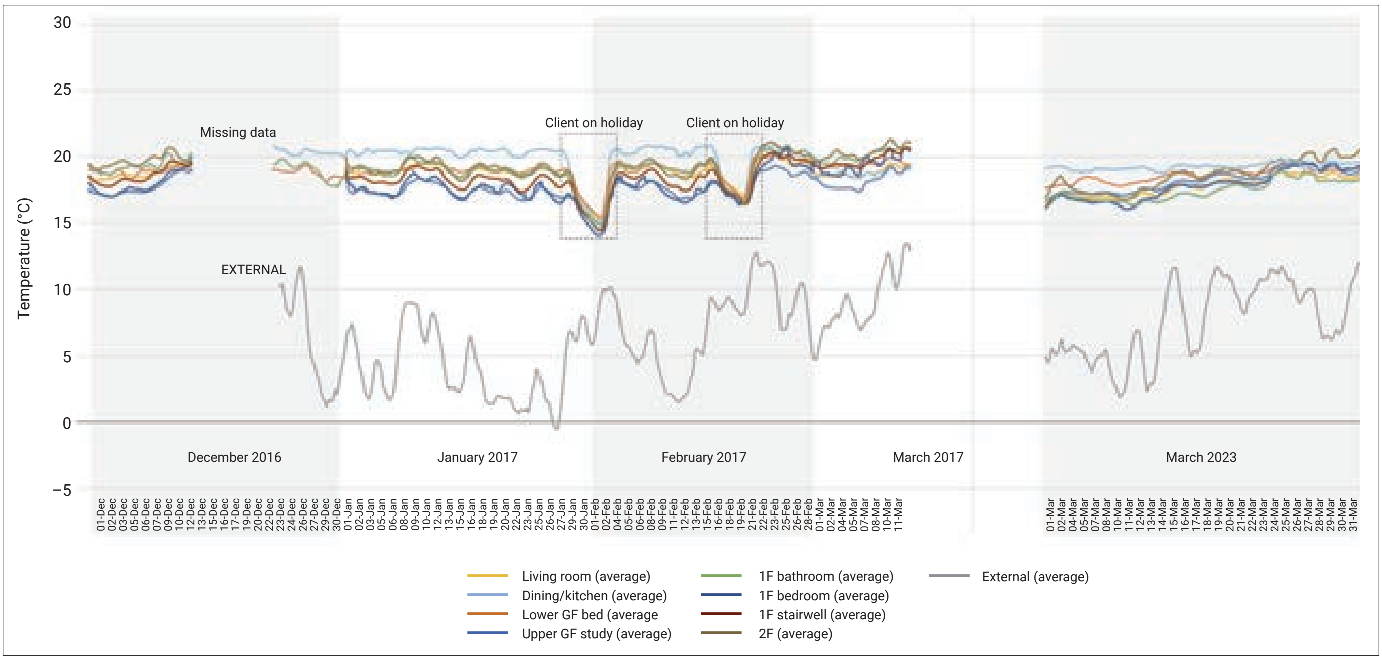


Figure CS4.8 Temperature plots of various rooms during winter 2016–17 and March 2023; average overall 18.5 °C

Generally constant temperature in each room, but rooms vary to one another, mainly as a result of some having heat emitters and others not. Rooms with sash windows (only slim double glazing) tend to show lower temperatures. Note that the client switches off the heating when on holiday and temperature drops, but not that far. The recovery time on return appears to be relatively quick (less than a day). The March 2023 temperature record showed an average internal temperature of around 18.7 °C. Previous data collected over winter 2016–17 showed an 18.5 °C average, which was a period more representative in terms of occupancy. The living room and study on upper ground have no heat emitters and the temperature varies a little more and on cold days gets as low as 17.5 °C.

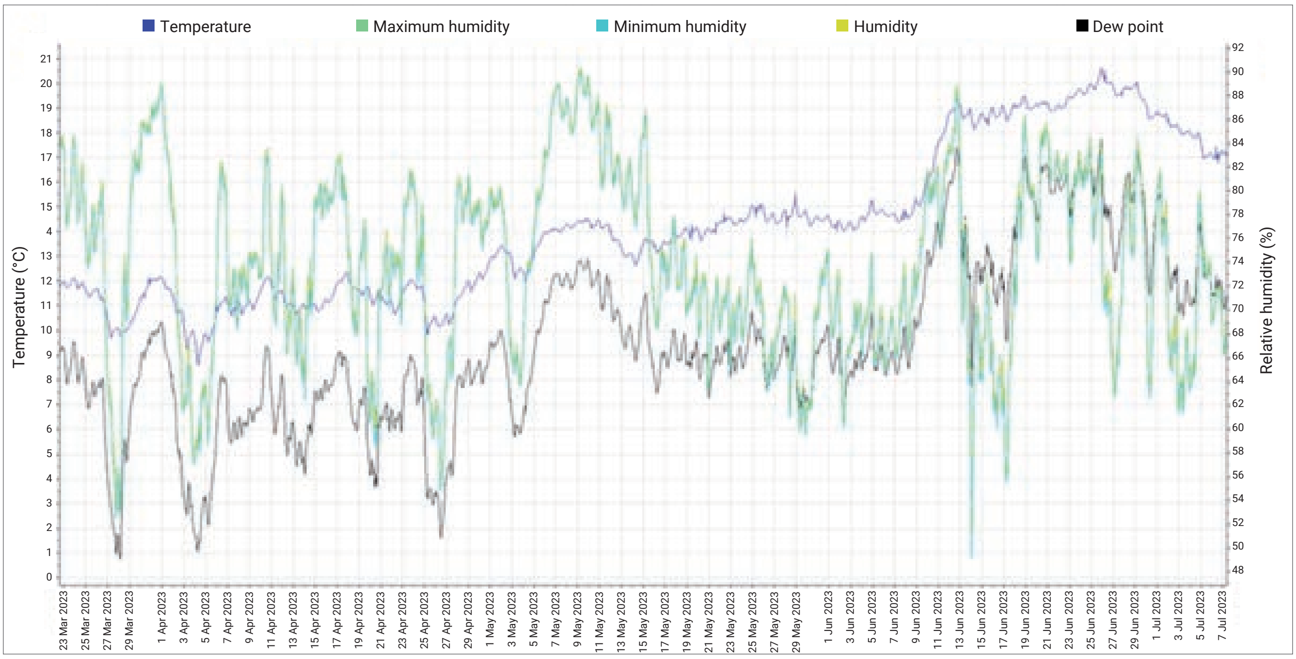


Figure CS4.9 Relative humidity in wall cavity (from 23 March to 21 June 2023)

The RH values (green) vary between 50% and 90%. The fluctuations are quite rapid suggesting that they are following external ambient RH levels. The location of the sensor (at the base of the wall in a lightwell that tends to harbour puddles that probably exaggerate this tendency. On average the RH is around 70%. The temperature (blue) and the dew point (black) plots do not cross and indeed remain several degrees apart, suggesting no interstitial condensation risk.

CS5 Hensford Gardens

Hensford Gardens

Companies involved in the 2023 BPE
Prewett Bizley
Aldas
Build Test Solutions
UKCMB
SOAP Retrofit

Original retrofit architect
Prewett Bizley

Property age
Post-1919 (1969)

GIA area
107 m^2

Typology
Mid-terrace house.

Occupancy
Private homeowner; family of four (two adults and two children)

This is a staged retrofit to the EnerPHit level of performance.

Overview of the original retrofit

Step 1: Cavity wall insulation and internal wall insulation combination to all flank/party walls. Existing flat roof insulated alongside small loft extension. Ground floor slab overlaid with EPS and thin screed. Airtightness measures to walls, though existing windows with large gaps ensured adequate 'natural' ventilation through infiltration. Ductwork for MVHR unit was fitted in 2019.

Step 2: 'End walls' (front and rear elevations) were mostly rebuilt using insulated studwork, and the existing double glazing (with failed units and large gaps) were replaced with triple glazing with very good seals. The heat recovery ventilation unit was fitted shortly after the wall/windows as the natural infiltration plummeted, resulting in variable air quality managed by opening windows.

Step 3: Patio doors at rear and completion of some small areas of insulation and removal of last cold bridges.

An EnerPHit fabric focussed 'step-by-step' process due to budget constraints.

Fabric strategy

The form of the house is a simple 'shoebox', with six faces (i.e. two flank walls, two end walls (elevations), a roof and the ground). Different faces were dealt with in different steps. The adjoining houses are staggered in plan and section, which complicates the insulation strategy. The original solid slab ground floor was insulated in Step 1 by overlaying 80 mm EPS. The original uninsulated flat roof was upgraded with a 200 mm layer of PIR and a new waterproofing membrane.

The walls were mostly cavity wall construction with the floor joists spanning from one party wall to the other. During Step 1, the party walls were filled with insulation and, where the party wall is exposed externally, internal wall insulation was also fitted. The 'end' walls (elevations) were non-load-bearing and were entirely rebuilt as highly insulated timber-framed walls during Step 2.

Thermal bridges: The insulation strategy was carefully planned to almost completely eliminate thermal bridges by the end of the three-step process.

Key areas of focus have been:

1. Heavily bridged infill walls at front and rear, which were simply rebuilt
2. Thermal bridges between party wall and floor slab treated by use of IWI at low level
3. Similar approach between party wall and roof

Airtightness: Unplastered brick areas between floors were parged and joist ends taped onto wall. XPS IWI was taped at joints and abutments with other elements. New VCL below roof insulation provided a continuous airtight barrier to roof. New timber frame walls at ends (elevations) and triple-glazed windows built as-new with robust taping created very tight elements there.

Figure CS5.1 Blower door test through window in 2015

Figure CS5.2 Blower door test through front door in 2023

Services

Hot water is currently produced by a gas combi boiler. A switch to all electric is planned.

Ventilation: PassivHaus certified MVHR unit with 89% efficiency and low specific fan power.

Currently no renewables but PV and solar thermal units are both planned.

Publications of reference

Referenced in the LETI retrofit guide case study 7.

Expected for inclusion in a new version of RIBA's *Residential Retrofit* book by Justin Bere.

selfbuilder+homemaker, July/Aug 2023.

Fabric improvement description and values

Flank walls: 100 mm cavity wall insulation + 100 mm XPS internal wall insulation to, typically, 0.17 W/m²·K.

End walls (elevations): non-structural 'infill' rebuilt entirely as 100 mm insulated timber frame, plus 100 mm PIR with a typical *U*-value of 0.14 W/m²·K.

Roof main: 'Warm' roof with 200 mm PIR insulation. Typically 0.10 W/m²·K.

Windows: Mostly Velfac triple-glazed windows. Average window *U*-value: 0.90 W/m²·K.

Rooflights: Triple-glazed fixed. *U*-value: 1.00 W/m²·K.

Front door: Velfac. *U*-value: 0.45 W/m²·K.

Ground floor: The ground floor was a solid concrete slab which has been insulated over with EPS insulation providing a *U*-value of 0.18 W/m²·K.

Insulation properties: Warm flat roofs are inherently a moisture-closed construction and PIR insulation was used. Similarly the solid ground floor is a moisture-closed system. EPS has been installed above a DPM. The cement-based brickwork is more closed than open and moisture-closed XPS has been used as IWI, well taped on all edges and junctions with airtightness tape.

Overview of the revisited retrofit

Figure CS5.3 Internal wall insulation on party wall exposed to the outside

Figure CS5.4 Step 1: cavity wall insulation with XPS internal wall insulation and plaster board finish

Figure CS5.5 Step 1: cavity wall insulated with polystyrene beads being removed

Significant changes since the original retrofit

As a 'step-by-step' project, building works have continued since the initial occupation in 2016. Figure CS5.6 shows space heating demand and total energy use progressively reduced as fabric is improved incrementally.

Occupancy: The family group has remained the same but the children have grown up from baby and toddler. Pandemic lockdowns for 2020 and 2021 likely increased both domestic electrical loads and hot water use, a pattern which is still partly true.

Building: Refer to step-by-step timeline, Figure CS5.9.

Envelope

Overall fabric performance: After an 8-year process the external envelope work is complete and the space heat demand for 2022–23 meets the PassivHaus Enerphit target. While a number of cold bridges had been left during the process, no condensation was ever observed and these have now been made good. During the March 23 Retrofit Revisit testing, the airtightness test showed that a high level window in the bathroom had been left open for some weeks and this may explain why gas use that month exceeded expectation and why HTC measurements from that month were also much higher than expected. Using data from December 2022, the measured and calculated HTC values show a much closer relationship.

Airtightness integrity: There appears to be a modest difference between the 2016 airtightness test and the 2023 test (0.63 $m^3/m^2 \cdot h$ (q50) and 0.96 $m^3/m^2 \cdot h$, respectively). This may have been due to fabric degradation or the test rig not fitting especially well in the front door opening (it dislodged twice). Post-Retrofit Revisit note: another test was carried out in December 2023, which resulted in q50 0.59 $m^3/m^2 \cdot h$, which confirmed the possible issue with the previous blower door test.

Further investigations: The owner has a moisture content sensor located in one of the cavity walls. The moisture content of a block of timber attached to it varied over the year from 10% to 16%, indicating that the cavity insulation remains 'dry'.

Rectifications: The building fabric is all in good condition and no defects were observed. There was a leak in the flat roof in 2020–21, which has been rectified.

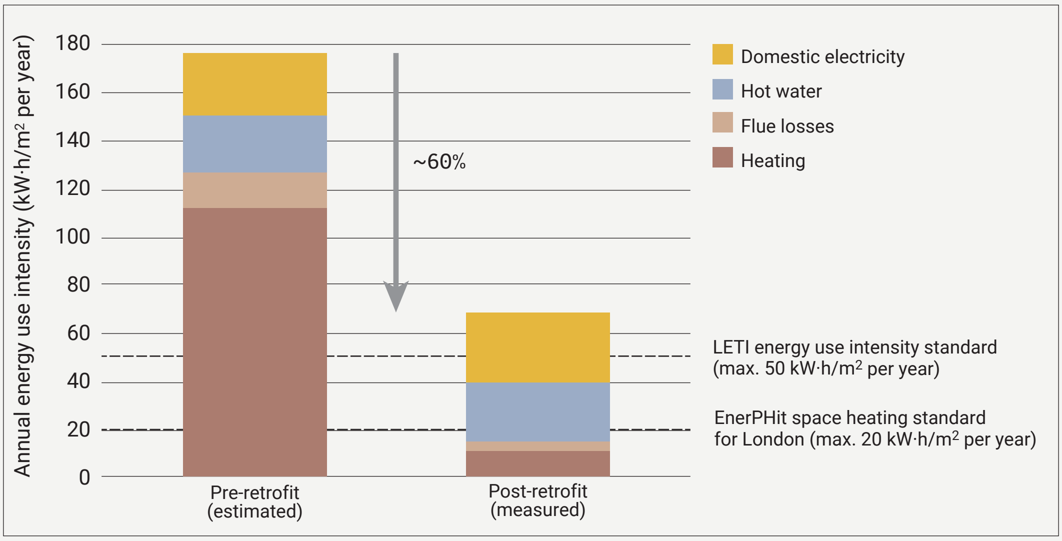


Figure CS5.6 Hensford Gardens; overall EUI comparison before and after retro-fit

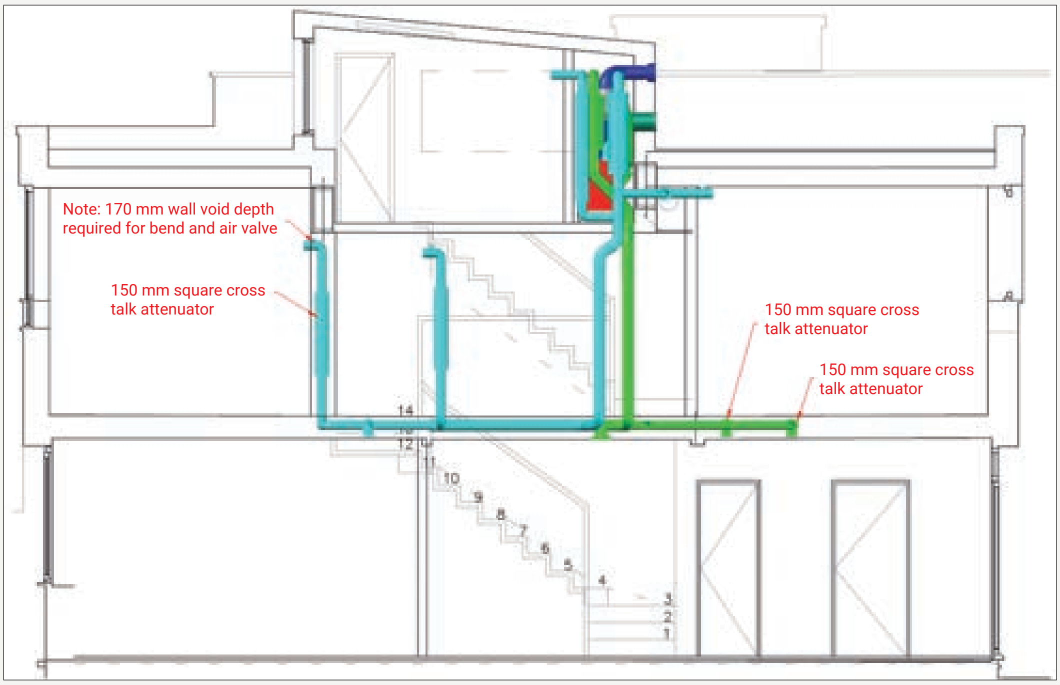


Figure CS5.7 MVHR ventilation distribution diagram

Figure CS5.8 Happy occupant

Services

Heating: The simple 'wet' heating system consisting of five small radiators has provided adequate heating for the whole house since the first retrofit step.

Hot water: 'Combi' boiler. The hot water consumption appears to be relatively high (around 1800–2500 kW·h/year, depending on the year) based on summer measurement, suggesting a daily consumption of 7 kW·h/day. This may be due to poor boiler efficiency associated with short duration wash handbasin and kitchen tap use, possibly exacerbated by a long
pipe run (6 m) to the kitchen tap.

Ventilation: The MVHR unit was installed by the building owner who is an architect who used a balometer to roughly balance the system, and has tested the CO_2 count within rooms. Measurements of electrical use suggest an annual consumption of 460 kW·h/year, in line with the PassivHaus PHPP estimate of 480 kW·h/year. The primary ducts are made of EPS insulation but are missing a layer of 'armaflex' neoprene closed cell insulation around, which has left galvanised jointing pieces exposed giving rise to occasional 'sweating'. Filters are changed three or four times per year.

Energy performance (averages over 12-year measurement period)

March 2023 data: The gas usage in March 2023 was around 17 kW·h/day. Discounting for flue loss and hot water left around 9 kW·h/day, whereas a PHPP model suggested around 6–7 kW·h/day. So, March 2023 appears to be an outlier (see note earlier about a window that was apparently open during the testing period).

Annual data for Step 1 project: The PHPP model predicted heat demand of the original retrofit was around 60 kW·h/m^2 per year (assumed internal temperature of 20 °C), and the measured use was around 50 kW·h/m^2 per year (internal temperature of 21 °C).

Annual data for the completed project in 2022–23: The total annual gas use for 2022–23 was 39 kW·h/m^2 per year (using GIFA) with a split of 24 kW·h/m^2 per year for hot water, assumed waste of 4 kW·h/m^2 per year associated with the flue and an interpolated space heat demand of 18 kW·h/m^2 p.a.

The EUI measured for 2022–23 was approximately 70 kW·h/m^2 p.a. (with a high-ish domestic electric use of 30 kW·h/m^2 p.a.).

Indoor environment: Temperature, relative humidity have all been good since Step 1 of the retrofit and have tended to become more stable as the retrofit steps progressed (refer to Figures CS5.9 to CS5.11). During winter 2022–23 the average temperature was 19.7 °C and the previous two years were almost identical. Living spaces tend to be around 21 °C and bedrooms closer to 19 °C as a matter of occupant choice. During the summer periods, it is clear that the relatively large glazing area can make the house prone to overheating, though when the occupants are at home and able to manage natural ventilation and shading, the annual overheating is only 7%. The relative humidity plots for various rooms falls within the 40–60% ideal bandwidth. The CO_2 levels in March 2023 were invariably below 1000 ppm and have been consistent since the MVHR installation. Before that point the occupant had managed to keep CO_2 levels low by relying on infiltration and opening/closing windows.

User feed-back: (Based on survey provided by Zack Gill of SOAP Retrofit).

The homeowner is generally very satisfied with the house, except for some reservations regarding the tendency to overheat in the summer peak temperatures. An effective seasonal shading system is being investigated to mitigate this risk.

Description of the BPE approach:

- SmartHTC measurement/calculations
- mould risk assessment
- airtightness measurements (blower door test and Pulse)
- eight years of energy consumption and internal environment data.

Table CS5.1 2023 BPE findings: details

	Pre-retrofit	Original retrofit	Retrofit revisit
Annual energy use	178 kW·h/m² per year (robust estimate)	110 kW·h/m² per year (in 2016) Gas: 8787 kW·h, i.e. Step 1 retrofit Electricity: 2844 kW·h	70 kW·h/m² per year (in 2022–23) Gas: 4214 kW·h Electricity: 3264 kW·h (Both extrapolated to a full year, from data covering 11th June 2022 to 6th June 2023.)
Airtightness levels		0.63 m³/h·m² @ 50 Pa	Blower door test: 0.96 m³/h·m² @ 50 Pa Pulse test: 0.17 m³/h·m² @ 4 Pa (estimated 1.02 m³/h·m² @ 50 Pa)
Fabric moisture tests			
Thermography			See images (Briefing 4)
Pre-retrofit	No measurements from pre-retrofit, but there were some signs of modest damp issues in lower ground and mould around windows. Neighbouring houses suffer similarly.		
Original retrofit	There were no observable moisture issues following the retrofit works. RH levels have been consistently stable save for some rooms with slightly elevated RH which may be associated with a small roof leak (now resolved).		
Retrofit revisit	The sensor fitted within the cavity showed moisture content below 18% that falls to less than 10% in summer, indicating safe cavity insulation.		
HTC	450 W/K (taken from PHP)	147 W/K (taken from PHP)	Several tests were carried out over the evaluation period. The one shown here had the smallest (i.e. best) confidence interval. 67 W/K (taken from PHP) 109 W/K [−31/+27] (BTS March 2023) 110 W/K (BTS Dec 2022 data)
Mould risk	Using data gathered in a neighbour house as a 'proxy' the BTS calculation showed a medium score of 36/100.	Have not yet run risk test for mid retrofit though do have data.	BTS mould risk score showed 'very low' with 3/100 score, i.e. 1 on 0–4 scale.
Walls	Generally cavity wall, though some sections solid including corners and around windows. The cavities were clear and the face of the wall in good condition.	The party cavity walls were all filled with 100 mm glass-wool and 100 mm of XPS was used as IWI on all external areas. The front and rear walls were also filled with polystyrene beads.	The Step 2 retrofit involved the front and rear walls being rebuilt as insulated stud construction. A sensor in he cavity wall indicates that moisture levels are satisfactory.
Ground floors	Solid slab with screed topping on ground with DPM between.	80 mm EPS insulation added over brush-applied DPM with thin screed over.	No change but tiled floor finish now complete and all in good condition.
Roofs (retrofit revisit)	Original flat roof with 50 mm 'woodwool'. Poor condition.	New 200 mm thick PIR warm flat roof. New GRP membrane failed at two junctions, leading to water ingress during 2020–21 and has been overlaid with and EPDM system.	All in good condition. No further water ingress.
Windows and doors	Double glazed UPVC. Numerous units had failed. Gaps between opening and fixed frames, and glazing gaskets decayed. No airtightness foam/tape between frame and wall.	UPVC double glazing left in as part of Step1 retrofit, leading to drafts at building perimeter and levels of infiltration for no mechanical ventilation.	New triple-glazed units were fitted during 2019 as part of Step 2. These have performed well and greatly enhanced the airtightness.

Indoor environmental performance

Temperature: See Figure CS5.12. The March 2023 temperature record showed an average internal temperature of around 19.5 °C, which closely matched the winter average of 19.7 °C (perhaps a little cooler due to the open window). Rooms are set (by TRV) to differing temperatures but generally between 19–21 °C. Temperatures look very stable with a modest daily fluctuations less than 1 °C.

Relative humidity: Generally 40–60% for the March 23 period. This is seen as very 'good' (see Figure CS5.14).

CO_2 concentration: The CO_2 levels during March remain constantly below 1000 ppm, indicating very good air quality, except when the airtightness test was done and the unit switched off. The monitoring done from 2018 to date showed similar continuous low levels of CO_2.

Commentary on physical findings versus user feedback: The internal temperature, RH and CO_2 levels have been stable and at close to ideal levels which matches the positive feedback. Looking at the longer-term measurements provided by the occupant, the home appears to have become more comfortable over time. It is interesting to note the slight reduction in internal air temperature that took place when Step 2 was carried out, suggesting that fewer drafts and higher internal surface temperatures allow a slightly lower internal temperature. The current heating demand appears to be under prediction, though this may be partly accounted for by the higher than normal internal gains associated with the domestic electrical use, as well as the internal average temperature being just below the modelled 20 °C assumed in PHP. After the new airtight windows were fitted, the occupant noted that commissioning the MVHR became essential as managing CO_2 by opening/closing windows became very difficult.

Services strategy

Hot water: The hot water is produced instantaneously by combination boiler.

Space heating: The space heating has heat emitters in only five spaces. The system is powered by a Worcester condensing boiler without weather compensation, operated by simple thermostat/programmer.

Electricity: Measured data shows an annual domestic electrical use of 3150 kW·h/year (29 kW·h/m² per year), which is quite high. This appears to be inflated by a 'rogue' refrigerator which consumes close to 3 kW·h/day (almost three times its declared value). If this is replaced, the annual use is expected to fall to less than 2300 kW·h/year.

Ventilation: There is a 'Paul 200' MVHR unit in the loft extension with short insulated primary ducts and a rigid metal branch ductwork system for supply and extract. PHP indicated a performance of 89% heat recovery.

Renewables: Currently there are none. PV and solar thermal planned for future.

User feedback

Questionnaire findings: SOAP BUS used. The homeowner is generally very satisfied with the house, except for some reservations regarding the tendency to overheat and the overabundance of daylight within some of the spaces. Both are a result of the original glazing pattern and large glazed area to the new loft extension. While the glazing area at the rear was reduced a little, a bolder approach would have reduced the overheating. The owner/designer is intending to fit 'clip on' external shades to a number of windows in 2024, having trialled some mock-ups in 2023 to good effect.

BPE techniques: lessons learned

The short time to plan the testing, combined with limited study period to carry out the tests, reduced the potential scope and value of some of the findings.

Airtightness testing (blower door and Pulse): The blower door test was hampered by the owner not having closed all windows and the door rig slipping out of the opening more than once. The difference between previous tests was around 0.3 m³/h·m² @ 50 Pa, which is small and could be attributed to measurement error. The blower door test and Pulse results seemed to align quite well, indicating that PULSE may be useful for measurement of permeability, if not leak detection. It is worth noting that, in this case, open windows were only disclosed by running the blower door fan. As PULSE does not highlight such issues it may be prone to recording misleading measurements.

Views on methodology: While the March 2023 HTC measurement seems to be unrepresentative due to a window being left open for most of the period (resulting in higher than normal gas use). A similar SmartHTC calculation has been performed using available data for December 2022. This output was much closer to that from PHPP but still markedly different (110 versus 67). This may be due to assumptions made by the HTC calculator regarding hot water use, compared with a known high-ish consumption. The more energy efficient any house is, the bigger any impact between real and assumed hot water consumption will have in the HTC assessment. So, for highly efficient houses, this tool may be less reliable.

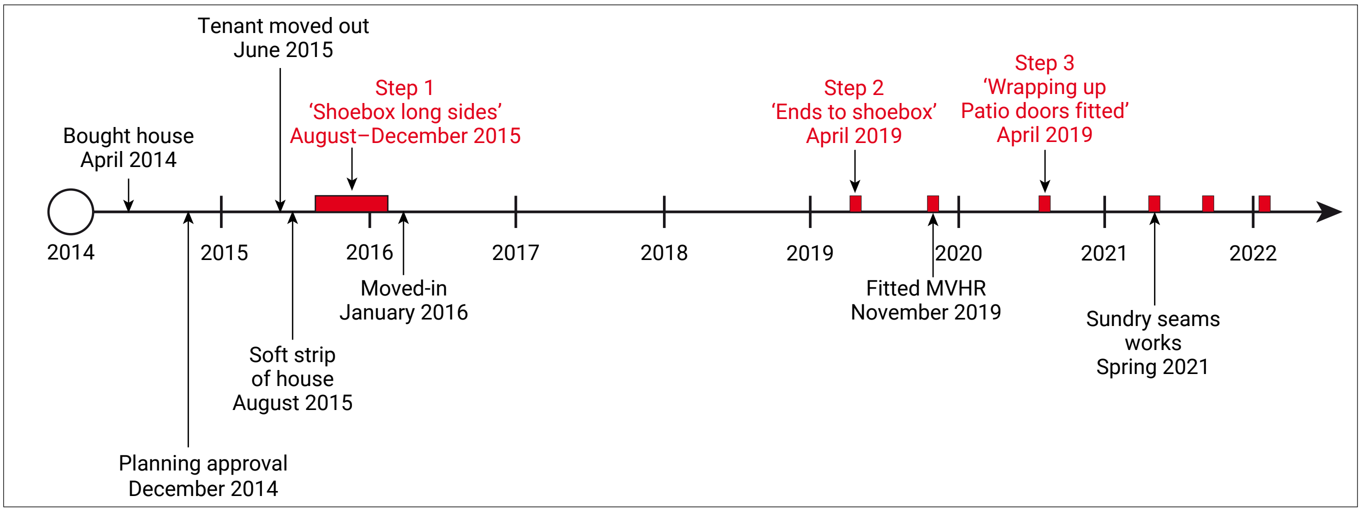


Figure CS5.9 Timeline showing when key retrofit steps were taken.

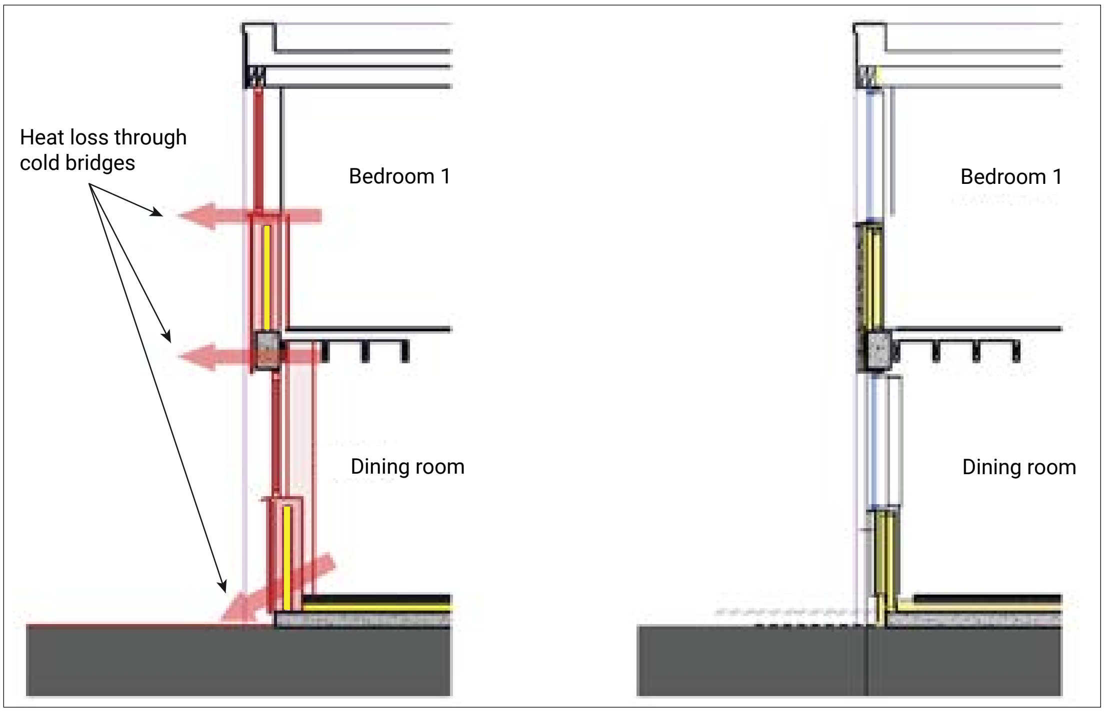
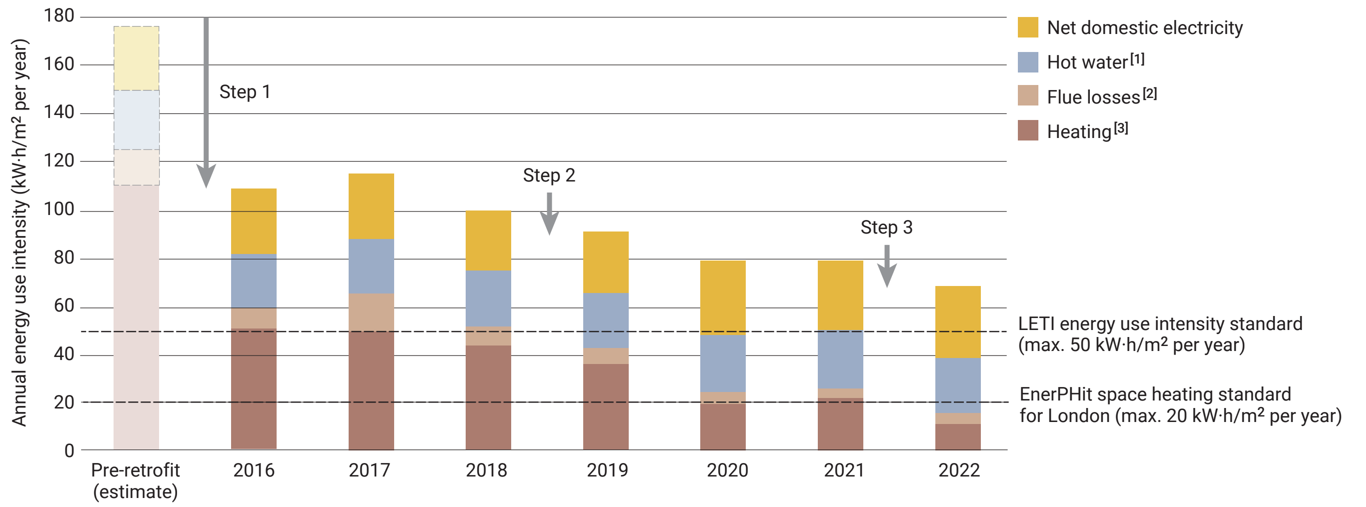


Figure CS5.10 Section drawings showing before and after Step 2. Note how the rebuilding of the wall facilitates the removal of a number of cold bridges.



Notes:

[1] Annual hot water use is inferred as 10 kW·h/m² per year, based on recording gas use over one summer when heating was off.

[2] Overall gas use has not changed significantly, therefore it is assumed that boiler efficiency (and flue losses) have remained consistent. The boiler was assumed to be 90% efficient.

[3] Space heating demand is inferred having made the assumptions on energy use for hot water and flue losses.

Figure CS5.11 Hensford Gardens; EUI following retrofit.

This bar chart depicts seven years of measured EUI, showing how the 'step-by-step' process has lead to a very large energy reduction.

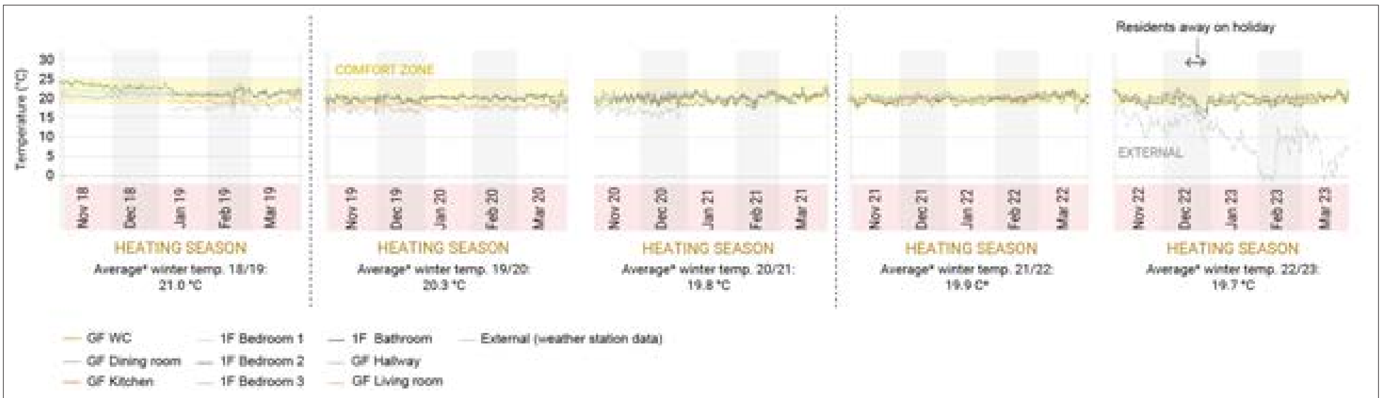


Figure CS5.12 Temperature in various rooms over five heating seasons

Generally the internal temperatures can be seen to be very stable and getting more so as further retrofit steps are completed. It is interesting that the average temperature year-on-year has fallen a little, possibly as the occupants have got used to 'tweaking' TRVs to optimise room temperatures but also possibly due to fewer and fewer draughts and higher and higher internal surface temperatures.

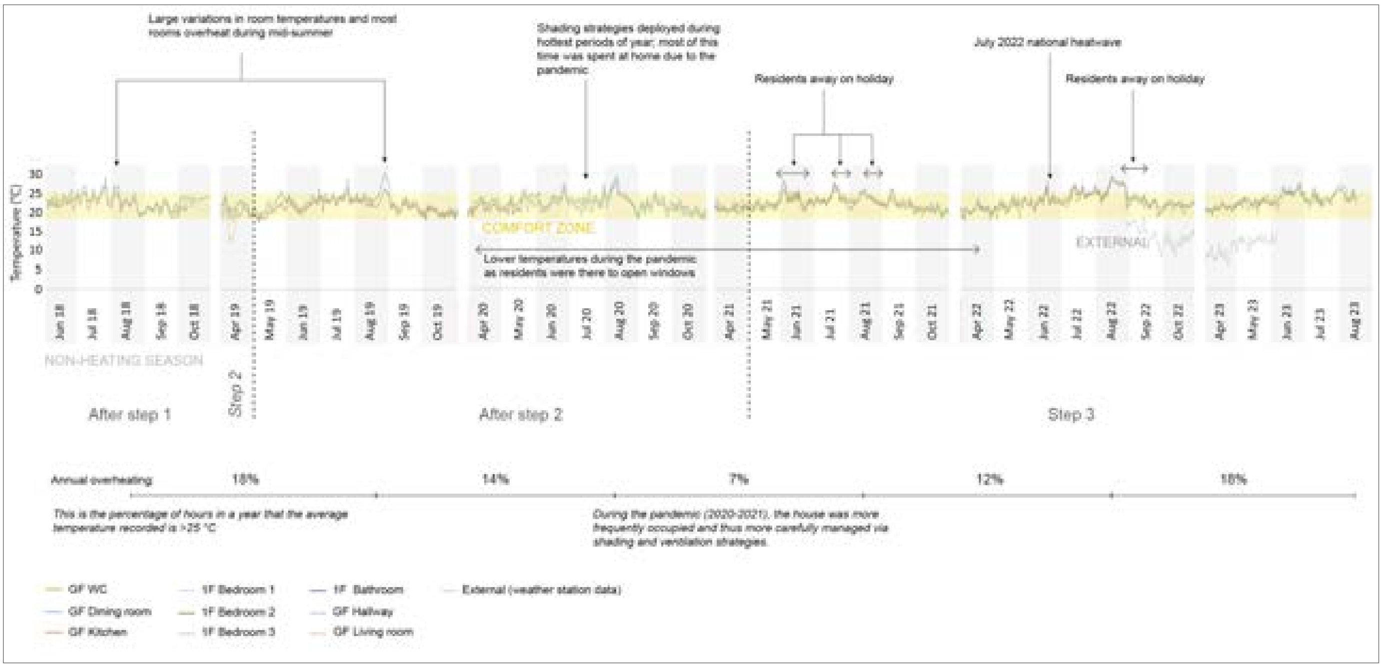


Figure CS5.13 Summer seasons 2018–2023; temperature sensor data (°C) daily average)

The graph above shows internal temperatures within several rooms outside the hating season. It can be seen that the house is prone to overheating, varying in annual percentage between 7% and 18%. Much of this occurs when the occupants are away in the summer time (they tend to spend 4–6 weeks in France with family) and the windows remain closed. The Covid-19 lockdown of 2020 reduced the overheating to 7% of the 2020–21, as the occupants were able to purge ventilate and deploy external shading. During the July 2022 heatwave, temperatures inside were held down to 26 °C despite external temperatures of almost 40 °C, by deploying makeshift shading to all openings and keeping windows closed all day. This suggests that if additional retractable shading devices are fitted that the overheating can be controlled much more successfully.

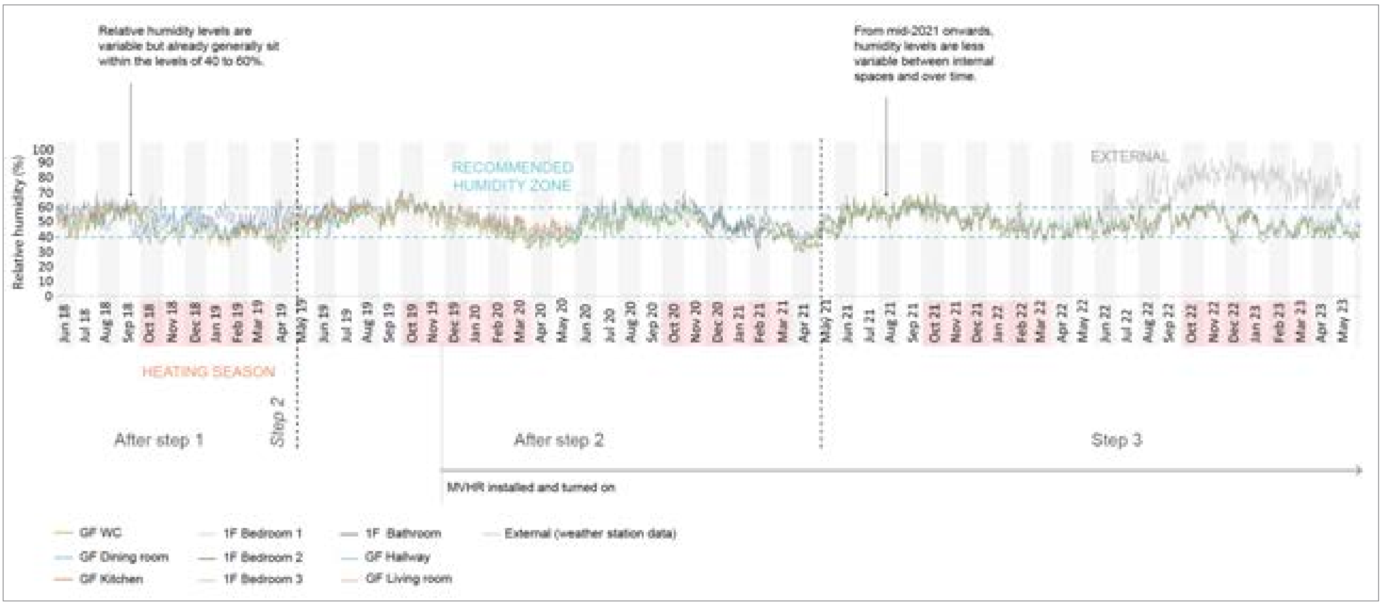


Figure CS5.14 Relative humidity, June 2018–present

Relative humidity plots of various rooms from June 2018 to present. It can be seen that for all stages of the retrofit, the RH generally falls close to the ideal 40–60% band. That is even before the MVHR was fitted and ventilation was provided by large infiltration only. The stable and warm internal temperature during that period has supported good RH levels. The plot for the year 2022–23 is especially close to the 40–60% range, and much lower generally when compared to the external levels (see May 2022 to May 2023). This improvement is coincident with the resolution of a roof leak that took place in some of the upstairs bedrooms and may have resulted in elevated RH levels in those spaces.

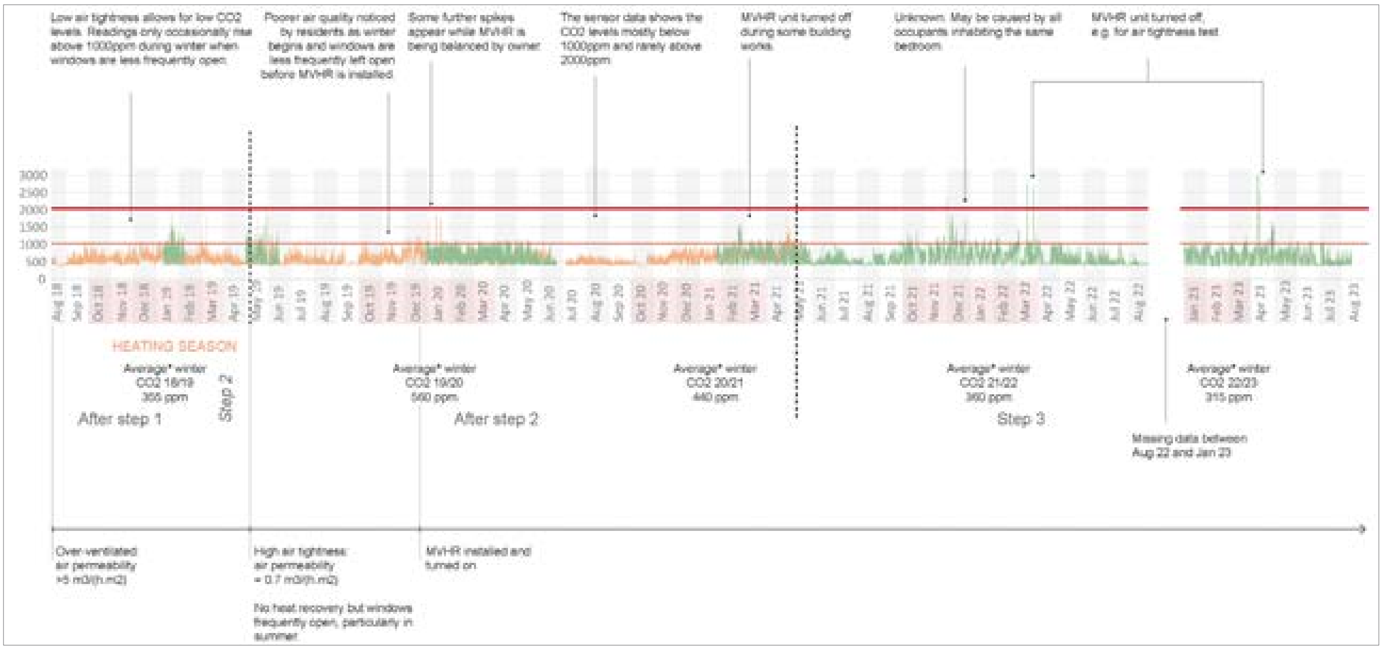
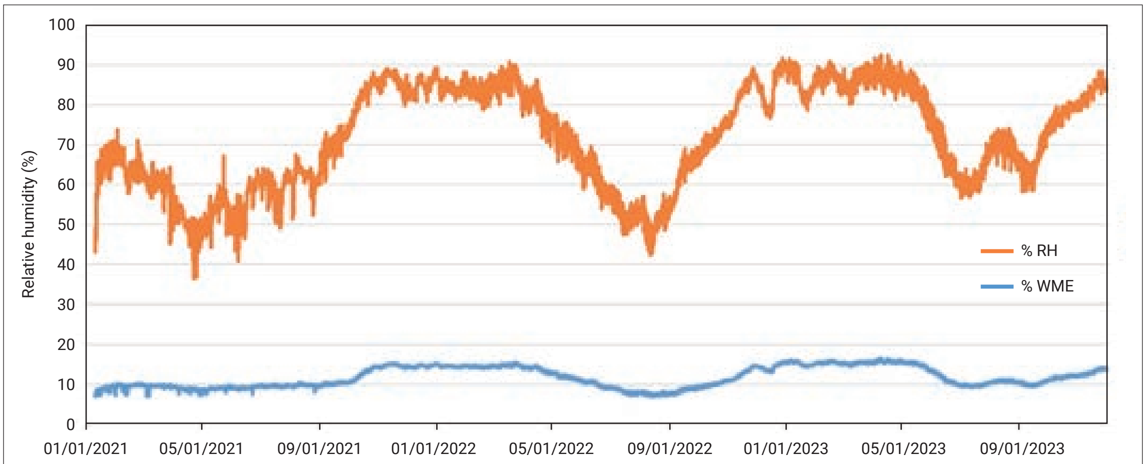


Figure CS5.15 CO_2 sensor data (ppm, hourly average)

CO_2 measurements from August 2018 to August 2023. The CO_2 records indicate that generally CO_2 levels have stayed well below 1000 ppm for the entire project including Step 1, when there was no MVHR but significant infiltration. During spring 2019, after new windows 'tightened' the fabric, one can see an elevation in concentration but that falls away as summer allows windows to stay open. After December 2019 when the MVHR is commissioned, concentrations fall to a steady level below 1000 ppm. There are a few isolated spikes after this, for instance when the MVHR is switched of for testing or due to building works taking place. During winter 2021 there are some spikes that are coincident with a period when one of the children regularly slept with her parents during the nighttime.



	Relative humidity (RH) within wall insulation within cavity (%)	Moisture content of timber block attached to sensor (WME) (%)
Minimum	36.40	6.90
Maximum	91.70	16.00
Difference	55.30	9.10

Figure CS5.16 Moisture content within timber block in the middle of one of the cavity walls (from 1.01.2021 to 9.01.2023)

There is a clear rise and fall of moisture content as the RH rises and falls due to the changing temperature. The moisture content never goes above 16.6% — 18% or 20% are normally considered thresholds at which concerns might be raised over potential timber decay. The results indicate that the cavity wall insulation is not giving rise to any long-term moisture problem and that if additional retractable shading devices are fitted that the overheating can be controlled much more successfully.

CS6 Rectory Grove

Rectory Grove

Companies involved in the 2023 BPE
QODA
BTS
Aeldas

Original retrofit architect
Arboreal (Harry Paticas)

Property age
Pre-1919 (built in the 1840s)

GIA area
Approx. 201 m^2 GIA from SAP (170 m^2 TFA from PHPP)

Typology
Semi-detached Grade II listed Victorian townhouse in conservation area

Occupancy
Freehold; occupancy two adults

One-off retrofit. Completed October 2013.

Overview of the original retrofit

The retrofit design ambition was to sensitively restore the structure and fabric of the house by respecting original features (see Figures CS6.8 to CS6.10); install quality kitchens (Figure CS6.10) bathrooms and services fit for a modern lifestyle; open-up dark lower ground floor (Figure CS6.11); thermally upgrade the house following English Heritage retrofitting best practice; create a comfortable and liveable home, fit for the 21st century and beyond.

Fabric strategy

Insulation strategy: Fabric-first approach. IWI — solid brick building internally insulated with nine types of insulation material including Woodfibre, Aerogel, IQ Therm (capillary active polyurethane rigid foam panel), responding directly to localised historic fabric and performance requirements (see Briefing 5, Figure 5.1).

Thermal bridges: Careful analysis of building material elements pre-retrofit provided key information for appropriate strategies. Long-term monitoring has further vindicated this approach.

Airtightness: All walls plastered with lime plaster as air tightness layer.

Services

Heating and hot water: gas central for heating and hot water with solar thermal panels top-up, and a back-up fireplace for low occupancy. DHW cylinder thermostat was initially set high at around 65 °C but reviewed and lowered to 55°C after occupation, thus reducing hot water energy costs.

Ventilation: Continuous mechanical extract (MEV) from kitchen and wet rooms, extracting a total of 0.4 ach, ensuring warm moist air pulled away from fabric out through fans.

Publications of reference

First listed building in England to meet the AECB Silver Performance Standard 2013; Low Energy Building Database 02.06.2014; LETI Climate Emergency Retrofit Guide Case Study 9; *A study of the Roof Environment in Four Domestic Buildings* (Historic England, 2022); *Passive House+*.

Fabric improvement description and values

Pre-design investigations included *U*-value monitoring of brick walls, brick permeability and air leakage testing.

Walls: Various types of insulation (see Briefing 5, Figure 5.1) with *U*-values improved performance from 0.11 W/m^2·K to 0.58 W/m^2·K. External insulated walls achieved an average *U*-value of 0.15 W/m^2·K.

Roofs: Blown cellulose insulation improved the *U*-value to 0.15 W/m^2·K.

Windows and doors: Original single-glazed sash windows with secondary double-glazing with *U*-value of 1.25 W/m^2·K (Figure CS6.1). Front and back doors insulated to give a *U*-value of approx. 0.9 W/m^2·K.

Insulation properties: Vapour-open materials except at lower ground floor level where moisture levels below ground require vapour-closed materials and membranes. Generally low or non-flammable attributes enclosed in wall or roof compartments. See Briefing 5, Figure 5.1 for palette of insulation materials used.

Overview of the revisited retrofit

Figure CS6.1 Condensation.

Build-up on outer panes of most exposed east-facing top floor sliding sash as a result of secondary glazing overcome by discrete angled slot at top and bottom of single-glazed sashes to create air circulation but without impairing visual appearance required for conservation guidelines.

Figure CS6.2 Insulated back door, with good seals and locks.

Figure CS6.3 Blower door test

Figure CS6.4 Pulse test equipment

Significant changes since the original retrofit

Occupancy: The same residents have been in continual occupation over the past 10 years.

Building: No significant changes. In September 2022, roller blinds were install on some larger windows to control solar gain and ensure privacy on east-facing wall.

Envelope

Overall fabric performance: Consistent over 10 years suggesting a detailed and thoughtful approach with a high quality level of construction and skill. Minor deterioration in performance can be attributed to settling of elements and irregular maintenance schedule (not unusual). *U*-value test on north wall implied a slight deterioration from the original result of 0.41 $W/m^2 \cdot K$ in 2013 to 0.45 $W/m^2 \cdot K$ in 2023, but the location tested may be a factor.

Airtightness integrity: While the original retrofit in 2013 achieved an air permeability of 2.6 $m^3/h \cdot m^2$ @ 50 Pa, the 2023 results held up relatively well at 3.01 $m^3/h \cdot m^2$ @ 50 Pa.

Further investigations: Thermograpic survey of entire building would be informative. Effect of blinds on overheating risk. Ventilation rates checked.

Rectifications needed: Minor maintenance and repair works. None significant.

Services

Heating: No change to gas central heating system. Hot water: a new manual override control was added to enable more immediate hot water heating if required. No changes in recent years.

Ventilation: No changes to original strategy but one unit may require refixing as vulnerable to knocks (Figure CS6.5).

Energy performance:

SAP GIA 201 m^2	2020	2021	2022	March 2023
EUI ($kW \cdot h/m^2$ per year)	75.58	83.25	66.80	7.54
Gas ($kW \cdot h$)	10478	12088	8859	1186
Electricity ($kW \cdot h$)	4043	3975	3227	291
Space heating (gas) ($kW \cdot h/m^2$ per year)	52.13	60.14	44.07	5.90
Output from onsite solar thermal system ($kW \cdot h$) (actual for March 2023; estimated for previous years)	670.6	670.6	670.6	39

Figure CS6.5 Low level extract unit in WC

The unit is taped for air test but vulnerable to knocks from vacuum cleaners and floor mops — there was evidence of its having been dislodged before the tape was applied.

Figure CS6.6 Worcester heating controls in hallway

Symbols, layout and buttons are reported as confusing for a non-technical person to use.

Figure CS6.7 Solar thermal panels

The panels have remained robust and consistent over 10 years.

The onsite energy generation over a 10-year period was 6706 kW·h, which has been allocated equally over each year indicated (670.6 kW·h/year). The onsite generation for March 2023 was 39 kW·h.

Indoor environment: The average temperature from bottom to top of the house ranges from 19.5 °C to 21.0 °C. Min. temperature recorded: 18.4 °C. Max. temperature recorded: 23.0 °C Average relative humidity from bottom to top of house ranges from 56.3% to 54.2%, being relatively drier in the middle floors at around 47%. Min. RH recorded: 39.4%. Max. RH recorded: 79.6%. Average CO_2 over 29 days in sitting room: 607 ppm (7am–11pm) with min. 421 ppm and max. 1583 ppm recorded. Max. CO_2 recorded (night time family event) 2381 ppm (see Figure CS6.14).

User feedback: Property has very few issues and the whole house (deep retrofit) is generally performing well. It is rated 'good' at 81% compared to benchmark scores, with little negative feedback from the residents (see 'User feedback' below).

Description of the BPE approach: Core BPE approach. In addition, the house was monitored extensively for several years by the architect working with Historic England, with results published in several articles freely available on the internet. The architect has stated that monitoring showed that three years was needed for the property to stabilise to ensure results are not skewed. The performance of the roof, for example, showed a continued low condensation risk in 2016 with the summer condition allowing drying out (Figure CS6.15). Given the detailed historic monitoring and the fact that the owners did not wish to have further invasive testing, as well as evidence of consistent performance and low risks of mould, the property was not selected for further detailed testing.

Table CS6.1 2023 BPE findings: details

	Pre-retrofit	Original retrofit	Retrofit revisit
Annual energy use	152 kW·h/m^2 per year (SAP GIA) gas + electricity. No breakdown available. No solar on-site	2014: • Gas: 9146 kW·h • Electricity: unknown • Solar thermal: 671 kW·h (estimate based on 10-year output) i.e. EUI: unknown (gas + solar thermal EUI: 49 kW·h/m^2 per year)	2022: • Gas: 8859 kWh • Electricity: 3227 kWh • Solar thermal: 671 kWh (estimate based on 10-year output) i.e. EUI: 63 kW·h/m^2 per year
Airtightness levels	Pre-retrofit: 9.6 ach^{-1} @ 50 Pa (blower door test) (Archimetrics)	Air permeability: 2.6 m^3/h·m^2 @ 50 Pa (Aldas) (2.0 ACH @ 50 Pa)	Blower door test: 3.01 m^3/h·m^2 @ 50 Pa (BTS) (2.36 ach^{-1} @ 50 Pa) Pulse test: 0.51 m^3/h·m^2 @ 4 Pa (estimated 2.81 m^3/h·m^2 @ 50 Pa)
Fabric moisture tests	Detailed tests investigated fabric condition and performance. Karsten tests carried out to establish the relative porosity of the existing brickwork and establish the appropriate type and level of internal insulation to ensure there would be little or no interstitial condensation build-up.	Sensors installed in the retrofitted walls, in the roof space and in between existing retained sliding sashes and the new secondary glazing. Results over seven years showed a reduction in moisture levels as the house was occupied and gradually dried-out after the building and plastering work, reaching a reassuringly steady and safe state. All results previously published.	No further tests
Thermography	N/A	N/A	N/A
HTC		Estimated design HTC from PHPP is 171.6 W/K	SmartHTC measured results: (HTC) of 208 W/K [–99/+81] and heat loss parameter (HLP) of 1.1 W/m^2·K giving a 'good' rating
Mould risk			BTS mould risk score is 12/100, or 1 on 0–4 scale, which gives property a low risk rating for mould and indicates a good level of ventilation. Results are consistent with internal conditions, i.e. Internal temperatures are at around 20 °C with average internal relative humidity level across the property of 52.2% RH.
Walls	Overall 0.88 W/m^2·K (*U*-value test) (significantly lower than calculated value (1.14 W/m^2·K)	0.41 W/m^2·K (2013)	North wall *U*-value plates results: 0.45 W/m^2·K (2023)
Floors		New floors	Well maintained
Roofs		New roof elements	Well maintained
Windows and doors		Refurbished and upgraded windows and doors with good seals. Secondary double glazing (DG) installed to retain period facades as required by listed status and conservation area guidelines. DG also helps maintain even temperatures and reduces drafts and heat losses.	10 years later some windows in need of repainting depending on exposure levels and orientation. Garden doors are experienced as a little heavy but have good seals. Occupier considering replacement of ground and lower ground doors to ease usage.

Indoor environmental performance

Temperature: Generally comfortable and even temperatures. Average 20.2 °C (i.e. consistent with the temperature setting of 20 °C) with average minimum 18.8 °C and average maximum: 21.8 °C. Hottest temperature recorded during March was in top bathroom at 23 °C. Average temperature difference across the house, from bottom to top floor, of 1.5 °C (Figure CS6.13).

Relative humidity: Generally stable humidity levels with average across house of 51.2% RH. Average min. recorded: 44% and average max: 66.5%. Highest RH recorded during March were in the kitchen/diner at 79.6% and top bathroom at 77% for a short period only. Average RH differences across house of 2.1%.

CO_2 concentration: The CO_2 sensor in sitting room gave average daytime (7am—11pm) level of 607 ppm and night time average was 704 ppm over 29 days, regarded as very good generally and within a safe range suggesting that the mechanical extract ventilation strategy is working well whilst also noting low occupancy. A family occasion created a night time peak of 2381 ppm otherwise the min. daytime figure recorded was 421 ppm and a max. of 1583 ppm. The peak, min.and max. figures were for relatively short periods. The family occasion with a sleepover elicited a figure of 1250 ppm or over for about six hours. This would suggest the need to ventilate locally, e.g. by opening a window, when a party is underway.

Commentary on physical findings versus user feedback: The evaluator visited on three occasions for several hours and noted that the indoor air quality felt clear, unstuffy and without odours. The occupiers reported they are very satisfied with the indoor temperatures and air quality. Their only concern is seasonal, when the house can feel overheated in summer months, particularly at upper floors. Internal roller blinds installed as shading on some of the larger East facing windows in the gap between the original windows and the secondary glazing but this has not yet been put fully to the test as only operational since mid-September 2022. This shading can be controlled wirelessly for ease and speed. Humidity levels feel comfortable. The mould risk score indicates there is little to worry about in terms of moisture management, which confirms the visual inspections.

Services strategy

Hot water: Lowering of DHW thermostat from 65° to 55°, which was done in the early years post-retrofit, noticeably reduced hot water energy costs. It appears immersion heater may have boosted electricity use but is now controlled, leading to lower usage.

Space heating: Occupants reported controls are over-complex and unclear for a non-technical user (Figure CS6.6) and could be simplified to enable easy reading of significant data points, i.e. temperature, energy use and generation. The wood-burning log fire (sealed unit with CO sensors and ducting) has only been used twice as it is not necessary for heating. The residents have commented that it was an 'expensive decorative feature'.

Electricity: New smartmeters installed in July 2022 meant a short period of estimated billing. With mostly only two people in the house, appliance use is relatively low. Lights are routinely turned off when rooms are unoccupied. Task lights in studies.

Ventilation: Continuous mechanical extract ventilation units all operating very quietly and seem well maintained. The unit in utility room is at low level near the WC and may be prone to being slightly knocked with consequent pulling away from the wall and possible compromise of air leakage around the ventilation duct. A small protective grille may be useful. Unusually, kitchen ventilation has both recirculating and direct extract options (Figure CS6.11).

Renewables: Very compact solar thermal array with consistent performance (Fig.15). More and new PV panels may generate more useful energy in kW·h but cost, disruption and embodied carbon of replacement are factors against upgrade. Note that solar thermal panels are typically 70% efficient whilst PVs are around 20%. Helpful contribution to overall energy bills. Panels cleaned annually but on separate maintenance contract by service provider, so limited financial benefit.

User feedback

Questionnaire findings: Property has very few issues and the whole house (deep retrofit) is generally performing well. It is rated 'good' at 81% compared to benchmark scores, with little negative feedback from the residents. The designed temperature preference of 20 °C is consistently met and very steady in winter. Current concern is to control cooling: roller blinds are anticipated to help from next summer to counteract effects of overheating during heat waves. Condensation arises when using clothes dryer otherwise very little between outer windows and secondary glazing. No signs of mould. Building handbook is most useful for knowing makes and models of items if they need attention, otherwise introduction to building provided by builders and design engineer. The main other reported downsides are:

- no water on principal floor (upper ground).
- many flights of stairs can be a challenge as the owners get older but this was appreciated at the time of buying and it was noted that stairs can be beneficial for continued agility.

BPE techniques: lessons learned

A thorough investigation into the fabric of the building prior to any retrofit measures being implemented combined with careful attention to detail by the builder meant quality work and long-term benefits in performance have been achieved. Long-term monitoring post-occupancy (at least three years) by Historic England has vindicated this approach. This quality has indicated a more comfortable home with less maintenance costs over the longer term, albeit that some maintenance work is now due. Low occupancy has tended to skew energy use intensity per person. There may be a tendency to maintain heat demand for longer in an already warm house so energy use creeps up but milder winters are contributing to lower energy costs as comfort is maintained. Occupant behaviour in relation to energy usage also has a significant impact.

Airtightness testing (blower door and Pulse): Both original and retrofit revisit blower door test were located at the front door for consistency. The size of the house meant two Pulse test units were required.

Views on methodology: The extensive monitoring undergone at this house historically has informed much of the approach. The revisit methodology has helped to indicate that the fabric investigation and resulting retrofit is an exemplary approach.

Figure CS6.8 Front façade

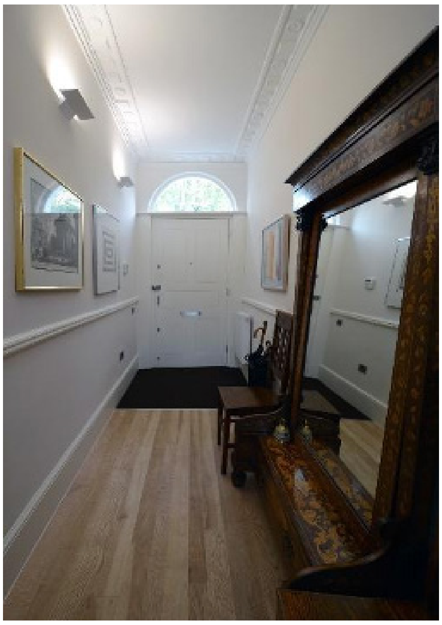


Figure CS6.9 Hallway

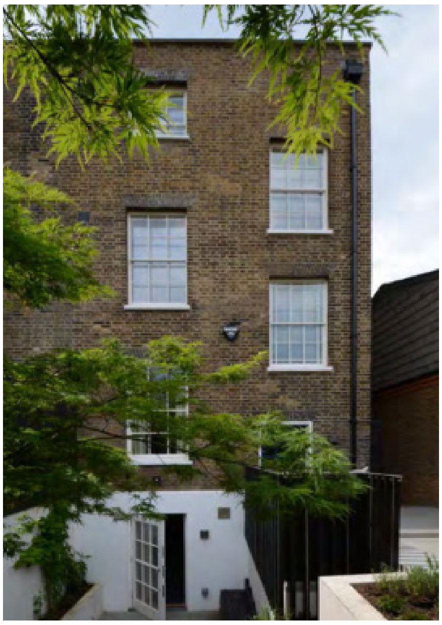


Figure CS6.10 Rear façade

Figure CS6.11 Light kitchen at lower ground floor

Figure CS6.12 Lower ground opened up for dining and kitchen with improved light levels

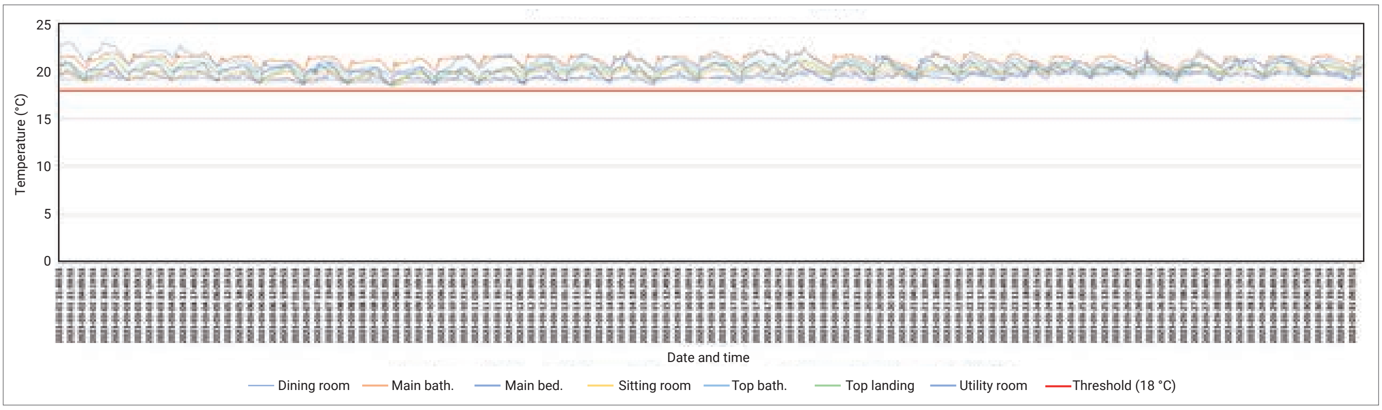


Figure CS6.13 Rectory Grove; internal temperatures (°C) during March 2023

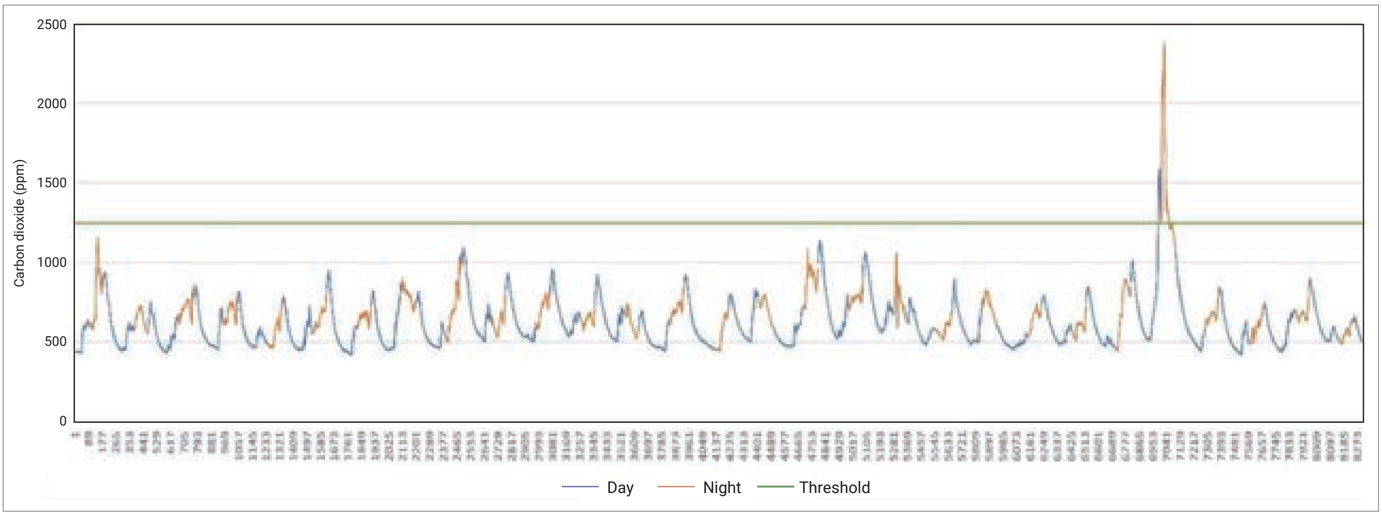


Figure CS6.14 Rectory Grove; carbon dioxide (ppm) — data logger results for March 2023

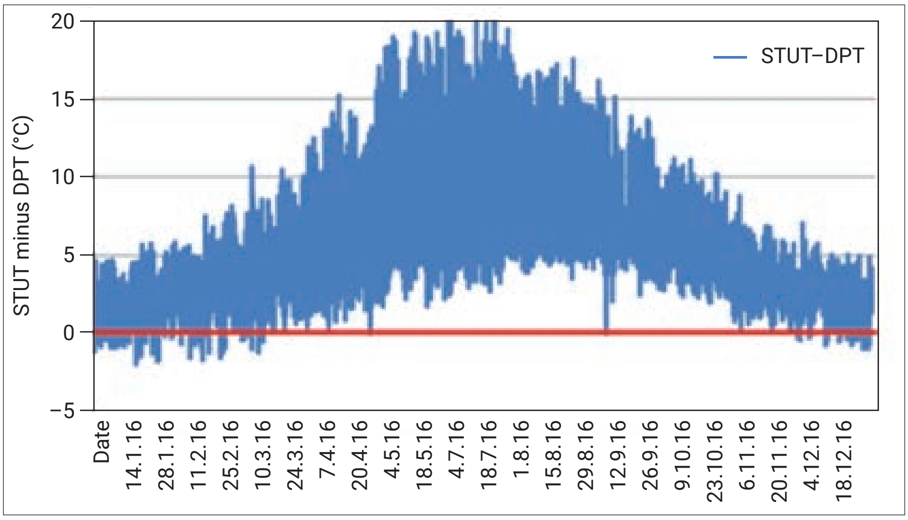


Figure CS6.15 The condensation risk (below red line) on the north slope of the roof during 2016, obtained by subtracting dew point temperature (DPT) from the surface temperature under slates (STUT)

From *A study of the roof environment in four domestic buildings* (Ridout, McCraig and Rhee-Duverne, 2016).

CS7 Princedale Road

Princedale Road

Companies involved in the 2023 BPE
Carbon Co-op
Build Test Solutions
Studio PDP
People Powered Retrofit

Original retrofit architect
Studio PDP

Property age
Pre-1919 (1869)

GIA area
115 m^2

Typology
Mid-terrace house, three-storey plus basement

Occupancy
Housing association tenant; family (five people)

One-off; date of completion March 2011

Overview of the original retrofit

First UK residential retrofit to be certified to full PassivHaus standard. Whole-house internal insulation, combi MVHR-hot water unit, solar thermal panels, triple-glazed windows and underground labyrinthine heat exchanger.

Fabric strategy

Insulation strategy: Internal wall insulation (PIR) with ventilated cavity, roof insulation at ceiling, ground floor insulation (on top of labyrinthine heat exchanger).

Thermal bridges: Largely eliminated thanks to a drastic approach during the original retrofit. Minor residual thermal bridges did not show any issues during the visits. Original design consisted in new floor joists re-hung on steel beams resting in insulated pockets within party walls. Insulation boards pass uninterrupted between the new floor structure and the existing facade.

Airtightness: Continuous OSB layer between layers of insulation on walls, ground floor and roof, taped at joints at all junctions.

Services

Heating and hot water: A Genvex Combi 185 (the size of a tall fridge freezer) houses both a domestic hot water cylinder and an MVHR with heated supply air (via integrated mini air-source heat pump), the unit also works in combination with a roof mounted solar thermal panels (Ecosol 2.32).

Ventilation: MVHR from Genvex Combi 185 and circular galvanised ducts.

Publication of reference

Residential Retrofit: Twenty Case Studies (Baeli, 2013)

Fabric improvement description and values

Walls: IWI system to front and rear walls (0.1 W/m^2·K) — metal frame with ventilated air gap, 150 mm polyurethane, continuous airtightness layer (OSB taped), 50 mm polyurethane with 15 mm Duraline plasterboard. Party walls (0.25 W/m^2·K) — cavity with two layers of 25 mm PIR insulation topped with 15 mm Duraline plasterboard.

Roofs: Existing butterfly roof retained, insulated at horizontal ceiling level (0.17 W/m^2·K) with 250 mm polyurethane, OSB airtightness layer, 50 mm battens (service void), 12.5 mm plasterboard.

Windows and doors: Bespoke triple-glazed timber 'fake-sash' operating with a tilt/turn mechanism (0.8 W/m^2·K) and door (1.2 W/m^2·K).

Insulation properties: PUR (polyurethane) foam insulation as vapour-closed system with ventilated cavity. Unlikely these materials would be specified now due to industry approach to combustibility and fire toxicity potential.

Overview of the revisited retrofit

Figure CS7.1 Joists re-hung on steel beam set in party walls

Figure CS7.2 Triple-glazed sash lookalike tilt/turn window

Figure CS7.3 Internal wall insulation with vented cavity

Significant changes since the original retrofit

Occupancy: same tenant, overall occupancy remains at five (though children are now adults).

Building: no changes to envelope, services, internal layout/uses.

Envelope

Overall fabric performance: integrity of the fabric is generally good. Bespoke triple glazed timber windows and door remain in good condition, loft hatches remain well sealed.

Airtightness integrity: loss in airtightness (i.e. increase from 0.33 to 1.60 $m^3/h.m^2$ @ 50 Pa) may be partly explained by differences in testing, but also slight movement over time which may have affected joins in rigid PU insulation and OSB layer, plus internal floor finishes. Airtightness is, however, still exemplary compared to the existing stock and most new-builds.

Further investigations: build-up of water from a blocked roof gutter penetrated the insulated roof/ceiling and may be a slight contributor to increased heat loss (though not evidenced). Full access to roof void is difficult so it is hard to ascertain whether the OSB layer has been affected.

Rectifications needed: some OSB boards above the insulation in the roof have been pulled aside as a result of the water ingress issue and may require attention.

Regular building maintenance is key to minimise risks to the performance and the building fabric — highlighted in this case by the blocked roof gutter.

Services

Heating: The house has offered a comfortable environment for the family for the last 12 years. However, in February 2023, before the BPE and monitoring took place, the Genvex combi MVHR fans failed and the comfort level dropped. The tenant used minimal supplementary heating in short bursts due to the excellent heat retention of fabric. The house could be heated in less than one hour with a small 2 kW portable heater.

Ventilation: Air quality was also affected when the Genvex MVHR fans failed. The tenant resorted to opening windows to obtain acceptable air quality. However, condensation on the windows and walls could be seen, which disappeared when the fan was replaced and the MVHR was able to purge the house's humidity. This event illustrates very well the benefit of the MVHR in an airtight and well insulated house. Maintenance has become more reactive in recent years, with evidence that filters are not changed regularly. Recommissioning, including control settings (which are quite complex), would be beneficial following repairs.

Figure CS7.4 Utility cupboard with MVHR hot water and mini air source heat pump next to complimentary hot water cylinder

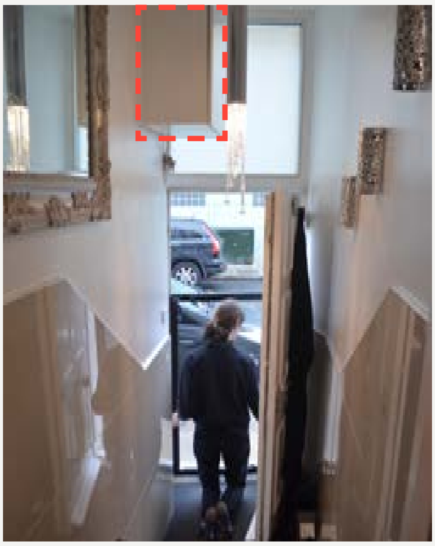


Figure CS7.5 Cupboard housing all meters located over 2 m from floor finish, making it very difficult to read the meters

Figure CS7.6 Electric consumer unit and meters; the old meter had not been removed

Hot water: solar hot water collectors, drainback and storage appear to have performed well with minimal maintenance over the whole 12 years. This was unexpected as this was a relatively unusual system at the time of installation.

Energy performance: The energy performance analysis was made difficult due to poor access to energy data — see details in 'Services strategy' below. EUI: best estimate of 62 to 77 kW·h/m² per year (based on 2020 supplier estimate and cumulative average from meter). This is an underestimate, as it does not account for solar thermal contribution. This is an increase on the EUI in 2012 (48.5 kW·h/m² per year).

Gas: Not applicable.

Electricity: During March, average use 24 kW·h/day. 2020 bill estimate of 8841 kW·h/year. Cumulative metering from 2011 allows crude average of 7093 kW·h/year, suggesting an increase from the 5553 kW·h/year in the first year of occupation.

Space heating demand: 10 kW·h/m² per year estimate (assumption that June–September does not include space heating).

Solar thermal: This is not metered, so its contribution is unknown. The original PHPP estimated the solar contribution to useful heat at 1231 kW·h/year (14 kW·h/m² per year).

Weather adjustment: Annual energy use per degree day of 10 kW·h (using estimated space heating demand for 2020 of 1199 kW·h/year, and heating degree day of 120).

The below-ground heat exchanger temperature at intake and exhaust into the MVHR is not monitored and therefore its impact is unknown. It is possible, however, that it contributes to a lower temperature in the hot summer months — further monitoring during those months would help clarify.

Indoor environment: Average internal temperature during March 2023 of 18.4 °C with peak temperatures in non-master bedrooms ranging from 17.4 °C to 18 °C (lower than 2012 post occupancy evaluation). Average internal relative humidity 59.7%, with peaks returning below 60% within an hour. Overall within acceptable range.

This Passivhaus retrofit has delivered a stable and comfortable environment for tenants over many years.

Future retrofits may need to consider active cooling and/or external shading (subject to potential Conservation Area restrictions).

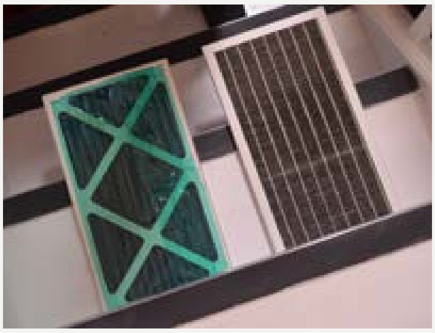


Figure CS7.7 MVHR filters clogged with dust and particles

Figure CS7.8 MVHR fan and filters in the Genvex unit

Figure CS7.9 Access panel in MVHR unit to change the filters need a screwdriver to open

User feedback: High to very high rates of satisfaction across most themes, especially winter comfort and noise, with the tenant very proud of her home. The only constructive feedback related to managing comfort during hot summer periods and maintenance. The upper floors can feel too hot in heat waves and there is no external shading.

The combined heating/hot water/MVHR unit is a relatively large unit with user controls which have proven to be complex and difficult to understand, resulting to inefficient operation.

Description of the BPE approach: Core methods including site visits, occupancy survey and conversations, blower door and Pulse airtightness tests, SmartHTC and MouldRisk (including internal temperature and RH monitoring), review of available energy data.

Table CS7.1 2023 BPE findings: details

	Pre-retrofit	Original retrofit	Retrofit revisit
Annual energy use		Electricity: 5436 kW·h/year (April 2011 to April 2012) Gas: none Solar thermal: unknown	Electricity: 7093 kW·h/year (12-year average based on meter readings) Gas: none Solar thermal: unknown
Airtightness levels	19.87 $m^3/h{\cdot}m^2$ @ 50 Pa	0.33 $m^3/h{\cdot}m^2$ @ 50 Pa	Blower door test: 1.60 $m^3/h{\cdot}m^2$ @ 50 Pa Pulse test: 0.30 $m^3/h{\cdot}m^2$ @ 4 Pa (estimated 1.72 $m^3/h{\cdot}m^2$ @ 50 Pa)
Fabric moisture tests			N/A
Thermography			N/A
HTC		PHPP-calculated HTC of 115 W/K	Measured HTC 136 W/K confidence interval [−43/+42], HLP 1.2 $W/m^2{\cdot}K$ (rated 'good') (indicative 18% performance gap)
Mould risk			BTS mould risk score 9/100, or 1 on 0–4 scale. i.e. low risk. Spaces ranging from 2 (stairs/landing) to 9 (e.g. bathroom basement). Passed Part F compliance metrics.
Walls	Exposed brick with plaster finish	Internal wall insulation with PIR boards and OSB board as airtight layer.	No in-situ *U*-value measurements as part of this or previous study. Minor climbing vegetation on the rear wall.
Floors	Ground earth in unoccupied basement.	Insulated floor with OSB airtight layer on top of new concrete labyrinthine heat exchanger.	No in-situ measurements as part of this or previous study. Tenants have the responsibility for the internal floor finishes which may be a contributor to airtightness loss.
Roofs	Slate butterfly roof uninsulated	Insulation installed horizontally at ceiling level below the butterfly roof structure.	Cause of historical water ingress rectified, but may be contributing to greater heat loss as penetrated roof layer locally
Windows and doors	Single glazed timber sash windows	Triple glazed timber look-alike sash windows	Doors and windows in good condition. The prototype tilt/turn sash look-alike triple-glazed timber windows seem to have passed the test of time very well.

Indoor environmental performance

Temperature: Average internal temperature during March was 18.4 °C. 2012 study reported peak winter week average temperature in non-master bedrooms at 20.8 °C — in 2023 this was 17.4 to 18 °C. The MVHR system was operating sub-optimally during this period, with a replacement part fitted after the monitoring period ended.

Relative humidity: 59.7% average in March. Despite sub-optimal MVHR (replacement part not fitted until after monitoring period), humidity levels managed in 'wet rooms' of the basement (peaks of 81% and 86%), returning below 60% within one hour. Average humidity higher on first and second floors (63%).

CO_2 concentration: Failure to record data (caused by operator/user error). 2012 study reported average CO_2 concentration of 620 ppm, rarely beyond 1000 ppm.

Commentary on physical findings versus user feedback

Average temperatures align with occupant preference (17 to 18 °C). Humidity aligns with feedback, with only incidences of condensation and mould earlier in 2023 when the MVHR failed.

Services strategy

Hot water: The solar hot water was designed to provide the majority, with top-up by the Genvex heat pump. See 'renewables' section below.

Space heating: No modifications to space heating since the retrofit. Supplementary heating (electric radiant halogen heater) used when the Genvex unit failed, but the tenant found this was only needed for very short bursts (e.g. 30 minutes) due to heat retention of fabric.

Electricity: No sub-metering. Meters are housed in a high cupboard which is difficult for the tenant to access, and meant it was not possible to obtain weekly manual reads during the study. Energy supplier issues meant it was not possible to get the half-hourly, nor historical, smartmeter data. Complex factors contributed to this, including a change of supplier in the previous year, an energy debt issue and tenant difficulties accessing an online account. Support included investigations to ascertain which meter was operational for billing (legacy equipment from the original BPE exercise was not well documented), with a check on the Citizens Advice web tool confirming the smartmeter was working in 'smart' mode. Despite this, attempts to connect to the Bright app (so that smart meter data could be accessed via SmartHTC) were unsuccessful because the tenant did not have the documents required to confirm identity. Citizens Advice was providing support at the close of the study, but the priority was resolving the energy debt issue.

Ventilation: No measurements of flow rates and specific fan power for this study. MVHR failed for the first time a few weeks before monitoring. There is evidence filters are not being changed regularly. The system may benefit from a recommissioning exercise, including checking the settings on the control panel and sensors (e.g. possible fault in supply air sensor).

Renewables: The design team anticipated that the solar thermal system would be the first to fail, but this appears to be performing well. The tenant is very satisfied with the availability and temperature of hot water. There is no sub-metering, so difficult to ascertain the contribution of solar thermal. The original PHPP estimated the solar contribution to useful heat at 1231 kW·h/year (14 kW·h/m^2 per year).

User feedback

Questionnaire findings: Occupants express high to very high rates of satisfaction, especially for winter comfort and noise. The SOAP survey scored 95% (rated 'great'). The only constructive feedback related to managing high temperatures in summer, with the tenant feeling that because summer heat events are more frequent and severe, that active cooling would be beneficial. Whilst home user guides and demonstrations were rated highly, there would be value in revisiting this as settings have been tweaked (on MVHR control by residents) and maintenance knowledge and behaviours weakened. Documentation from 2012 stated that regular filter replacement and cleaning of the heat exchanger was occuring (by the landlord), but this did not seem to have happened for some time prior to the revisit exercise. In terms of behaviour, the residents suggested they open windows and the back door during high temperatures (which may be counterproductive when outdoor temperatures are higher than inside). The home user guide could not be located, but it is possible that it did not include advice on managing high temperatures back in 2010. Sustained engagement on metering and energy consumption (initiated by the housing association) may have mitigated some of the current billing issues.

BPE techniques: lessons learned

Getting data for this property from the energy suppliers has been very difficult and has taken a considerable amount of time to resolve. This is a significant risk for BPE projects that should be investigated as early on as possible. In this case there were several, complex factors and a need to refer the resident on to external support services (such as Citizens Advice). Having early access to metering schematics and photographs would also be helpful, particularly where the original monitoring kit has been partially left in place.

The difference in airtightness value from the original retrofit and the revisited BPE may have happened due to different calculations. Obtaining the original calculations early on would be helpful.

The impossibility to open-up the fabric means that it is not possible to ascertain the condition of the various layers forming the building envelope.

Airtightness testing (blower door and Pulse): There was some difference in volume calculations between testing then and now, with adjustments to allow comparison. There may also have been differences in the sealing of the MVHR unit during the test. Investigations during the test would have been valuable — this needs to be clearly outlined in the scope for evaluators, with equipment provided if required.

Views on methodology:

- SmartHTC data input was a learning curve, and felt more geared towards users of SAP/EPCs (e.g. generating a design HTC value). However, guidance on this was established as the project progressed.
- Hardware/software requirements could be smoother (e.g. lack of remote access to check data, need for manual upload, lack of compatibility of some software with common operating systems).
- Future exercises could revisit during summer to explore overheating and the interaction with occupant behaviour.
- Energy supplier issues demonstrate the need to allow sufficient time for evaluation, how the 'reality of life' impacts on data availability, and the 'people' skills needed alongside technical knowledge.

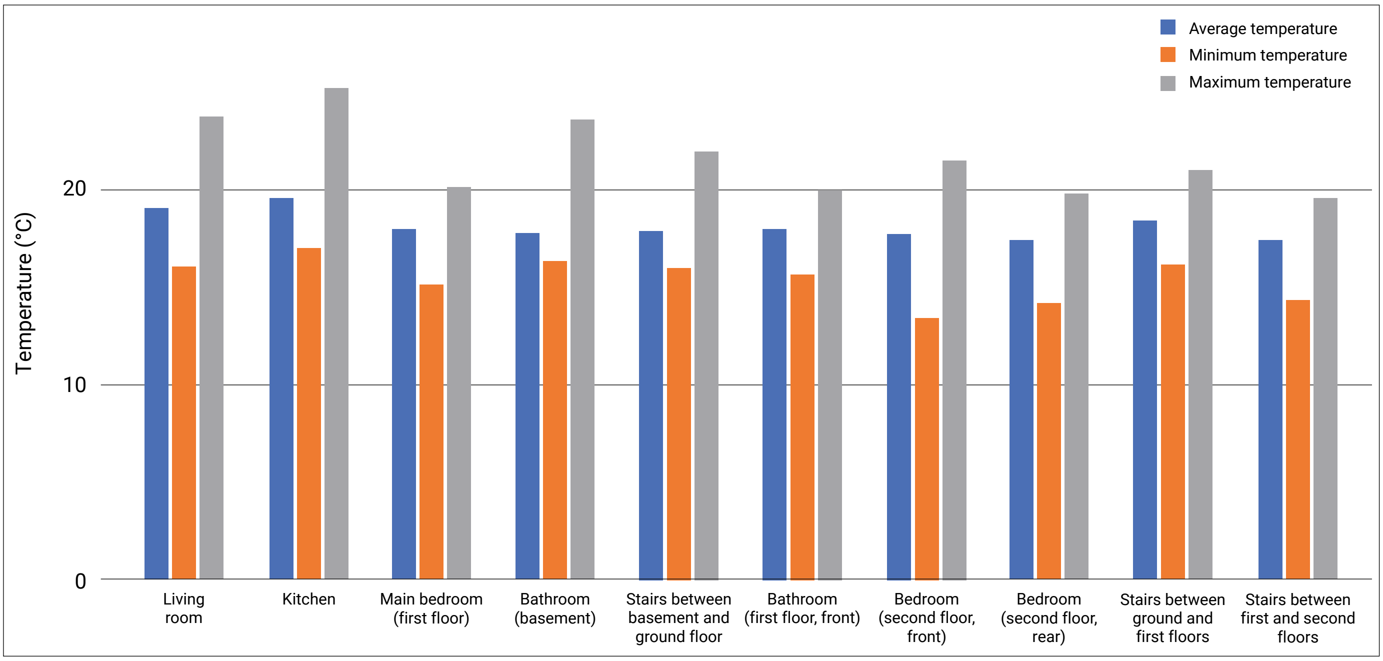


Figure CS7.10 Average, minimum and maximum internal temperatures by room (°C)

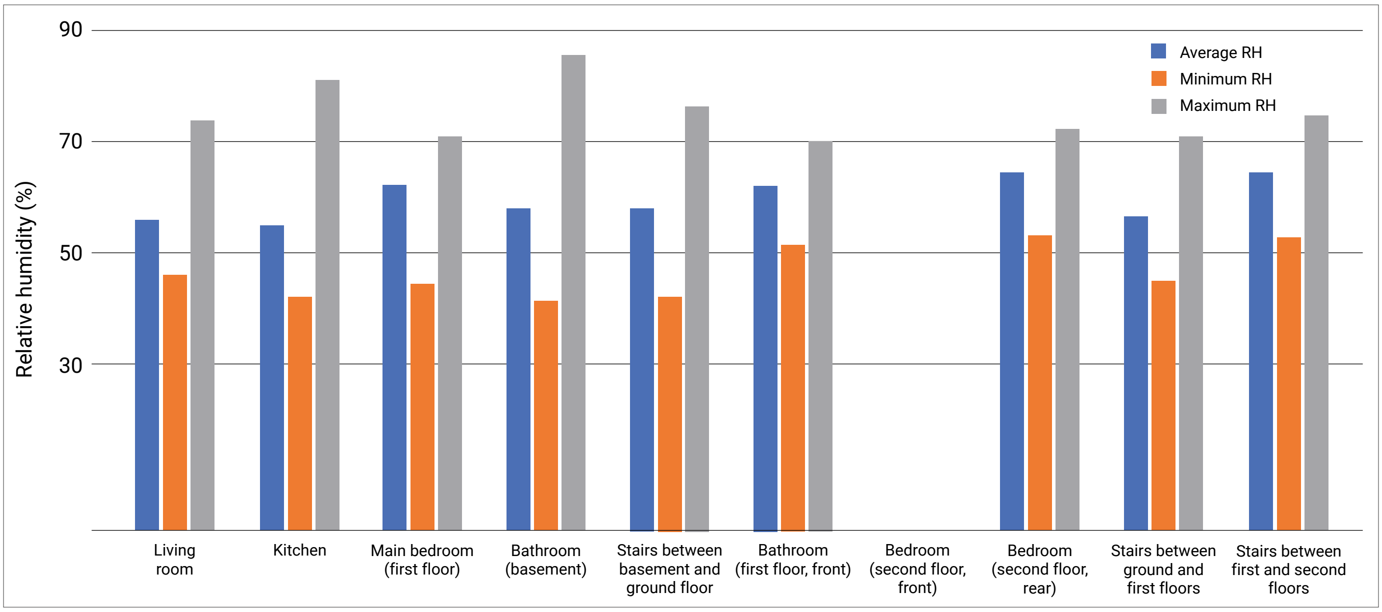


Figure CS7.11 Average, minimum and maximum relative humidity by room (%)

CS8 Shaftesbury Park Terrace

Shaftesbury Park Terrace

Companies involved in the 2023 BPE
Feilden Clegg Bradley Studios
Max Fordham
Peabody
Rickaby Thompson Associates

Original retrofit architect
Feilden Clegg Bradley Studios

Property age
1876

GIA area
61 m^2

Typology
Terrace

Occupancy
One occupant full time, semi-retired. One occupant part time, semi-retired. Main resident lives and works at home, with the rear bedroom used as a therapy room. Part time resident splits time between this home and a studio outside of London.

One-off property retrofit

Overview of the original retrofit

The property is a mid-terraced, two-storey, two-bedroom house on the Shaftesbury Park Estate in a conservation area. The house dates from approximately 1870s, with an L-shaped footprint, and is of solid brick wall construction with a pitched roof. The retrofit was implemented with residents in-situ for the majority of works. Works included internal insulation to the front wall; a mix of external and internal insulation at the rear; roof and floor insulation; solar thermal panels; and an experimental exhaust air heat pump integrated with a fan-assisted passive stack ventilation system in order to reduce ventilation losses and recover internal heat gains

Fabric strategy

Insulation strategy: The home has aerogel IWI to the front and rear facades, with a limited amount of EWI applied to the rear kitchen outshot. Original sash windows were replaced with double-glazed sash windows to the front and triple-glazed tilt/turn windows to the rear. The ground floor void was full-filled with EPS beads, and the cold roof insulated with 400 mm of mineral wool.

Thermal bridges: No particular focus on thermal bridging was included within the retrofit, with a more moderate approach to fabric performance than other deep retrofits. The ground floor joists were pulled back from the external wall to within the insulation line, but predominantly to reduce the damp risk associated with the end of the timbers.

Airtightness: The retrofit focused on improving the air tightness to a reasonable level, looking to test a less onerous target than Enerphit and recognising the leaky state of the existing building. The design aim was for 5 m^3/h.m^2 @ 50 Pa, with a focus on the window and door junctions as key areas to reduce infiltration.

Services

Heating and hot water: The building contained an innovative mix of solar thermal and a bespoke exhaust air heat pump acting as lead heating system, with a boiler topping up the thermal store.

Ventilation: The home is ventilated using a passive stack ventilation unit located in the loft, with extract vents in the bathroom and first floor bedroom. Make-up air is through trickle vents in each window.

Publication of reference

Residential Retrofit: Twenty Case Studies (Baeli, 2013)

Fabric improvement description and values

Walls: The front and rear walls of the home were internally insulated with Aerogel to achieve a *U*-value of 0.14 W/m^2·K.

Floors: Ground floor void was insulated using a full-fill of EPS beads on top of a vapour membrane, with the floor joists pulled back from the external wall and instead rested on supports within the floor void. A *U*-value of 0.14 W/m^2·K was targeted.

Roofs: The pitched roof was insulated on along the ceiling line with 400 mm of mineral wool insulation to achieve a *U*-value of 0.10 W/m^2·K. The flat roof extension targeted a *U*-value of 0.16 W/m^2·K.

Windows and doors: As the home is within a conservation area, the front windows were required to maintain the look of the original sash windows. UPVC, double glazed sash windows were installed, achieving a *U*-value of 1.40 W/m^2·K. To the rear, triple-glazed tilt/turn windows were installed, achieving a better *U*-value of 0.90 W/m^2·K.

Insulation properties: The aerogel IWI has very low conductivity and is vapour open and hygroscopic. The EPS beads are coated to improve material handling, making them less prone to static and making them slightly sticky.

Overview of the revisited retrofit

Significant changes since the original retrofit

Occupancy: The occupancy remains the same as during the original retrofit.

Building: Residents have made no significant changes to the building since the retrofit, but had customised their home more extensively prior to the retrofit. The resident uses the rear, south facing bedroom as a treatment room, rather than the originally intended bedroom.

Envelope

Overall fabric performance: The airtightness of the property is worse than measured immediately following the original retrofit, and likely relates to the building elements move and wear, such as windows, but further investigation is needed to identify their particular impact.

Measured *U*-values for the walls showed an increase from 0.14 to 0.20 W/m^2·K using heat flux plates, but at 0.10 W/m^2·K for the Heat3D measurement. The Heat3D also showed good uniformity, suggesting that either the initial calculation was wrong (e.g. brick is thermally worse than expected perhaps), or the aerogel performance is less than expected.

Floor *U*-values were measured at 0.14 W/m^2·K with a 0.04 uncertainty, which indicates that, given the uncertainty range, this is likely performing similar or better than expected, and suggests that the method is durable.

Airtightness integrity: The airtightness had decreased since the original retrofit, from 5.92 m^3/h·m^2 @ 50 Pa to 7.58 m^3/h·m^2 @ 50 Pa using the blower door method.

Pressurisation showed more leakage than depressurisation (9.5%) (using the blower door test) suggesting that outward openings were more of an issue.

During the visit it was found that the seals to the first floor sash windows, between the panes, were either missing or significantly worn, likely forced out as the panes slide over each other (the resident had no recollection of their wear/damage). The bathroom window was also found not shut fully, with a noticeable 'wobble' between the window and the frame (see Figure CS8.5). This has since been adjusted to fit more snuggly against the seals. Both will have led to an increase in the air permeability, as noticed in the tests.

The loft was actively used for storage, and the hatch simply rests on the seals, with no way to pull it tightly shut. However, no smoke testing was undertaken to determine the routes of air leakage, therefore it is not possible to ascertain the extent of leakage from that hatch.

Figure CS8.1 Floor void

Figure CS8.2 Sound proof membrane

Figure CS8.3 Void filled with insulating beads

Further investigations: A further smoke test to ascertain the underlying cause of the air leakage is encouraged, enabling targeted fabric improvements.

Rectifications needed: It is advised that the windows are serviced, replacing the seals throughout, and adjusting the hinges to enable a good seat, particularly on the tilt/turn window in the bathroom.

Regular building maintenance is key to minimise risks to the performance and the building fabric — highlighted in this case by the blocked roof gutter.

Key lessons learned: The building fabric has aged well, with little damage or modification, and no signs of mould or damp that would indicate an issue with the insulation approach. UCL study reported that RH and particle counts were found to be within acceptable limits based on literature. Fungal risk is deemed to be minor as Class A according to Mycometer's classification system (dominant fungal species were: Aspergillus versicolor 54.45%, Cladosporium sphaerospermum 24.97%).

Airtightness has been significantly affected, but is still much better than the initial building, and suggests that this is where the maintenance should be targeted for the fabric of the building. A simple review of the quality of the moving parts of a home, the windows and doors, could provide significant benefits for the ongoing performance of the fabric.

High growth thermal performance assessment: The assessment of the risk of deterioration of the timber joist ends due to rot illustrated the high possibility that timber degradation is likely to be occurring in the front and the rear elevations. Lastly, the assessment against the risk of freeze-thaw deterioration indicated no high risk for the external face of the front and the rear elevation to suffer from spalling or face loss.

Caveat and context: The results presented in this analysis have been produced by WUFI Pro which is a one-dimensional software and therefore not ideal for bridged structures with more complex geometry. Also, the impact of the type of mortar in the brick wall has not been taken into account in this study. In regard to the assessment of each modelling case, there is not a clear set of moisture risk assessment criteria agreed upon within the industry yet, especially as different build-ups of materials and applications will require different criteria. Therefore, the criteria used by the author are based on guidance from the Fraunhofer Insitut and from the relevant bibliography. Furthermore, the simulations are based on synthetic climate data and not measured climatological data for the project's location.

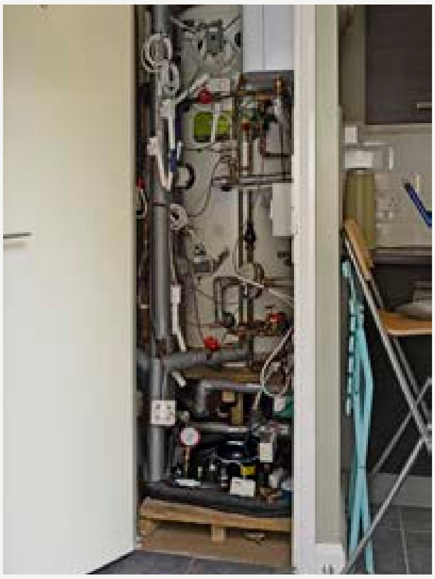


Figure CS8.4 Utility cupboard with conflicting MEP installation

Services

Heating: The retrofit contained a comparatively experimental heating system, using solar thermal and an bespoke exhaust air heat pump (EAHP), which reclaimed the heat from the passive stack ventilation system, to preheat the hot water in a cylinder. This is topped up by a gas boiler to more typical flow temperatures for heating (80 °C/60 °C). This provided two key issues for the residents:

1. The boiler was an unusual unit from Germany, with little access to information and spares.
2. The system was far too complex for simple maintenance by Peabody's maintenance team

The mix of complexity of the system and the unusual boiler led to an increased difficulty in ongoing maintenance. With a large institution, such as Peabody, maintenance contracts are not readily able to work with these unusual systems, creating frequent delays to maintenance. The resident noted that it was typical for the heating system to fail upon the first use in winter, leading to a nervousness about using the central heating.

The revisit found that the EAHP and solar thermal heating system was not operating, instead solely relying on the gas boiler and local electric heaters to ensure that the home had heating and hot water.

During the revisit, the main gas boiler was not being used for heating. This was due to the rising energy prices, the residents had switched from the central heating system to local electric heaters used occasionally, with gas being used for cooking and domestic hot water only. Unfortunately, due to the lack of data on the internal environment, it has not been possible to establish whether this also resulted in reduced internal temperatures — but it is expected this may have been the case.

Hot water: The hot water system is fed from a central tank, but has had significant issues over the past 10 years. Boiler issues have led to a reliance on the immersion heater at points to provide DHW, despite the solar thermal and EAHP. The resident was dissatisfied with the DHW control, largely due to the occasional outages of overall provision.

Ventilation: The ventilation system has been running since the original installation with little additional maintenance (10+ years).

Local trickle vents are often closed to reduce drafts and heat loss, but there was no sign of condensation or mould growth within the property, suggesting that despite the age of the positive stack ventilation (PSV) and closed trickle vents, air quality remained good (confirmed by UCL findings too). No logged temperature or RH

Figure CS8.5 Sash window seal missing to the left of the window catch, contributing to the increased permeability.

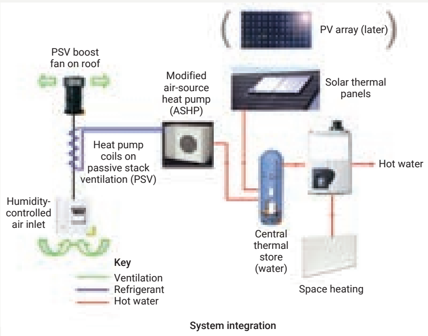


Figure CS8.6 Schematic of the MEP system

data was available, but spot checks by UCL and resident feedback suggested the home was comfortable throughout the year.

Energy performance (2022 values):

- EUI: 52.7 kW·h/m^2 per year
- Gas: 1360 kW·h/year
- Electricity: 1857 kW·h/year.

Indoor environment: Unfortunately, due to a logger misconfiguration, no internal temp or RH data was collected.

During the monitoring period, spot measurements of indoor temperatures around 18 ºC were recorded during conversation with the resident in the main living spaces, and 22 ºC recorded in the second bedroom, which was being used as a therapy space. The residents were heating only spaces that were occupied, and over the winter had been wearing more jumpers to save energy. The higher temperatures in the second bedroom were caused by a heater being used the previous day, passive solar gains during the visit day, and the door being kept closed to keep the cat out. This suggests that the improved fabric is reducing the heat loss and contributing to the stability of conditions reported by the residents.

No condensation issues were reported in the home, but over the winter, limited amounts were recorded for the first time on the north facing bedroom windows. All trickle vents had been left closed, with the resident not sure of their purpose, and significant difficulty in accessing them due to their height above floor level. This was the first time the residents had avoided using the heating, so suggests that low temperatures had been experienced over the winter.

User feedback: Overall, the residents were satisfied with the building, but the residents had considerable problems with the boiler, leading to periods of no heating, and DHW from the immersion heater. The maintenance team has been responsive, but the complexity of the system was felt to have caused significant delays in repair.

The home was reported as being generally comfortable, with a stable temperature throughout the year, although overheating was reported in the south-facing bedroom.

Description of the BPE approach: Core + Detailed BPE, with mould measurements, moisture measurements of floor joists. *U*-value measurements of IWI wall and insulated ground floor. A structured interview was undertaken in addition to the SOAP retrofit survey.

Table CS8.1 2023 BPE findings: details

	Pre-retrofit	Original retrofit	Retrofit revisit
Annual energy use	Gas: 25810 kW·h/year Elec: 1097 kW·h/year	Gas: 4076 kW·h/year Elec: 1017 kW·h/year EAHP and solar thermal: unknown	Gas: 1360 kW·h/year Elec: 1857 kW·h/year EAHP and solar thermal: 0 (not operating)
Airtightness levels	16.77 $m^3/h{\cdot}m^2$ @ 50 Pa	5.92 $m^3/h{\cdot}m^2$ @ 50 Pa	Blower door test: 7.58 $m^3/h{\cdot}m^2$ @ 50 Pa 8.95 ach^{-1} @ 50 Pa Pulse test: 1.33 $m^3/h{\cdot}m^2$ @ 4 Pa (estimated 6.84 $m^3/h{\cdot}m^2$ @ 50 Pa)
Fabric moisture tests			
Thermography			
HTC	N/A	N/A	SmartHTC (measured HTC) could not be measured, as the temperature sensors were not installed properly and did not log
Mould risk	N/A	N/A	BTS mould risk score could not be measured, as the temperature sensors were not installed properly and did not log
Walls	Not tested	0.14 $W/m^2{\cdot}K$	Plate *U*-value: 0.20 $W/m^2{\cdot}K$ (0.06 uncertainty) Heat3D *U*-value: 0.1 $W/m^2{\cdot}K$ (0.1 uncertainty)
Floors	Not tested	0.16 $W/m^2{\cdot}K$	Plate U-value: 0.14 W/m^2K (0.04 uncertainty)
Roofs	Not tested	0.10 $W/m^2{\cdot}K$ (pitched) 0.16 $W/m^2{\cdot}K$ (flat)	Not tested
Windows and doors	Not tested	1.40 $W/m^2{\cdot}K$ (front, sash, DGU) 0.90 $W/m^2{\cdot}K$ (rear, tilt turn, TGU) 1.10 $W/m^2{\cdot}K$ (doors)	Not tested

Indoor environmental performance

Temperature (March 2023): no measured data.

Relative humidity (March 2023): no measured data.

CO_2 concentration: no measured data

Commentary on physical findings versus user feedback

Unfortunately, due a logger misconfiguration, no internal temperature or RH data were collected.

During the monitoring period, spot measurements of indoor temperatures around 18 °C were recorded during conversation with the resident in the main living spaces, and 22 °C recorded in the second bedroom, which was being used as a therapy space. The residents were heating only spaces that were occupied, and over the winter had been wearing more jumpers to save energy. The higher temperatures in the second bedroom were caused by a heater being used the previous day, passive solar gains during the visit day, and the door being kept closed to keep the cat out. This suggests that the improved fabric is reducing the heat loss and contributing to the stability of conditions reported by the residents.

No condensation issues were reported in the home, but over the winter, limited amounts were recorded for the first time on the north facing bedroom windows. All trickle vents had been left closed, with the resident not sure of their purpose, and significant difficulty in accessing them due to their height above floor level. This was the first time the residents had avoided using the heating, so suggests that low temperatures had been experienced over the winter.

Services strategy

Hot water: The hot water system is fed from a central tank, described in detail below, but has had significant issues over the past 10 years. Boiler issues have led to a reliance on the immersion heater at points to provide DHW, despite the solar thermal and EAHP. The resident was dissatisfied with the DHW control, but largely due to the occasional outages of overall provision.

Space heating: The retrofit contained a comparatively experimental heating system, using solar thermal and an bespoke Exhaust Air Heat Pump (EAHP), which reclaimed the heat from the Passive Stack Ventilation system, to preheat the hot water in a cylinder. This is topped up by a gas boiler to more typical flow temperatures for heating (80 °C/60 °C). This provided two key issues for the residents:

1. The boiler was an uncommon unit in the UK as it came from Germany, with little access to information and spare parts.
2. The system was far too complex for simple maintenance by Peabody's maintenance team

The mix of complexity of the system and the unusual boiler led to an increased difficulty in ongoing maintenance. With a large institution, such as Peabody, maintenance contracts are not readily able to work with these unusual systems, creating frequent delays to maintenance. The resident noted that it was typical for the heating system to fail upon the first use in winter, leading to a nervousness about using the central heating.

Due to the increase in cost of energy, the resident has rarely used this central heating system over winter, instead using a local electric heater to warm the occupied rooms. This has significantly reduced the gas energy use, but it is likely the thermal stability provided by the additional insulation has enabled this approach by the resident.

Electricity: The house was rewired as part of the retrofit, with submetering installed for each circuit. Metering was extended to heat meters for the solar thermal, exhaust air heat pump, heating and hot water circuits. This was all connected to a wireless monitoring station in the cloud, that unfortunately could not be accessed at the time of the retrofit.

No significant changes were made to the lighting, maintaining ceiling mounted pendants with a mix of occupant installed CFL and LED lamps.

Ventilation: The ventilation system has been running since the original installation with little additional maintenance (10+ years).

Local trickle vents are often closed to reduce drafts and heat loss, but there was no sign of condensation or mould growth within the property, suggesting that despite the age of the PSV and closed trickle vents, air quality remained high. No logged temperature or RH data was available, but spot checks and resident feedback suggested the home was comfortable throughout the year.

Renewables: The inclusion of the EAHP and the solar thermal as a preheat has not been possible to monitor. There have been reports of over-pressurisation within the hot water tank, likely caused by the solar thermal providing too much heat with a sticky bypass valve. The complexity of the system has made maintenance and rectification of these types of issues more difficult than would be hoped.

User feedback

Questionnaire findings: Residents were generally satisfied with their homes, noting comfort in all seasons, low energy use, and pleasing building appearance. However, they expressed concerns about the heating and hot water systems, storage space, and the retrofit process. The heating system maintenance posed difficulties, creating anxiety when first used each winter.Home Characteristics: A small home in a conservation area with limited garden space meant additional storage was unlikely during the retrofit. Internal Wall Insulation (IWI) reduced floor space, but using Aerogel minimized this impact despite higher costs and embodied carbon. Occupants reported good internal conditions, relying on a portable electric heater in winter to save money. They preferred local radiators over the heating/DHW system for reliable, controllable heat. The home was stable with no drafts or cold spots, retaining warmth in winter. Overheating occurred in the south-facing bedroom due to a large window, but no major condensation issues were noted, indicating effective ventilation. Some condensation on the north-facing replacement sash windows was attributed to split seals.

Residents' feedback: Residents were surprised by the lack of follow-up post-retrofit. Although monitoring equipment was installed, there were no visits after the initial handover. Residents had little understanding of the works and the complex heating system. During a recent revisit, they received drawings, the original case study report, and a tour of the improvements, enhancing their appreciation of the home.

BPE techniques: lessons learned

Check the data loggers, as issues in this BPE exercise means that no data was gathered limiting the opportunity for learning key lessons and occurring unneccesary costs and wasted time for the team.

Airtightness testing (blower door and Pulse): Blower door testing and pulse testing all very straightforward.

Views on methodology: Moisture testing of the floor joists was quite invasive, but the home has coir matting and screwed floor boards allowing relatively simple access.

The *U*-value measurements were simple, but the Heat3D was much more appropriate for homes at scale, despite the reduction in accuracy compared to the heat flux plate measurements (±0.1 compared to ±0.04). However, Heat3D was able to visually show the variation in *U*-value across the wall, which provided an important context of the spaces between the heat flux plates.

For the ground floor, the heat flux plates showed a large variance in the *U*-value, but the Heat3D equipment was not able to provide that additional context to support the reasons for the variance (a range of 0.11 to 0.17 W/m^2·K, likely caused by the floor joists within the insulation).

The tight timeframes for the study produced an incredibly focused research piece, and the close deadlines kept the pressure on the team to deliver the study. A year long study would be more appropriate to draw out detailed conclusions, but the pressure helped to realise the outputs more readily.

CS9 Wilmcote House

Wilmcote House

(One maisonette within the building)

Companies involved in the 2023 BPE
ECD Architects
Portsmouth City Council

Original retrofit architect
ECD Architects

Property age
1968

GIA area:
Pre-retrofit: 89 m²

Post retrofit: 96 m² (GIA of the maisonette subject to BPE, including the sun space and excluding the communal corridor)

Typology
Mid-terrace maisonette

Occupancy
Tenant (social rent)

Phased retrofit, completed in 2018

Overview of the original retrofit

The project is made of three residential blocks (111 units) retrofitted to achieve a significant reduction in space heating demand while retaining residents in-situ during the works. It was designed to the EnerPHit standard (not certified).

Fabric strategy

Insulation strategy: The three blocks were externally insulated with mineral wool insulation, which wrapped the entirety of walls and roofs. Two of the four existing stair cores were left uninsulated and outside the thermal envelope, which improved the building's form factor.

Thermal bridges and airtightness: The thermal and airtightness strategy involved the simplification of the thermal envelope, with a new load-bearing steel frame erected on the garden-side elevation. This allowed the external corridors to be enclosed, allowed the living rooms to be extended to meet the new simplified external envelope and avoided extensive thermal bridges around the walkways slabs.

Services

Heating and hot water: Minimal heating was required after the refurbishment. The council/landlord have been removing old storage heaters (1no per room) and replacing them with small direct electric heaters (generally one per maisonette, in the living room).

Publications of reference

LETI Climate Emergency Retrofit Guide (Case Studies chapter)

Retrofit to the Rescue (Rockwool/LSE)

EnerPHit: A Step by Step Guide to Low Energy Retrofit (James Traynor)

Teli et al. (2015) 'Fuel poverty-induced "prebound effect" in achieving the anticipated carbon savings from social housing retrofit', *Building Services Engineering and Technology* 37 (2)

Fabric improvement description and values (for the building)

Walls: EWI in metsec framework, 300mm non-combustible mineral wool insulation (*U*-value: 0.14 W/m²·K), XPS below DPC level.

Roofs: variable thickness non-combustible mineral wool insulation (340 mm on average) (*U*-value: 0.09 W/m²·K)

Windows and doors: Triple-glazed windows.

Insulation properties: Non-combustible mineral wool insulation.

Overview of the revisited retrofit

Figure CS9.1 Some signs of weathering on the 'road side', also showing the vertical brise-soleil

Figure CS9.2 View of external elevation

Figure CS9.3 The only radiator in the maisonette with on/off switch only

Significant changes since the original retrofit

The sunspace room is not used for drying clothes as originally envisaged but, in this unit, it is rather a toy store/smoking room, so is not always treated as part of the thermal envelope. This was anticipated and double-glazed sunspace doors and insulation mitigate heat losses.

No change in residents. The residents arrived in 2017, just as the retrofit was being completed, witnessing the replacement of storage heaters with electric panel heaters.

Envelope

Overall fabric performance: Access control to communal corridor doors which are part of the thermal envelope is reported to be regularly failing due to vandalism.

In response to antisocial behaviour, on some floors (including where the studied maisonette is located) windows in the communal corridors have had handles removed and are now operated by the landlord by request and in response to the seasons. The windows were not part of purge ventilation strategy so this is unlikely to have a major impact.

Airtightness integrity: No changes.

Services

Heating: Electric radiator — typically not used, over 20 °C temperature achieved without heating. Residents reported to have used the radiators three times in over four years.

Hot water: Dimplex 210l electric immersion heater provides enough water at the right temperature for the kitchen and bathroom, albeit the shower is electric.

Ventilation: MVHR Zehnder ComfoAir200 — potential under-ventilation for the maisonette's current occupancy, as shown by elevated moisture and CO_2 levels (see Figures CS9.8 and CS9.9).

It is suspected that the MVHR was set on a low flow-rate (holiday mode) as the tenant was worried about the MVHR increasing the energy bills.

Further investigations and possible rectifications: Landlord confirmation would be required to measure the MVHR ventilation rate and assess possible underventilation in the maisonette. It is possible that recommissioning the MVHR unit would be needed to reflect higher occupancy levels. The installation of a wireless humidistat sensor in the bathroom could also be considered to automatically activate the boost mode.

Figure CS9.4 Access panels to MVHR duct distribution in the hall and WC

Figure CS9.5 Mould to the window seal in upstairs bedroom

Figure CS9.6 Evidence of mould to the ceiling in the upstairs bathroom

Energy performance: The energy performance analysis was made difficult due to poor access to energy data.

EUI: average of 56 kW·h/m^2 per year.

Gas: No gas supply to the property.

Electricity: Between 08/03/23 and 06/04/23, 462.2 kW·h was supplied to the dwelling, of which 58.2 kW·h at Rate 1 and 403.9 kW·h at Rate 2 (refer to graphs 1 to 5).

Due to the lack of available annual energy data (despite repeated efforts made to gather energy bills and trying to link the meter via Powershaper/Bright app without success, and no historic records from Utilita were provided), there were only two ways to estimate the annual energy data, as follows:

- Resident top-ups £150 per month, from which the annual energy use could be estimated at 4874 kW·h. For this maisonette, this would be equivalent to 50.7 kW·h/m^2.
- Ofgem data for 2021 showed a median annual electricity use for the postcode (i.e. this block of the building) of 5895 kW·h. For this maisonette, this would be equivalent to 61.3 kW·h/m^2.

Indoor environment: Almost 21°C on average, without residents putting the heating on during the monitoring period, but relatively high RH and CO_2. Some mould was observed on site and the locations correlate with BTS mould risk score of 'high' (52–53) (see Figures CS9.5 and CS9.6).

The low flow-rate (holiday mode) of the MVHR may have contributed to this under-ventilation resulting in the presence of mould.

User feedback: SOAP score: 'poor'. Users reported the maisonette as being 'too cold' and somewhat 'uncomfy'. They were 'somewhat dissatisfied' with their utility costs, but found their energy use 'neutral'. In terms of hot water, they were 'somewhat satisfied' and they were 'neutral' about their heating, ventilation, controls and general satisfaction and comfort. Their internal air conditions in winter were deemed 'somewhat still, dry and with some odours'. However, during summer conditions, they found their temperatures to be 'just right' and 'somewhat humid' and air movement 'just right'.

Description of the BPE approach: CoreBPE — four weeks' monitoring, site visit, airtightness test, interviews with resident and landlord; alternative ways to estimate energy use, due to lack of available energy data — see above.

Table CS9.1 2023 BPE findings: details

	Pre-retrofit	Original retrofit	Retrofit revisit
Annual energy use	8759 kW·h	6111 kW·h	Two estimates were made: Resident top-up 4874 kW·h (year leading up to March 2023) Postcode-level OFGEM data: 5895 kW·h (2021)
Airtightness levels	May 2012 blower door test: 3.38, 3.09, 2.81 ach @ 50 Pa (different dwellings)	2018 blower door test: 2.05, 2.35, 3.17 ach @ 50 Pa (different dwellings)	Blower door test: 1.77 $m^3/h{\cdot}m^2$ @ 50 Pa (1.85 ach^{-1} @ 50 Pa) Pulse test: 0.28 $m^3/h{\cdot}m^2$ @ 4 Pa (estimated 1.62 $m^3/h{\cdot}m^2$ @ 4 Pa)
Fabric moisture tests	N/A	N/A	N/A
Thermography	Available	Available	N/A
HTC	N/A	96 W/K based on PHPP	SmartHTC: 97 W/K [−65/+35]
Mould risk	Mould and damp in this maisonette according to 2009 asbestos report	N/A	BTS mould risk score of 53/100, i.e. 3 on 0–4 scale overall (high). This aligns with residents' reports of mould on site — see Briefing 6, section 6.1.4.
Walls			Some mould on wall/ceiling junction in bathroom and upstairs bedroom window seal
Floors and roofs			N/A – mid floor maisonette
Windows and doors			Reported as easy to operate and effective.

Indoor environmental performance

Temperature: Broadly between 20 and 22 °C during the monitored period (20.86 °C average), achieved with no active heating (refer to Figure CS9.7). Disregarding the sunspace, it is warmer upstairs, i.e. 21.1 °C as opposed to 20.6 °C downstairs. It was shown by previous studies (carried out by the University of Southampton) that residents in the block were typically not keeping their home warm prior to the retrofit (more than 50% of maisonettes failed to reach minimum WHO acceptable indoor temperatures), so the less than anticipated reduction in total energy use pre and post retrofit (39% from 2013 to 2021 as per OFGEM) may be partly explained by this. The monitored flat has enough internal gains not to require heating at all.

Relative humidity: RH was consistently above 60% in the three rooms monitored (refer to Figure CS9.8). Upstairs bedroom and bathroom (see Figures CS9.5 and CS9.6) in particular have an elevated RH, with averages of 69.9 and 68.9% and maxima of 81% and 90.1%, respectively. PCC reviewed their repairs and maintenance records and confirmed there are no widespread mould and condensation problems within the building. However, the resident treated some mould twice during six years in the upstairs bedroom and bathroom — the rooms with highest BTS mould risk scores (53 and 52 respectively). ECD suggested to PCC two possible solutions to improve the elevated RH levels in the monitored maisonette: to install a wireless humidistat sensor in the bathroom to automatically activate the MVHR boost mode; and to recommission the MVHR to increase the ventilation rate.

CO_2 concentration: In excess of 1250 ppm (1403.8 ppm overall mean), with concentrations peaking at weekends and nights (refer to Figure CS9.9). During the typical hours of occupation (16:00–23:00) the average was 1308 ppm. Alongside elevated RH levels, this supports the hypothesis of insufficient ventilation.

Commentary on physical findings versus user feedback

There were no draughts or noise issues reported with the ventilation, and the air was rated as 'somewhat still', with 'some odours' and 'somewhat dry', with the latter indicating the subjectivity of perceptions given the high average RH. The MVHR boost button is located in the hall and not linked to the bathroom switch. The boost mode is never used due to resident's concerns about running cost.

The CO_2 sensor was opposite the balcony door, and it is likely that the balcony door was being left ajar at times, judging by the falls in CO_2. Although winter temperatures were rated as 'too cold' (see details in the User Feedback section), with 'socks and blankets' frequently deployed, probably because of cost of living concerns and lack of active heating, the average temperatures during the monitoring period were well above the WHO guidelines and almost 20.8 °C without the use of any heating.

Services strategy

Hot water: Dimplex qwcd210 (210 litres) with two 3 kW immersion heaters and electric shower.

Space heating: One direct electric panel heater for the whole maisonette (located in the living room, see Figure CS9.3) and according to the resident it has only been used three times in four years. It replaced old electric storage heaters which had been gradually phased out by the landlord.

Electricity: There is a prepayment meter with dual tariff. The more expensive First Rate is collected for the first 2 kW·h per day, with the Saver Rate for remaining kW·h used that day.

Ventilation: MVHR unit is maintained every six months by the landlord's service provider, latest maintenance dated 22/9/22. Maintenance regime includes cleaning of the heat exchanger and filter replacement. The resident does not engage with the unit but the external contractor is tasked with undertaking interim cleaning as well as filter replacement (see Figure CS9.4 for manifold access cover in hall).

Renewables: N/A

User feedback

Questionnaire findings: Gathered through the SOAP survey, the resident's comments about the physical property were mostly negative but were more neutral about the thermal performance and comfort. The property was acknowledged to be 'better' than their previous home (not at Wilmcote House), and it is likely that the frequent episodes of antisocial behaviour in the communal areas (mentioned during the interview) had a big impact on the overall satisfaction. The resident stated they had not received any training sessions nor a building guide. Informally, the resident shared that they did recall a brief walkaround with the council representatives, with the key message being that ventilation was not to be touched. The O&M records show that the resident was trained in the use of MVHR, cooker hood, booster switch, lights and restrictors just over five years ago. The council has confirmed that a building guide was left at the time of handover and will provide another copy to the resident for reference. The water heater provides 'the right amount' of hot water at 'just the right' temperature for five residents to take a total of three showers and four baths per week, leaving them 'somewhat satisfied'.

A 'neutral' rating was given to the ease of controls, which perhaps is not surprising given that controls are rarely adjusted, and the boost MVHR controls and separate kitchen extractor are not used as they are perceived to be expensive to run. Informally, it was shared that the windows were of 'perfect size', good at reducing noise, very easy to operate and were frequently used outside of the heating season. Some restrictors appeared to have been disengaged, presumably to help with purge ventilation. The survey results suggest summer temperatures are 'just right' and, in addition to keeping the windows open, one fan is enough to see the property through heatwaves. Informally, the kitchen was noted to be overheating, mostly due to the fixed windows.

Clothes drying area was rated 'somewhat poor' — likely due to the fact that the kitchen extract fan was not being used and hence did not purge humidity, and the sunspace was used for another purpose. So clothes drying happened in the living space.

The resident's main concern with the property was the ventilation in the kitchen. Due to the overly sensitive smoke alarm in the hall, the door is kept shut while cooking, which exacerbates the situation. Records show that the ventilation issue was anticipated and ducted hob extractors were installed as part of the mitigation strategy following experiments in the show maisonette. The resident is concerned about running costs and is not convinced the extractor is effective, hence it is not being used.

BPE techniques: lessons learned

From the 13 residents pre-screened by the council, only eight were contactable and did not present language constraints. Only six had lived at Wilmcote House for over a year, and only four were not affected by health issues which precluded them from participating. Only three had not switched electricity providers in the past year, and only one was in possession of utility bills. However, that resident dropped out without explanation, despite the incentive (£50 in cash or vouchers) offered for the provision of energy data. Six invitations to fill out the SOAP questionnaire were circulated via email, with zero responses. The council was not able to identify further residents that would meet the criteria of this study, so the study was undertaken with the resident on a pre-payment meter, despite challenges to obtaining energy data. Given the small sample rate (i.e. one maisonette out of 100), the findings may not be representative for the block as a whole.

OFGEM postcode-level data can provide valuable evidence of energy use over time, especially for large developments that have dedicated postcodes.

Airtightness testing: Sensitivity is needed when seeking to install test equipment where the residents are on a budget — it would be useful to have an estimate of the extra power consumption for transparency. The need to keep doors open during the airtightness test should be communicated clearly in advance.

Views on methodology: By default, SOAP questionnaire results are provided as a summary, but the individual responses (available on request) are more useful in clarifying specifc responses.

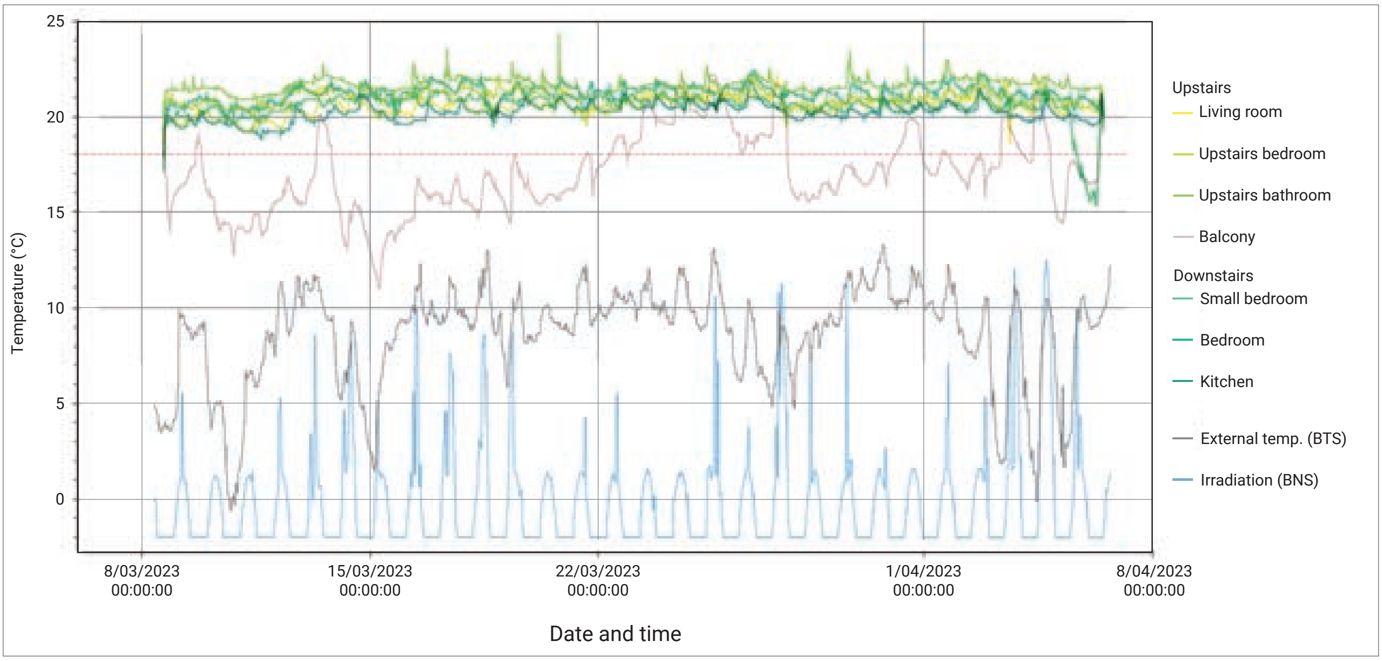


Figure CS9.7 Wilmcote House; internal and external temperatures (°C)

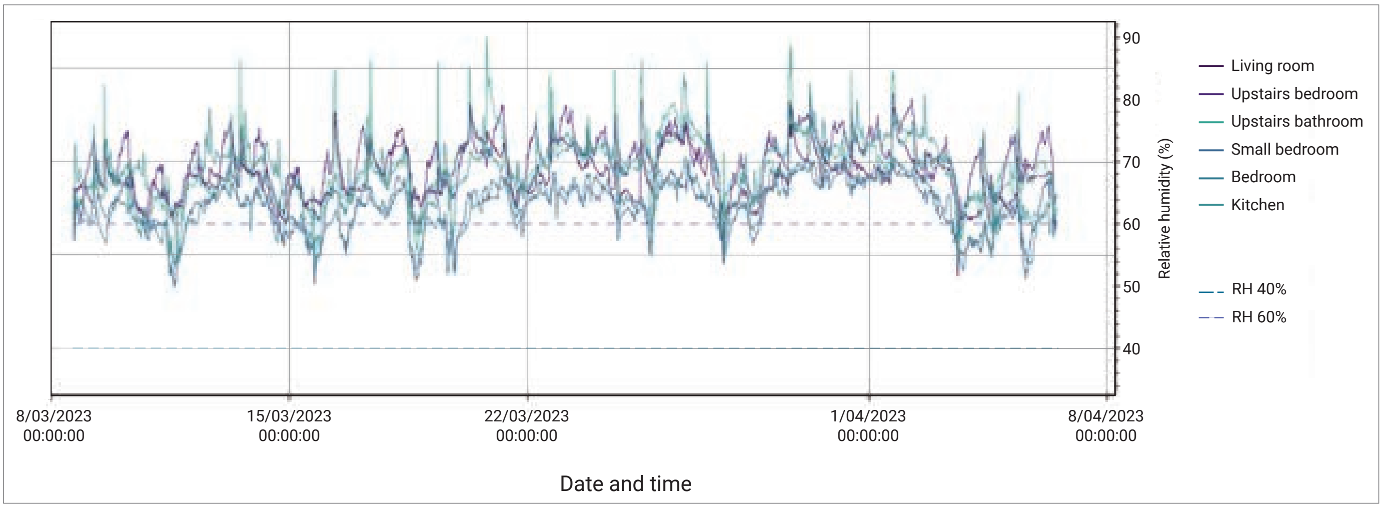


Figure CS9.8 Wilmcote House; relative humidity (%)

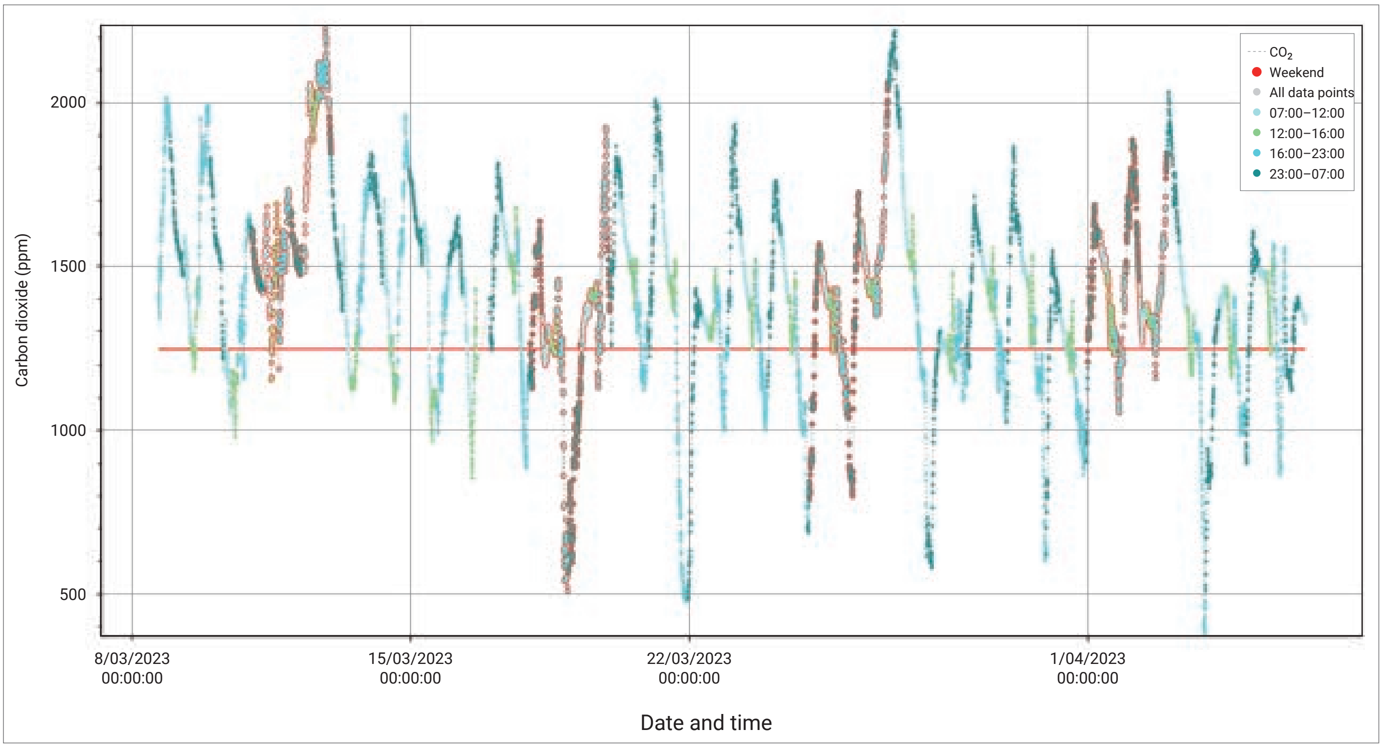


Figure CS9.9 Wilmcote House; carbon dioxide (ppm)

CS10 Passfield Drive

Passfield Drive

Companies involved in the 2023 BPE
bere:architects

Original retrofit architect:
Bere Associates Limited

Property age
Post-1919 (1960)

GIA area
96 m^2

Typology
Mid-terrace house

Occupancy
Family tenant, Southern Housing Group.

Occupants remained in-situ during retrofit to control costs if replicated at scale.

Project completed 12/07/2011.

Overview of the original retrofit

The house was insulated externally. This allowed occupants to remain at home during the retrofit. Designed for large-scale retrofit, the walls between houses are uninsulated, so the full energy-saving potential requires neighbouring properties to be insulated and warm. In the 2012 performance evaluation, the measured space heating demand showed a 40% reduction from pre-retrofit demand. PHPP modelling indicates a potential 90% reduction in space heating demand, from 303 kW·h/m^2 per year to 25 kW·h/m^2 per year after neighbouring houses are retrofitted.

Fabric strategy

Insulation strategy: External wall insulation (party walls between houses not insulated), loft insulation, vacuum insulation on concrete ground slab, triple-glazed windows.

Thermal bridges: Insulation in corners next to the cold facades of uninsulated neighbours mitigated the thermal bridges.

External wall insulation extends below ground, creating a thermal 'bubble' under the concrete floor slab and reducing thermal losses between the internal ground floor slab and the external ground.

Airtightness: A continuous flexible membrane in the loft space was sealed to the parge coat on the external walls. The membrane was carefully taped around existing roof timbers. Passive House windows were positioned in the line of insulation and taped to the parge coat with the addition of an acrylic glue to ensure permanent adhesion. Airtightness collars fitted to all new and existing service penetrations.

Services

Heating and hot water: A new gas boiler was retained, and solar thermal panels installed.

Ventilation: MVHR whole-house ventilation system installed

Publication of reference

Residential Retrofit: Twenty Case Studies (Baeli, 2013)

Retrofit Insights: perspectives for an emerging industry (Lowe, Chiu, Raslan and Altamirano, 2021)

Hindsight Review (Raslan, Lowe, Chiu and Altamarino, 2012)

Passfield Drive - Hindsight Review Washup Report (UCL Energy Institute, 2011)

Fabric improvement description and values

EWI to previously uninsulated solid brick walls.

200 mm on south elevation achieving a *U*-value of 0.138 W/m^2·K (93% improvement).

250 mm on north elevation achieving a *U*-value of 0.112 W/m^2·K (94% improvement).

Party walls: Uninsulated (to demonstrate an efficient, low cost, large-scale approach).

Roof insulation 490 mm achieving a *U*-value of 0.080 W/m^2·K (95% improvement).

Floor slab: 10 mm vacuum insulation, *U*-value: 0.378 W/m^2·K (80% improvement)

Windows and doors: Passive House triple-glazed, draught-free windows and external doors.

Glazing *U*-value: 0.60 W/m^2·K; frame *U*-value: 0.72 W/m^2·K (90% improvement).

Insulation properties: External wall insulation with non-permeable Permarock EPS-Premium with flame-retardant additive and protected by a multi-layer fire protection coating.

Overview of the revisited retrofit

Significant changes since the original retrofit

Occupancy: No significant changes

Building: No significant changes

Figure CS10.1 Continuous insulation and airtightness at eaves detail

Envelope

Overall fabric performance: The retrofit significantly increased the indoor comfort of the house while reducing energy consumption.

Airtightness integrity: Testing found slight improvement in air test result after 10 years, which indicates that there has been no deterioration of the airtightness strategy.

Further investigations: None identified.

Rectifications needed: The rear garden door performs as designed when shut, but required adjustment of one hinge — a minor maintenance job. The housing association owner sent a window specialist who recommended replacing the door with a non-Passive House door which would have undermined the performance of the house. The architect and the tenant worked together to repair the door.

Figure CS10.2 Ventilation duct concealed in wardrobes

Services

Solar thermal system has not been functioning since 2012 due to lack of maintenance.

Heating: There is minimal radiator use. Instead, a very high level of gas cooking by the household provides most winter space heating.

Hot water: Residents are satisfied with their hot water system. However, the energy saving potential of the solar thermal system is no longer realised due to lack of maintenance.

Ventilation: MVHR has performed well. However, filters have not been provided to the tenant on a regular basis for replacement. The tenant regularly cleans the filters and occasionally the architect donates a box of filters.

Energy performance:

EUI: 65% of pre-retrofit EUI. This has stayed the same in the 10 years since retrofit.

Figure CS10.3 Thermal image of the front facade

Gas: 6.7% higher in 2022–23 than it was in 2012–13. The increase equals the heating previously provided by the solar thermal hot water heating system until it stopped working,

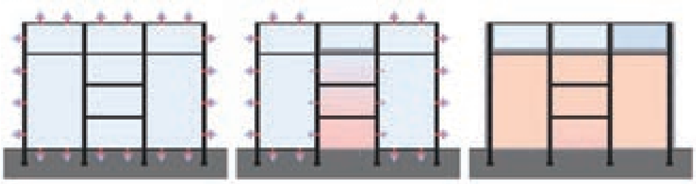
Electricity: 9.2% lower in 2022–23 than it was in 2012–13. This may be because in the 2012 winter the family also used two electric oil-filled radiators on the second floor.

Space heating demand: Lower demand than expected because of high level of gas cooking contributing to heating the house.

Indoor environment: Average temperature and humidity levels are in a comfortable, healthy range; slightly higher on the ground floor due to cooking but remaining healthy.

User feed-back: SOAP survey was positive with overall score 'good' (75%). Residents also found improved health, with asthma symptoms from pre-retrofit entirely gone.

Description of the BPE approach: Core BPE scope, no detailed tests. Temperature and relative humidity sensors placed in every room in the house. CO_2 sensor placed on the first floor living room. Smartmeter data downloaded for the recorded period.



	Pre-retrofit	Retrofit Revisited	Complete retrofit potential
HLP (W/m²·K)	**3.9** **Poor** (PHPP predicted)	**1.9** **Good** (SmartHTC estimated)	**0.6** **Excellent** PHPP predicted
HTC (W/K)	**378.9** (PHPP predicted)	**181** Confidence interval [−81, +31] (SmartHTC estimated)	**57.1** (PHPP predicted)
Actual recorded energy use (kW·h/m²·p.a.)	**262** (winter internal temperatures below 20 °C)	**169** (March internal mean average temp. 20.2 °C) **59** (specific heat demand)	–
PHPP predicted specific heat demand to maintain internal temperatures of 20 °C (kW·h/m²·p.a.)	**303**	**59** (assuming neighbours achieved March internal mean average temp. 16.5 °C)	**25**

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Figure CS10.4 Building energy performance, pre-retrofit, retrofit revisit and retrofit potential

Table CS10.1 2023 BPE findings: details

	Pre-retrofit	Original retrofit	Retrofit revisit
Annual energy use	Gas (including high daily cooking): 20,045 kW·h Electricity: 3546 kW·h (343 days: 17/08/09 to 26/07/10)	Gas (including high daily cooking): 11,687 kW·h Electricity: 4142 kW·h Solar thermal: possible contribution in part of the year, but unknown (366 days: 05/02/12 to 05/02/13)	Gas: 12466 kW·h Electricity: 3763 kW·h Solar thermal: 0 (365 days: 29/03/22 to 29/03/23)
Airtightness levels	5.1 $m^3/h{\cdot}m^2$ @ 50 Pa	1.78 $m^3/h{\cdot}m^2$ @ 50 Pa	Blower door test: 1.60 $m^3/h{\cdot}m^2$ @ 50 Pa Pulse test: 0.25 $m^3/h{\cdot}m^2$ @ 4 Pa (estimated 1.47 $m^3/h{\cdot}m^2$ @ 50 Pa)
Fabric moisture tests	NA	NA	NA
Thermography		See Figure CS10.3	
HTC	Pre-retrofit HTC calculated from PHPP: 378.9 W/K	Post-retrofit HTC calculated from PHPP: 57.1 W/K The PHPP calculation assumed the mass-retrofit scenario, where neighbouring properties would also be insulated, resulting in ~zero heat loss through party walls.	SmartHTC: 181 W/K (confidence interval −87/+31) Retrofit of neighbouring properties has not yet taken place.
Mould risk			BTS mould risk overall score is 25/100, or between 1 and 2 on 0–4 risk scale; i.e. on the border between 'low' and 'medium' risk. The building being externally insulated and cold bridging risks having been carefully addressed, it is highly unlikely that the internal surface temperature will fall anywhere near to the dew point temperature of ~12 °C. First floor bedroom: 2/100 First floor lounge: 8/100 Ground floor kitchen: 25/100 Ground floor lounge: 17/100 Second floor bathroom: 24/100 Second floor bedroom: 1/100 Second floor bedroom: 5/100
Walls			No defects found
Floors			No defects found
Roofs			No defects found
Windows and doors			See Briefing 4

Indoor environmental performance

Temperature: In the monitored period of March internal temperatures were as follows.

Ground floor kitchen:
- mean 23.7 °C
- minimum 21.2 °C
- maximum 34.4 °C.

Entire ground floor:
- mean 21.7 °C
- minimum 18.6 °C
- maximum 34.4 °C.

First floor:
- mean 20.1 °C
- minimum 18.7 °C
- maximum 22.4 °C.

Second floor:
- mean 18.6 °C
- minimum 16.2 °C
- maximum 22.3 °C.

Residents reported using the radiators at most once a day for only 20 minutes. Most of the space heating is from ground floor cooking. The coldest second floor room was below 18 °C for 32% of the monitored period. If neighbours were insulated, using the scalable EWI approach, heat loss through party walls would be effectively eliminated and the temperature difference between top floor and ground floor would be much less.

Relative humidity: During the monitored period in March, relative humidity levels were as follows.

Ground floor:
- mean 52.1%
- minimum 38.2%
- maximum 76.3%.

First floor:
- mean 54.0%
- minimum 41.5%
- maximum 72.3%.

Second floor (excuding bathroom):
- mean 57.3%
- minimum 44.0%
- maximum 71.8%.

Second floor bathroom:
- mean 63.6%
- minimum 48.6%
- maximum 88.8%.

Note: the humidity sensor placed in the ground floor bathroom was nonfunctioning.

The 24-hour moving average RH never exceeded 75% anywhere in the house and only exceeded 65% at times on the second floor (for 266 hours in the bathroom, 57 hours in the rear bedroom and five hours in the front bedroom).

CO_2 concentration: CO_2 levels ranged generally between 700 and 1100 ppm and averaged roughly around 900 ppm. Slightly on on the high side but still in the comfortable zone.

Commentary on physical findings versus user feedback

In the SOAP survey the residents indicated a preference for a 'warm' (Q33), '22 °C' (Q22) internal temperature. General comfort is 'very comfortable' (Q48) and overall comfort in winter 'somewhat comfy' (Q49), but temperature in winter on the second floor is 'slightly too cold' (Q50), which reflects the lower recorded temperature on the second floor. Despite this, the residents are 'very satisfied' (Q32) with the heating system (radiators), which they try to avoid using. The humidity in winter was 'just right' (Q52), which reflects the recorded mean relative humidity falling within a normal healthy range. They were also 'very satisfied' (Q32) with the ventilation.

Services strategy

Domestic hot water: Based on data from when the solar thermal system functioned, also supported by PHPP predictions, the solar thermal system could provide 60% of the DHW demand (see appendix).

Space heating: Gas cooking produces far more heat than the house needs in the summer, and nearly meets the winter heat load without any supplementary heat. Annual gas use is significantly higher than would be the case if occupied with less intensive cooking habits.

Electricity: Nothing unusual to report.

Ventilation: Maintenance of the filters for the MVHR unit is an issue. Southern Housing has not provided replacement filters for the unit but the occupants regularly vacuum the filters and wash the kitchen extract filter monthly. The architects donate new replacement filters from time to time.

Renewables: See section above on domestic hot water

User feedback

Questionnaire findings: The EWI strategy minimised impact on the tenants who stayed in-situ during the retrofit and were 'very satisfied' (Q73) with the installation process. They also find the external appearance 'very good' (Q40). Despite the unrealised energy saving potential of a wider EWI rollout to eliminate party wall heat losses, the tenants are 'satisfied' (Q73) with the outcome(s) of the retrofit. They find stability of conditions 'consistent' (Q54, Q60) in both winter and summer. They find summer overall comfort 'comfy' (Q55), air movement and humidity 'just right' (Q57, Q58 but temperature is 'slightly too hot' (Q56). The tenants report 'no' (Q35) condensation but responded 'yes' (Q36) to mould, later confirmed verbally to be a mistake. There has been 'no' (Q22) building handbook use because the tenants have a user board on the cupboard door instead. Tenants found the quality and usefulness of the introduction 'very good' (Q26) and are 'satisfied' (Q29) with general controls.

BPE techniques: lessons learned

This deep retrofit enabled the occupants to remain in-situ while their home was improved. The results demonstrate the benefits of applying Passive House methodology to a deep retrofit. The occupants increased indoor temperature and eliminated asthma symptoms while reducing energy consumption. Retrofitting adjacent houses is a cost-effective way to achieve the full potential energy savings. This is due to reducing heat loss through the connecting walls between a warm insulated house and its cold, uninsulated neighbours.

Airtightness testing: The air permeability was lower (i.e. better) under the Pulse test than the blower door test.

Views on methodology: Concurrent temperature monitoring in the home and direct neighbours would give a more accurate evaluation of heat loss. To give the most accurate evaluation of heat loss through party walls, it would be necessary to monitor temperatures in both neighbours' homes.

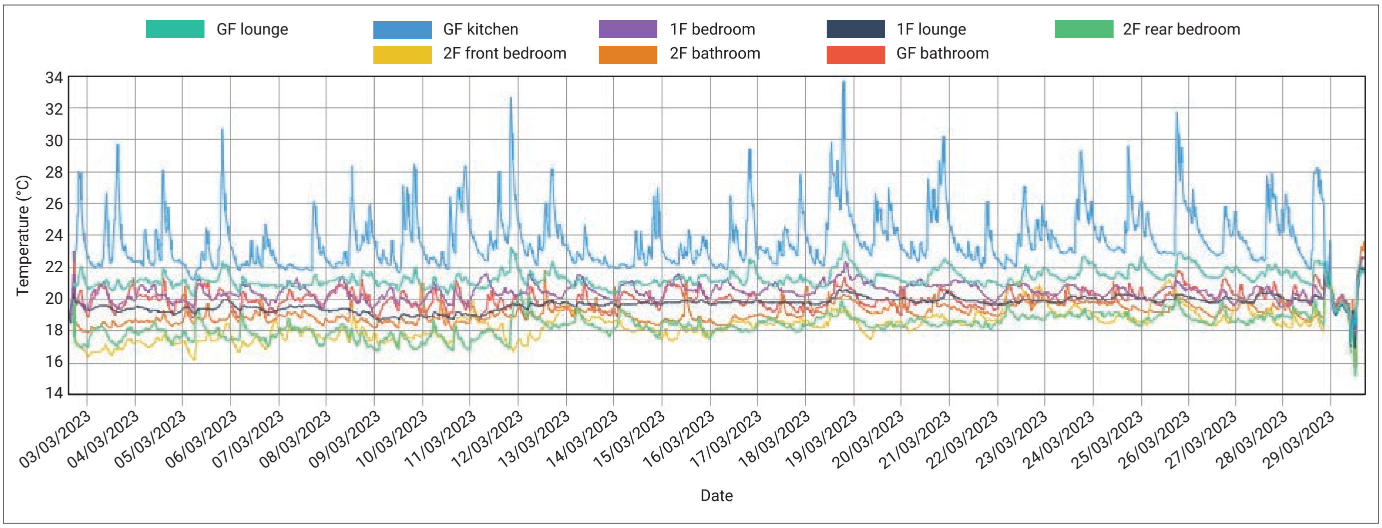

Figure CS10.5 Passfield Drive; internal temperatures (°C)

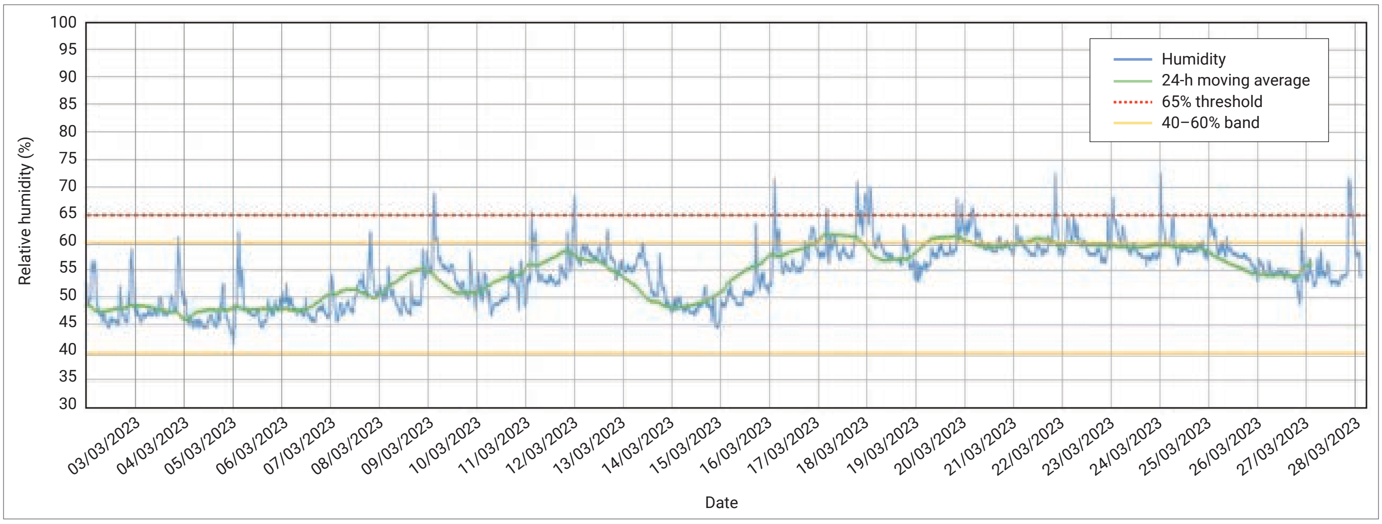

Figure CS10.6 Passfield Drive; Room 1 (GF lounge) humidity (%), March

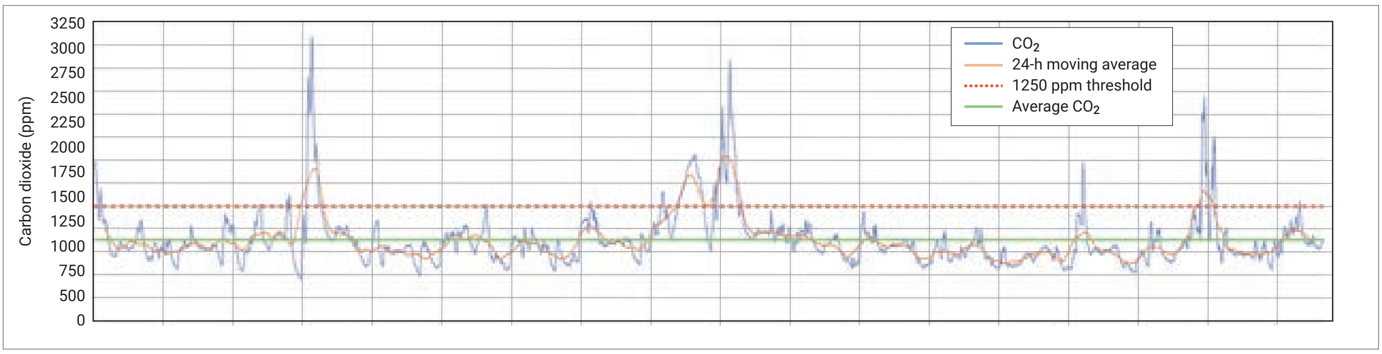

Figure CS10.7 Passfield Drive; Room 1 (GF lounge) carbon dioxide (ppm), March

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Appendices

Appendix 1: Briefing to evaluators and BPE methodology

Julie Godefroy and Marion Baeli

10 Years On: Retrofit revisit

Briefing to Evaluators: Methodology document
6th March 2023 – Rev3 as used by Evaluators

March 2024 version - Cleaned for project report, no change to methodology itself

Case studies - Overview

live version: https://docs.google.com/spreadsheets/d/1V0w_uwb-CABBcOxTF-oJgj2EWJy55Y3GFSxxjXeWwQg/edit?usp=share_link

RATIONALE FOR DETAILED TESTS: SEE NEXT 2 SLIDES

Case study	Evaluator	Typology	Age	Main insulation approach
Culford Road	**Bob Prewett**	mid terrace	pre-1919	IWI w/ glass wool and vented cavity (cavity approx. 25mm)
Grove Cottage	**Mike Roe** (w/ Andy Simmonds)	end terrace	pre-1919	mix incl EWI and IWI
Princedale Road	**Helen Grimshaw**	mid terrace	pre-1919	IWI (incl. PU foam w/ cavity approx. 25mm)
Rectory Grove	**Tim Wilcockson**	semi-detached	pre-1919	IWI (mostly permeable except wall at lower floor)
Hawthorn Road	**Tim Wilcockson**	mid-terrace	pre-1919	IWI (incl. sheeps wool & wood fibre), EWI at back
Shaftesbury Park Terrace	**Joe Jack Williams & Andy Macintosh**	mid-terrace	pre-1919	IWI aerogel; EWI at the back; suspended timber floor w/ ESP beads). Limited EWI to rear, with PUR (to be checked).
Blaise Castle Estate	**Ian Mawditt**	detached	post-1919	EWI and some IWI on EPS full fill cavity
Hensford Gardens	**Bob Prewett**	mid-terrace	post-1919	Phased - cavity then Reconstruction
Passfield Drive	**Justin Bere & Gabriel Anstee**	mid-terrace	post-1919	EWI
Wilmcote House	**Lilija Oblecova & Lizzy Westmacott**	apartments	post-1919	EWI

Case studies – Rationale for detailed tests – Pre-1919

live version: https://docs.google.com/spreadsheets/d/1V0w_uwb-CABBcOxTF-oJgj2EWJy55Y3GFSxxjXeWwQg/edit?usp=share_link

Case study	Typology	Age	Main insulation approach	Other relevant point in rationale for detailed tests?	Detailed tests	Airtightness expert (Paul J.)
Culford Road	mid terrace	pre-1919	IWI w/ glass wool and vented cavity (cavity approx. 25mm)	Generally should be example of best practice Air brick: RH in cavity? Joists taken out of front wall; some limited thermal bridging left, but probably difficult to detect (covered by fabric) Slimline double glazing: seals to check? Brick moisture test e.g. 2-3 core samples?	Yes: BTS + UCL	Yes - complex
Grove Cottage	end terrace	pre-1919	mix incl EWI and IWI (incl small area of PU foam w/o cavity)	Generally should be example of best practice Unheated cellar, suspended floor Detail at floor junction may need investigation e.g. thermal imaging, moisture test Existing extensive data/monitoring Thick EWI installation with good workmanship, attention to seals etc	Yes: BTS + UCL + use of Andy's data?	
Princedale Road	mid terrace	pre-1919	IWI (incl. PU foam w/ cavity approx. 25mm)	Generally should be example of best practice Air brick: RH in cavity? Joists taken out of front wall, fully detached Underground labyrinth: impact on ambient RH Underground labyrinth: impact on ambient RH and mould? MVHR not working for long period: impact on ambient RH and mould? BUT: many similar aspects to Culford, a lot of disruption to resident already	No BUT ambient mould test (Spyros)	
Rectory Grove	semi-detach ed	pre-1919	IWI (mostly permeable except wall at lower floor)	Generally should be example of best practice Many types of insulation Extensive pre-retrofit testing, and existing monitoring by HE Decaying unheated neighbour: possible mould risk? U-value testing if can put sensor on other side? Intrusive tests may be difficult given quality of the interiors	Yes but BTS only + access to HE sensors data?	Yes
Hawthorn Road	mid-terrace	pre-1919	IWI (incl. sheeps wool & wood fibre), EWI at back	Existing monitoring by UCL (Ben Croxford) Visual signs of mould risk: moss growth (north east wall), cracking in water works etc How to test sheep's wool insulation without breaking airtightness layer??	Yes but UCL only + Moth testing?	Yes - 1st property tested
Shaftesbury Park Terrace	mid-terrace	pre-1919	IWI aerogel; EWI at the back; suspended timber floor w/ ESP beads). Limited EWI to rear, with PUR (to be checked).	Intermittent occupation (resident splits time with Margate) Joists in the wall: need sensor test Existing moisture sensors in wall: working? access to data? Small area of PUR Peaboby and resident v interested	Yes: BTS + UCL	

Case studies – Rationale for detailed tests – Post-1919

live version: https://docs.google.com/spreadsheets/d/1V0w_uwb-CABBcOxTF-oJgj2EWJy55Y3GFSxxjXeWwQg/edit?usp=share_link

Case study	Typology	Age	Main insulation approach	Other relevant point in rationale for detailed tests?	Detailed tests	Airtightness expert (Paul J.)
Blaise Castle Estate	detached	post-1919	EWI and some IWI on EPS full fill cavity	Existing extensive monitoring Cold loft	No + use of Ian's data?	
Hensford Gardens	mid-terrace	post-1919	Phased - cavity then Reconstruction	phased	no	
Passfield Drive	mid-terrace	post-1919	EWI		no	
Wilmcote House	apartments	post-1919	EWI	only flats in the sample; previously v difficult to test airtightness	no	Yes - complex

BPE - Core scope

Minimum scope on all case study homes - all to be coordinated by evaluator, who is the main point of contact for residents

- Site visit
- User survey: Soap Retrofit, or otherwise BUS if it was used previously on that home (not known to be the case)

- Energy use audit based on 1-year of energy bills

- 1 month monitoring:
  - Energy meter readings in more detail e.g. smart meters, weekly readings
  - T, RH in several rooms (10 sensors provided to all homes)
  - CO_2 in main occupied room

- Airtightness testing: blower door & Pulse (by BTS, coordinated by evaluator)

Additions to initial core scope: as BTS are providing T & RH sensors to all homes:

- along with the energy meter readings there will be sufficient information for a SmartHTC measurement on all homes i.e. total building heat loss rate (using 4 weeks of energy and internal temperature monitoring data). This has therefore been added to the core scope. See more information on Smart HTC in later slides and training recording, https://drive.google.com/drive/folders/1yQjTRwBQO64XKlNjVEa8g782a9eUidOU?usp=sharing. A Smart HTC Login to SmartHTC have been provided to all evaluators.

- there will be sufficient information for a BTS Mould Risk assessment on all homes (using temp and RH data from the same 4 week period), so this has been added to the core scope. Login to be provided to all evaluators.

BPE - Detailed scope

Independent expert advice on airtightness tests

Paul Jennings will attend the airtightness tests on 4 case study homes:

- Culford Road
- Grove Cottage
- Rectory Grove
- Wilmcote House

This will include the first tests carried out by BTS on this project, to set the methodology applied throughout, therefore **one of these homes needs to be the 1st of all BTS tests.**

Visits to be coordinated with BTS and evaluator: evaluator is the main point of contact with residents.

Paul Jennings may carry out thermal imaging at the same time - at his discretion

BPE - Detailed scope

Additional investigations on up to 4 case study homes **<u>– long list selection on slide 3, final selection tbc with evaluators and specialist testers</u>**

Thermal performance testing

- HF Plate U-value measurement
- Heat3D U-value assessment

BTS

- Independent expert advice

To be coordinated by evaluator

+ thermal imaging: to be carried out by evaluators or airtightness testers / expert if they wish

Moisture investigations

Ideally before/after airtightness testing

- Physical testing e.g. moisture content, mould spore count in cavity air
- WUFI modelling

UKCMB

- Independent expert advice

Qoda

- Moisture risk assessment, for interstitial risk on walls with IWI

Loughborough University

Site visit

Aim:

- Gather insights on performance, occupant behaviour & satisfaction, changes since original retrofit, ease of use of some features, systems and controls, availability and quality of user manuals etc
- No need for formal write-up (but may be useful)
- For cross-checking and contextual information in the overall analysis

Photos subject to residents agreement – *Marion & Julie to confirm what is expected as minimum & what is already available for each home*

Approach left to the evaluator

Prompt questions from Woodknowledge Wales guidance may be used as example - *link & sheets in the resource folder*

Ideally on the same day as occupant survey and airtightness testing, to minimise disruption to residents – tbc by each evaluator with the residents

<u>Shared resource:</u>
Walk through capture form e.g. changes etc – *Ian Mawditt template*

User survey

As a minimum, all homes should be surveyed using the SOAP Retrofit survey, and all adult residents should be encouraged to fill the survey. Potentially, the evaluator may ask residents to provide just one response per household, if they are happy this would be representative of each adult resident's experience (note this may not be the case on many issues, such as noise, which can vary across individuals).

The survey is freely accessible: https://docs.google.com/forms/d/e/1FAIpQLSeWEcBb5RBY6yqXEeVtQ8Z98C_SvEajQs1nB878692wiw2xSA/viewform . A pdf copy is available in the shared resource folder for evaluators to see all the questions, and if needed to show to the residents in preparation for the survey: https://drive.google.com/file/d/1fB2aEDy_4ZyhC2p3UhIQr9NJAmtSJj3G/view?usp=share_link . It should **not** be used when recording responses: the online version should instead be used (this is much quicker too). The front page of the survey acts as consent form. Residents should fill the survey with their own email address. Once filled, the evaluators can let Zach know; he will send the report to both the residents and the evaluator.

If present during the surveys, evaluators may provide clarifications on the questions if requested by residents, but must be mindful not to influence the responses.

Evaluators may wish (but do not have) to use the following surveys, in addition and if the residents agree:

- BUS: in this case, the evaluator should be present: the SOAP survey is carried out first (for consistency across all homes), and the evaluator uses the answers to fill the equivalent BUS question, so the residents only have to fill the BUS questions which have no true equivalent in the SOAP survey. Evaluators wishing to use BUS should let Marion & Julie know, to agree the list of "truly equivalent" questions. No home was originally surveyed using BUS.
- The SOAP Retrofit survey, filled with the residents' recollections of the pre-retrofit situation. This will not be applicable to all residents, and the evaluator may in discussion with the resident decide whether recollections would be reliable. In this case, residents should add "PRE RETROFIT" after the name of their house (e.g. address: 206A Cassland Road PRE RETROFIT").

Evaluators may also wish to carry out interviews, to obtain more context and aid with the evaluation. A list of potential questions will be provided: the evaluators do not have to ask all of them, but for the ones they select they should follow the wording, for consistency of analysis. Questions on context are particularly helpful to the evaluation, for example their home pre-retrofit or their previous home, could this influence their satisfaction and experience now?

User survey

Reporting:

Key findings in main report, with context (including insights from interviews and the site visit) + full SOAP report in appendix

SOAP Retrofit (on all homes)

Online (17 pages)

- Includes pre & post retrofit questions, and as extra can also be filled separately as pre-retrofit situation (optional)
- Questions on hot water use, space for laundry drying
- Cannot scroll through without completing the mandatory questions
- No “not applicable”

Automatic analysis by SOAP, get scores & benchmarks (200+ homes) + list of free-text comments

BUS (optional)

Online or paper

- Many “free text” comment boxes
- Available in other languages (esp. the paper version)

Should have been used if it was used in the original retrofit, but this was not the case in any home

Automatic analysis by ARUP, get scores & benchmarks + list of free-text comments

Evaluators who are not BUS partners: let Julie know, she can be the official BUS partner

Airtightness testing

Carried out by BTS: Both Pulse and Blower door

Follow CIBSE TM23 methodology & reporting requirements

Both pressurisation & depressurisation to be carried out in the blower door tests.

Neighbouring properties: *tbc – BTS and Paul Jennings to confirm the approach*

Homes to be witnessed: Hawthorn, Culford, Rectory, Wilmcote

Some detailed tests should be carried out at the same time (e.g. mould spore count) – evaluator to coordinate

Visits to be coordinated by evaluator, as single point of contact for the residents

Reporting:

- Blower door result at 50Pa
- Pulse result at 4Pa
- Pulse result extrapolated to 50Pa (BRE formula – in SAP and TM23 – this will be in the template report)
- Commentary on results: comparison with pre-retrofit; possible points of leakage & possible causes (e.g. deterioration? Changes to the envelope since original retrofit?); comparison between actual and extrapolated 50Pa results;
- Commentary on methods

Energy use analysis

As a minimum, an analysis should be made of total energy use (= all fuels & electricity)

- Annual: based on bills provided by the resident to the evaluator, covering at least one full year. Analysis over several years is welcome but not essential.
- 1-month monitoring period: **<u>weekly readings as minimum (all fuels & electricity)</u>**. Additional readings or use of smart meters is welcome but not essential.

Further level of detail will depend on metering available on site

- Smart meter or not, and access to data or not. BTS can help facilitate the connection to the customer's smart meter (if it is an enrolled one), via app
- If no smart meter, regular past readings by residents (/ housing association) or not
- Sub-metering of systems or not
- Metering of output from on-site renewable energy systems, if available
- During the site visit, it can be useful to take readings off plant items, for example of heat output from heat pumps, or electricity output from PVs

<u>There is currently no plan for meters to be purchased and installed</u>, but:

- Evaluators can feel free to use their own clamp meters (/smart plugs etc) if they wish, subject to residents approval.
- If evaluators foresee a serious issue of access to total metered energy data, please let us know asap as budget may be found from the "buffer" budget.

Energy use analysis

Reporting :

- **As a minimum:** Total annual energy use, and breakdown into fuels. This should be TOTAL i.e. including contribution from on-site systems. If contribution from on-site systems is not known, this should be clearly stated. Indicate the associated year (this does not have to be a calendar year) + commentary if relevant e.g. "very cold winter" – see next slide .
- **As a minimum:** more detailed (e.g. weekly) analysis during the 1-month period, alongside degree hours or average external temperature
- If available: metered heat delivered by heating systems (e.g. heat meter on gas boiler or heat pump) over a year, or over 6 winter months
- If available: annual metered electricity or heat delivered by on-site renewables (e.g. PVs total production / export / used by the home, solar thermal: heat output …)
- If available from monthly readings: estimate of split between SH and DHW, at its very simplest using summer months as base DHW
- Evaluators may wish to report on other parameters, depending on their interest and the availability of data.
- Commentary incl. correlation with stated comfort levels, weather data, unusual occupancy, reported fuel poverty …
- Comparison with design calculation and with original retrofit – this will be provided for each home in the data reporting template

A data reporting template will be provided, to be used by each home to help clear and consistent comparison and analysis of results.

Energy use analysis

Analysis of energy use against the weather can be made:

As a minimum, by qualitative comparison against the weather, checking how the months within the period covered by energy bills are “unusual” in the table below

Calendar period	2002 deviation	2003 deviation	2004 deviation	2005 deviation	2006 deviation	2007 deviation	2008 deviation	2009 deviation	2010 deviation	2011 deviation
January	-1.1	-0.0	-0.6	-1.5	0.4	-2.0	-1.5	1.6	3.4	1.1
February	-2.1	0.7	-0.4	0.6	1.0	-0.9	-0.2	0.8	2.4	-1.2
March	-0.9	-1.1	-0.1	-0.5	1.8	-0.4	0.7	-0.2	0.7	-0.0
April	-0.5	-1.0	-0.7	0.1	0.4	-2.3	0.9	-0.8	0.0	-2.8
May	-0.1	-0.2	-0.5	0.5	-0.2	-0.2	-1.5	-0.3	1.1	-0.6
June	-0.3	-1.8	-0.7	-0.5	-1.1	-0.8	-0.1	-0.1	-0.7	0.2
July	0.0	-0.6	0.1	-0.5	-0.6	-0.1	0.2	-0.4	0.6	-0.1
August	-0.6	-0.4	-0.5	-0.4	-0.4	-0.2	-0.5	-0.5	-0.0	0.1
September	-0.7	-0.4	-0.7	-0.7	-1.7	0.2	0.1	-0.5	-0.2	-0.9
October	0.6	1.8	0.3	-2.1	-1.9	-0.1	1.1	-0.6	0.5	-1.2
November	1.2	-0.8	0.5	1.1	0.5	0.0	0.6	-0.9	2.2	-2.0
December	-0.8	0.1	-0.6	0.3	-1.2	0.1	1.4	2.1	5.4	-0.8
January-March	-1.1	-0.1	-0.3	-0.5	1.1	-1.1	-0.3	0.7	2.2	-0.0
April-June	-0.4	-0.9	-0.6	0.0	-0.3	-1.1	-0.2	-0.4	0.1	-1.1
July-September	-0.4	-0.5	-0.4	-0.5	-0.0	-0.0	-0.2	-0.4	-0.2	-0.3
October-December	-0.5	0.3	-0.2	-0.2	-1.2	0.0	1.1	0.2	2.7	-1.3
January-December	-0.8	-0.3	-0.4	-0.3	-0.3	-0.5	0.1	0.0	1.3	-0.7

Calendar period	2012 deviation	2013 deviation	2014 deviation	2015 deviation	2016 deviation	2017 deviation	2018 deviation	2019 deviation	2020 deviation	2021 deviation	2022 deviation
January	0.6	1.0	-0.7	0.1	-0.8	0.6	-0.1	0.7	-1.8	1.6	-0.3
February	0.8	1.8	-1.1	0.5	0.1	-1.1	2.1	-1.7	-1.2	0.0	-1.7
March	-1.7	3.8	-0.8	0.4	0.6	-1.2	1.9	-1.2	-0.0	-0.6	-1.0
April	1.5	1.5	-1.2	-0.2	1.8	-0.1	-0.6	-0.2	-1.4	2.3	-0.2
May	0.4	1.1	-0.6	0.8	-0.5	-1.0	-1.1	0.5	-0.8	1.5	-1.4
June	0.4	-0.0	-1.1	0.1	-0.8	-1.0	-1.2	-0.1	-0.4	-1.1	-0.8
July	0.2	-0.5	-0.5	0.1	-0.2	0.5	-0.6	-0.5	-0.0	-0.6	-0.5
August	-0.4	-0.6	0.2	-0.2	-0.5	-0.2	-0.1	-0.5	-0.2	-0.5	-0.7
September	0.7	-0.0	1.0	0.8	-1.2	0.1	0.1	-0.5	0.0	-1.3	-0.2
October	1.3	-1.5	-1.4	-0.0	-0.0	-1.4	0.2	0.7	0.4	-1.2	-1.9
November	0.9	1.2	-0.8	-1.5	1.7	0.6	-0.7	1.1	-1.2	-0.3	-1.5
December	0.1	-1.2	-0.3	-4.1	-1.3	0.1	-1.6	-0.9	-0.1	-1.2	[x]
January-March	-0.5	2.2	-0.9	0.5	-0.0	-0.7	1.2	-0.7	-1.0	0.4	-1.0
April-June	0.8	0.8	-1.0	0.2	0.0	-0.7	-1.0	0.1	-0.9	0.9	-0.8
July-September	0.2	-0.4	-0.4	-0.2	-0.7	-0.1	-0.2	-0.5	-0.1	-0.8	-0.5
October-December	0.9	-0.5	-0.9	-2.1	0.1	-0.1	-0.7	0.3	-0.3	-0.9	[x]
January-December	0.1	0.5	-0.8	-0.1	-0.1	-0.5	-0.2	-0.2	-0.5	-0.1	[x]

https://www.gov.uk/government/collections/weather-statistics

In addition, evaluators may want to carry out a degree day analysis, particularly if they have several years of coverage in energy bills. This could be done using site climate data, if available, or https://www.degreedays.net

IEQ monitoring

Obtaining at least one month over winter(ish) conditions is an important part of this study, and one of the drivers behind the programme.

The monitoring should include as a minimum:

- Over 4 weeks minimum, complete by end of March >> if possible installed by mid-Feb for sanity checks in early days. Historic data from sensors in the home may be used if available, but is not essential.
- T & RH: kitchen, living room, main bedroom. In some cases, evaluators may wish to install sensors in the bathroom (e.g. fan appearing not to work, visible mould)
- CO2: main occupied room – see details below.

Please follow the sensors' instructions on installation, and the usual good practice precautions e.g. not in direct proximity to a heat source, draught, or direct sunlight. Please take pictures of where the sensors were installed, ask residents not to move them, and check locations on subsequent visits (if any). If children or animals are present in the home, choose out-of-reach locations.

BTS are lending several T & RH sensors to all homes (posted to the evaluators), along with an explanation on how to use them. They can be set up by plugging to a laptop (USB), which is also how data is downloaded. They operate on battery.
If other sensors are already installed, the evaluators could use the data from these sensors alongside, for comparison.

Ian Mawditt are lending one CO2 sensor to each evaluator (posted to the evaluators who requested it), along with an explanation on how to use them. The evaluators should check with residents which room is the more consistently occupied, but this likely to be the master bedroom. Check occupancy patterns to help analysis e.g. if there is a shift worker, the bedroom may be occupied during the day. Instructions for the CO2 sensors and software are in a folder on the project drive accessible to all evaluators: https://drive.google.com/drive/folders/1B_8zHt4ZaJDOOIQ_NbepOwqyFavQRAQu?usp=share_link

IEQ monitoring

Reporting:

- Graphs over the 4 weeks, for T and for RH (per room or all combined)
- On RH graphs, mark 65% line and 40-60% RH band
- On T graphs, mark 18^{o}C and heating set point, if known
- Reporting against key criteria – see details in following slide
- Commentary, including correlation with site observations (e.g. extract fan off), user feedback, and energy use; consider day / night, weekday-weekend patterns, variations across the home (e.g. north / south halves of the house, GF / top floor…) , external conditions (if available or from local station)
- Commentary on sensors (especially if several types available)

Reporting should help establish the ability of the homes to maintain comfort conditions against the following criteria:

1. Internal temperatures maintained in each room monitored above 18°C during the monitored period (or ideally the whole heating season - 1 October to 31 March -, if available from sensors in the home) with assessment of hours below this temperature. In addition, mean internal temperatures should be reported.

   Note: If heating setpoint temperatures are known, then further assessment would be preferable to assess temperatures that are <18°C, e.g. if heating is programmed for 16°C overnight, this should be reflected in the analysis. This refinement may need to account for heating response times, e.g. thermostat hysteresis of 0.5°C.

1. Winter internal relative humidity maintained below 24-hr moving averages of 65% (over 4 weeks), 75% (over 7 days) and 85% (within a 24-hr period).
2. Carbon dioxide concentrations during the heating season maintained below 1250ppm using an 8-hour moving average (Part F calculated threshold for dwellings).

   Note: CO_2 concentrations should be assessed during occupied room times (as noted in the previous slide when selecting the room for the CO2 sensor). For consistency, occupied bedroom times could be taken as 10pm to 7am, except if there are night shift workers, in which case occupancy times will need to be determined.

Case study reporting

4-page report template

Excel data record sheet template

BPE Core Scope: between BS 40101 Lite & Standard

BS 40101 Standard BPE (individual dwellings)	Retrofit Revisit – Core BPE
Building parameters	
Occupant experience	
Post-construction review	
Energy use and generation	
Water use	✘ Voluntary – observations only
Internal monitoring	
External monitoring	

Appendix 2: Residents' briefing and consent form

Julie Godefroy and Marion Baeli

RETROFIT REVISIT
OVERVIEW & CONSENT FORM

RETROFIT REVISIT: WHAT IS IT?

Retrofit Revisit is an important new research project, supported by the UK's Research and Innovation agency (UKRI) and Historic England.
At a time when we understand more than ever the need for homes that do not require much energy to heat, do not emit much carbon, and which are healthy and comfortable to live in, this project is setting out to look back and learn from homes that were retrofitted about 10 years ago and considered to be among the best examples of retrofit in the UK.

Your home is one of these, so it is very interesting and could hold very useful lessons for designers, builders and housing associations.

What we need

For this study we would like, subject to your consent, to carry out the following activities. The data collected through these activities will help us understand how the home performs for the environment and for you:

- Ask you to fill a survey about your experience in the home; this will include some personal information (e.g. address, age range, number of people in the home). You can omit this information if you wish.
- Collect data on energy and water used by the home
- Monitor the conditions inside your home i.e. temperature, relative humidity, and CO_2 levels
- Take a few photos of the property, for example of the external walls or heating system and controls.

RETROFIT REVISIT
OVERVIEW & CONSENT FORM

What we will do with the data

This data will help us assess:

- How much energy is used, how it compares with expectations and with energy use originally, and what may explain energy use e.g. whether the heating system is working as it should, and the insulation still works as well as when originally installed to keep the home warm
- How well the home works for you in terms of its design and comfort e.g. temperature, ventilation, light levels etc. This provides valuable information on the home, and also helps us better understand how energy is used.
- Whether your home and its systems, for example the insulation, the ventilation unit, or the heating system, work as well as they should.

The findings gathered from your home and the other homes in the study will be used to inform the whole industry to understand how to improve homes, to cut energy use and carbon emissions, and make them healthy and comfortable for residents.

Usually, this type of study is also very interesting and useful to residents, as it can identify some issues which could improve your home, for example making it more comfortable, efficient, or easy to use.

Thank you very much for your participation!

RETROFIT REVISIT
OVERVIEW & CONSENT FORM

YOUR CONSENT

Under the General Data Protection Regulation (GDPR), explicit consent of personal data collection must be obtained so that we can analyse the information you have provided us. You can find more information on GDPR on the next page.

I confirm that I have read and understood the information on the Retrofit Revisit study and the evaluation team (xxx name) has answered any queries to my satisfaction.

I confirm that I understand how my personal information will be used and what will happen to it.

I understand that my participation is voluntary and that I am free to withdraw from the project at any time, up to the point of completion, without having to give a reason and without any consequences.

I understand that I can request the withdrawal from the study of some personal information and that whenever possible the evaluation team will comply with my request.

I understand that any information recorded in the project will remain confidential and no information that identifies me will be made publicly available, unless explicitly approved by me.
I consent to being a participant in the project.

PRINT NAME:
SIGNATURE :
DATE:

RETROFIT REVISIT
OVERVIEW & CONSENT FORM

ADDITIONAL INFORMATION (PERSONAL DATA)

- Your personal data. Personal data relates to a living individual who can be identified from that data. Identification can be by the information alone or in conjunction with any other information in the data controller's possession or likely to come into such possession. The processing of personal data is governed by the Data Protection Act 2018, which incorporates and enhances the General Data Protection Regulation (the "GDPR"). The GDPR section of the Act took effect on Friday 25th May 2018.
- Who are we? CIBSE and PDP are the data controllers. This means they decide how your personal data is processed and for what purposes. CIBSE and PDP comply with their obligations under the "GDPR" by keeping personal data up to date; by storing and destroying it securely; by not collecting or retaining excessive amounts of data; by protecting personal data from loss, misuse, unauthorised access and disclosure, and by ensuring that appropriate technical measures are in place to protect personal data.
- Only CIBSE, PDP and their authorised evaluation teams will have access to your name and contact details, for logistics during the project only.
- Reporting will not include residents name, nor full address (just name of the road / broad identifier, as currently). Photos of the homes would be ideal, but stripped of identifying factors and without people in (unless you wish to!). You will have an opportunity to read the outputs (e.g. report sections) related to your home for approval before publication and dissemination.

PDP contact: Marion Baeli m.baeli@pdplondon.com
CIBSE contact: Julie Godefroy jgodefroy@cibse.org

RETROFIT REVISIT
OVERVIEW & CONSENT FORM

ADDITIONAL INFORMATION ON THE STUDY

OMIT IF YOU PREFER TO COVER THESE POINTS VERBALLY WITH RESIDENTS

- The airtightness tests are the main disruptive activity. You can actually stay in the home while they take place, but some people may prefer not to for discomfort. They are standard tests carried out as part of the Building Regulations approval process, and will not damage your home. Overall, they will take a few hours, depending on the time it takes to set up.
- The sensors installed in the home monitor temperature, humidity levels and CO2. They are very useful to help us analyse how well the home is working, to provide a comfortable, healthy environment. The evaluation team for your home will agree their location with you, please do not move them once installed.
- Add if needed for homes subject to detailed tests, but probably best discussed verbally e.g. small hole to sample test wall etc…

Appendix 3: Comparison of BPE methodology with BS40101:2022

Julie Godefroy

BPE Core Scope: between BS 40101 Lite & Standard

BS 40101 Standard BPE (individual dwellings)	Retrofit Revisit – Core BPE
Building parameters	
Occupant experience	SOAP survey (BS compliant) to "at least 1 adult occupant"
Post-construction review	Airtightness test ✗ Acoustics: voluntary e.g. site observations ~ Reference to Post Construction Review e.g. observations on handover documents ~ Thermal imaging: voluntary (done in most cases)
Energy use and generation	1 year (start & end meter readings) ~ Monitoring: 1 month not 12 ~ On-site systems if available
Water use	✗ Voluntary – observations only
Internal monitoring	~ T & RH in most rooms – 1 month not 12 ~ CO_2 in main room – 1 month not 12
External monitoring	~ Nearest station

Appendix 4: Domestic occupant satisfaction surveying (SOAP survey)

Zack Gill

Domestic Occupant Satisfaction Surveying

Project: Retrofit Revisited

Results Analysis

"Occupants are the best (albeit uncalibrated) sensor of building performance that we have"

Prepared by Dr. Zachary Gill (Director), SOAP Retrofit Ltd
zack.m.gill@soapretrofit.com
11/05/2023

Executive Summary

Occupant surveying (pre-retrofit) at x10 properties for the Retrofit Revisited Retrofit project shows that the properties have very few issues and the whole-house (deep) retrofits are generally performing well. On average, they are rated **great** compared to benchmarks scores, with little negative feedback from the residents.

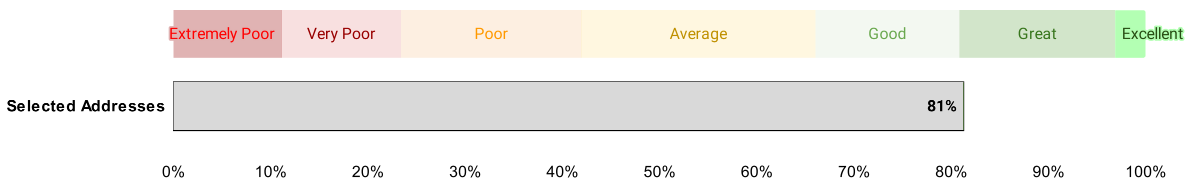
Results Summary

This report summarises the results from the following property(s):

Postcode	Quantity	Numbers	Address
W11 4NH; SW4 0DS; SW11 5XA; SE26 6JG; PO5 4NA; N8 7NA; N1 4HL; HR1 2SE; E14 6QT; BS9 2RH	10	51; 10; 28; 100; 3; 5; 57; 6; 26; 89;	Rectory Grove; Hawthorn Road, Hornsby; Hensford Gardens; Princedale Road, London; Passfield Drive; Pitchcombe Gardens, Bristol; Portfield Street; Wilmcote House; Eversleigh Road; Culford Road

Overall Results: **Great**

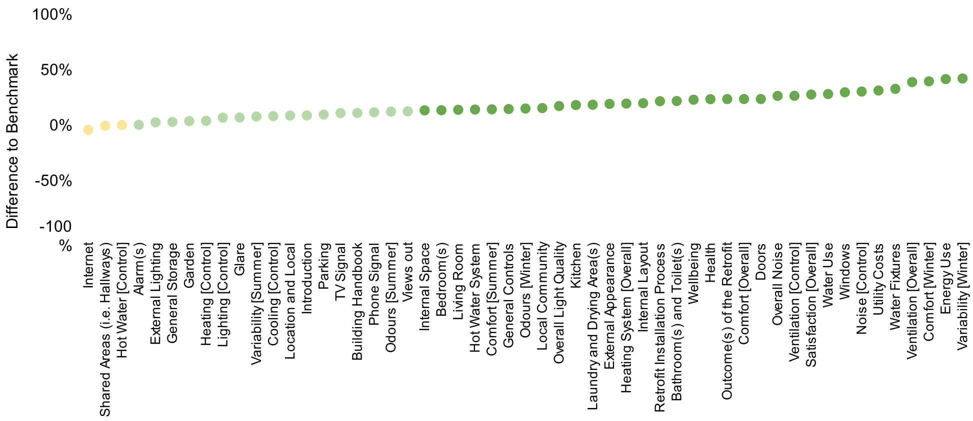
The graph below shows how the property(s) performs (on average) compared to benchmark values

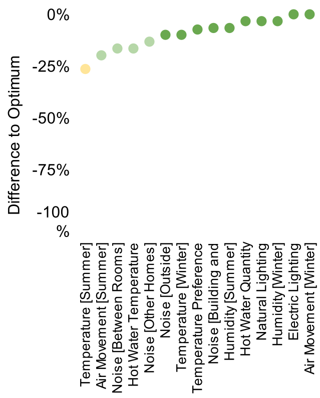


Detailed Analysis

In this section, a detailed breakdown of the average survey results is provided to explain the overall performance of the property(s). This data can be used to identify elements that require improvement and/or identify elements that are performing well and might be replicated in other properties.

The graphs below show how each metric compares to benchamark or optimum values. These results are then summarised below, in particular to highlight the pertinent issues which could be readily improved through retrofit or refurbishment.





Pertinent issues in order of severity:

Issues most influenced by deep-retrofit (in order of severity)

#N/A

Issues that can be improved through refurbishment, potentially integrated into a retrofit project (in order of severity)

#N/A

Quantitative Data

In this section, the quantitative data gathered in the survey(s) is summarised collectively for all properties.

Percentage (%) values refer to the percentage of surveyed properties that the question applies to. For instance, "Condensation presence = 75%" would mean that 75% of properties experience condensation

	Min	Average	Max
Number of Occupants	1	3.1	5
Adults (20+)	1	1.9	3
Teenagers (13 – 19)	0	0.7	3
Children (0 – 12)	0	0.5	2
Weekday Occupancy			
Morning	-	80%	-
Daytime	-	60%	-
Evening	-	100%	-
Night	-	90%	-
Weekend Occupancy			
Morning	-	100%	-
Daytime	-	90%	-
Evening	-	90%	-
Night	-	80%	-
Energy cost (£/yr)	£720	£1,455	£2,600
Water cost (£/yr)	£150	£468	£1,500
Electric vehicle charging at home	-	0%	-
Showers per week	3	15	30
Baths per week	0	2	7
Given a building handbook?			
No	-	40%	-
Yes	-	40%	-
Don't know	-	20%	-
Given an introduction?			
No	-	40%	-
Yes	-	60%	-
Don't know	-	0%	-
Want more control of:			
Heating	-	100%	-
Cooling	-	100%	-
Ventilation	-	100%	-
Hot Water	-	100%	-
Lighting	-	100%	-
Noise	-	100%	-
Temperature preference (°C)	17	19.4	22
Condensation presence	-	40%	-
Condensation locations	Only condensation since the MVHR stopped working in February this year. Just on windows. Shower downstairs also had condensation and mould. Downstairs shower used more - especially by kids. Better since one fan re-working, and should be even better again when second fan replaced. ; Very little between outer window and secondary glazing; when using clothes dryer; Yes; Yes; No		
Mould presence	-	40%	-

Mould locations	As above - related to MVHR failure recently. ; Yes; shower tray boundaries; Yes; No		
Laundry – Rack	-	80%	-
Laundry – Airing cupboard	-	20%	-
Laundry – Radiator	-	30%	-
Laundry – Tumble dryer	-	30%	-
Laundry – Other			
Intended or Achieved outcomes of a retrofit:			
Reduction in energy use	-	0%	-
Reduction in energy cost	-	33%	-
Reduction in carbon emissions	-	0%	-
Improvement in internal comfort	-	33%	-
Improvement in internal air quality	-	0%	-
Reduced risk of overheating	-	33%	-
Elimination of condensation / mould	-	0%	-
Improvement in energy rating	-	0%	-
Meeting a performance standard	-	0%	-
Improving usefulness of building	-	0%	-
Improving sustainability of building	-	0%	-
Protect against decay / deterioration	-	0%	-
Improve resistance to water	-	0%	-
Resilience against flood risk	-	0%	-
Integration of energy efficiency	-	0%	-
Architectural heritage	-	0%	-
Increased property value	-	0%	-
Improved appearance	-	0%	-
Improved desirability of the building	-	0%	-

Freeform Feedback

Please describe any special circumstances that require non-typical use of your home, and if they're properly catered for	None; None; No; One of us works from home; Two businesses operate from home
Any comments about the Building Handbook (if provided)	Really good. Handbook used for Genvex controls and cooker (appliances etc) but only really used when first moved in. Had everything we needed to know. E.g. pipes, could see what needed to be done (but haven't really needed it). ; Very useful to know the makes and model of items if they need attention; No
Any comments about the Building Introduction (if provided)	Was done by Phillip, original engineer - he was amazing, very friendly man. ; We had access to the builders and design engineer afterwards for questions; No; The builder was my partner's brother
Specific concerns about temperature or air quality in winter or summer	Not in winter, but summer high temperatures do trouble sometimes. ; Can get hot in a heat wave. Very steady in winter; None; Perfect in winter, can over heat in summer; Thermal comfort becomes less optimum in very cold or very hot weather; low temperature and draught only on top floor during winter
Any other comments regarding comfort	It's comfortable! ; Very comfortable most of the time, especially in winter. ; The best home comfort I have experienced in my life. ; Very satisfied overall
Any other comments regarding your home	Love it! Happy with the way it's designed, nothing negative really - just maybe would be nice to have cooling. Now it's 10 years on, maybe things need to be updated - for example, the MVHR recently breaking. But for 10 years it's been great. To keep it going strong, Octavia should look at that. The housing association needs educating - 10 years on it feels like they don't know anything about it still! ; Lot of stairs, but we knew that at time of buying. No water on principal floor; No

Appendix 5: Detailed testing: moisture

Dr Valentina Marincioni (UKCMB) and
Spyros Efthymiopoulos (UKCMB)

CIBSE / STUDIO PDP RETROFIT REVISIT DETAILED TESTING: MOISTURE

REPORT

Authors:
Dr Valentina Marincioni
Spyros Efthymiopoulos

Version 2.1

The research presented in this report has been funded by Historic England, with in-kind support from by Mycometer A/S and Housetest ApS

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Nomenclature

Bed – Bedroom
LR – Living room
BD – Before depressurisation
AD – After depressurisation
MVHR – Mechanical ventilation with heat recovery
IWI – Internal wall insulation
GF – Ground floor

1 Report brief

This report presents the results of a detailed moisture testing campaign conducted to evaluate the moisture performance of five properties, tested as part of the Retrofit Revisit project led by CIBSE and Studio PDP.

Five properties were tested in detail, to complement the results of the building performance evaluation carried out within the project. Four pre-1919 properties were tested:

- **Hawthorn Road**: building inspection, fungal testing of living spaces and loft, T/RH monitoring of internally insulated wall and loft, 2D hygrothermal simulations
- **Shaftesbury Park**: visual/IR inspection, fungal testing of living spaces and loft, T/RH monitoring of internally insulated wall (in intermediate floor) and loft
- **Grove cottage**: building inspection of living spaces, fungal testing
- **80% house**: building inspection, fungal testing of living spaces, T/RH monitoring of cavity

In addition, a more recent property (1950s) was tested, with a focus on the loft:

- **Blaise Castle estate:** building inspection, fungal testing of living spaces and loft.

The detailed analysis of each property can be found in the report on **"results from fungal testing and visual inspection",** and detailed analysis of the issues identified in Hawthorn road can be found in "**Hawthorn road hygrothermal risk analysis report**". Also, two Hygrothermal Performance Assessment Reports were prepared by QODA, for Hawthorn Road and Shaftesbury Park. Below, we summarise the findings across the different properties.

2 Methods

2.1 Building inspection

The visual inspection documented the areas of the building fabric that were visible, both from the inside and the outside. The visual inspection aimed at documenting any visible presence of mould, damp and degradation of the building fabric. Also, the inspection allowed to document the building materials and systems used in the buildings, if not available in the specification (e.g. type of brick and mortar). The visual inspection was supported by IR thermography, microscope analysis of insulation, and moisture content measurement of joists when possible and deemed useful. Finally, air flow measurements in properties with MVHR were carried out with a rotating vane anemometer when missing from the main report.

2.2 RH and particle count (spot measurements)

The concentration of fine (PM2.5) and coarse (PM10) particles was measured during the in situ testing before the mechanical resuspension of particles for the fungal testing. Measurements were collected on a 2sec interval for 2 min to (a) assess the risk of exposure to high concentrations of airborne fine and coarse particles and (b) indicate potential malfunction of the MVHR systems installed in the tested properties. Relative humidity readings were also recorded on a 2sec interval during the same time to get a rough indication of any potential moisture-related issues at the time of the in-situ testing.

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2.3 Fungal Testing Protocol

An activated/aggressive protocol was implemented for the estimation of the fungal burden in the tested properties[1]. Where possible the test was repeated in the same room twice, before and after depressurisation to estimate the fungal biomass in the room and identify potential interstitial mould-related risks. Fungal testing was carried out in a second room within the property (wherever possible) to identify any potential relationship between the fungal levels in different rooms and further assess potential fungal growth risks in the property.

The testing procedure involves the mechanical resuspension of mould particles from easily accessible interior surfaces to accurately estimate the biomass and pathogenic potential in the tested rooms. The samples are analysed using an enzyme-targeting method for the quantification of the fungal biomass (method developed and conducted by Mycometer A/S) and PCR for the species identification (conducted by HouseTest ApS).

The quantitative fungal biomass quantification test by Mycometer A/S allows the extraction of three mould growth indicators (for biomass estimation).

1. **The fungal levels.** Shows how many fungal particles have been detected in the 1st filter used during sampling.

2. **The allergen levels.** Shows the number of total allergens (Dust mites, pollen, fungi, pet dander, skin cells etc.) identified on the 2nd filter used during sampling.

3. **Fungal to Allergen Index (FAI):** measures the ratio between the two previous markers. High FAI values may indicate the presence of a hidden mould source while low FAI values are usually associated with low fungal activity.

The PCR analysis by HouseTest ApS also allows the DNA targeting of 16 fungal species, 3 fungal groups and quantification of total number of mould spores in the collected samples. The distribution of species and groups allows the development of a better understanding of the fungal contamination sources, if any.

2.4 In-situ monitoring

Three properties were monitored for at least one month, for the analysis of internally insulated walls, lofts and ground floors. Interstitial temperature and relative humidity sensors (TinyTag plus 2) were installed at the critical depth of two internally insulated walls, one suspended ground floor; temperature and relative humidity sensors were also installed in two insulated lofts.

2.5 Hygrothermal performance assessment

The hygrothermal performance assessment of Hawthorn Road and Shaftesbury Park was carried out according to BS 5250:2021 (BSI, 2021) and BS EN 15026:2007 (BSI, 2007), considering one-dimensional hygrothermal simulations in WUFI pro 6.5 and the following criteria for internally insulated walls:

- 80% relative humidity or higher to indicate mould growth risk (BS 5250:2021). If this threshold was exceeded, the WUFI Biohygrothermal model was used to evaluate the mould growth risk.

[1] Disclaimer: The fungal tests being conducted focus on the moisture damage in buildings. The team is not formed by health professionals and any comments on the fungal burden in the properties cannot be used to assess the health implications to the residents; this is not within the remit of the analysis.

- “persistent” moisture content (by mass) of 20% or higher to indicate wood rot (BS 5250:2021)
- 90% water content (compared with free water saturation) or higher when temperatures are below $0^{O}C$ to indicate freeze-thaw risk, considering the external 10mm of the brick.

The analysis considered a “medium” indoor moisture load (BS EN 15026:2007); a weather file constructed to cause the most severe conditions likely to occur once every 10 years; and the potential presence of an imperfect airtightness layer, i.e. adding a moisture source based on an envelope infiltration of 5 q50 (m3/(m2h)) onto the wall build-up. More information on the analysis can be found in the reports prepared by QODA.

2.6 Detailed hygrothermal analysis of moisture damage

A detailed hygrothermal analysis of the moisture damage found in Hawthorn Road was performed. The analysis consisted of Karsten tube testing of bricks and two-dimensional hygrothermal simulations, focused on exploring the relative influence of internal wall insulation and cement pointing on the moisture damage of the internally insulated wall. More information on the analysis can be found in the report prepared by Greengauge Building Energy Consultants.

3 Results

3.1 Building inspection

The building inspection was able to identify some areas of concern in the analysed buildings. For example, the moisture damage at Hawthorn road was visible and it was recorded in detail during two building inspections; the presence of salt efflorescence and a leak in the gutter were found during a site visit.

Where possible, the moisture content at joist ends was measured, and no issues were found in those joists. Finally, instances of escape of water were identified in some of the properties via visual inspection, combined with Infrared imaging.

3.2 RH and particle count (spot measurements)

The concentration of fine (PM2.5) and coarse (PM10) particles was measured before the fungal testing. The average concentrations of PM2.5 and PM10, along with the Relative Humidity measurements (RH) during the in-situ testing, are summarized in Figure 1.

The concentrations of PM2.5 and PM10 were found to be within the acceptable limits provided by EPA (EPA, 2012) in all tested homes. Higher levels of particulate matter (PM) were detected in the London properties, which may be attributed to the elevated concentration of PM in the city centre compared to the rural/suburban areas in which the rest of the properties were located. It should be pointed out that, although the elevated levels in London homes were reasonable and within EPA's acceptable limits, the PM10 concentration in the property located at Hawthorn Road was considerably higher than in the other properties. All properties tested had MVHR, apart from Shaftesbury Park terrace, which has passive stack ventilation.

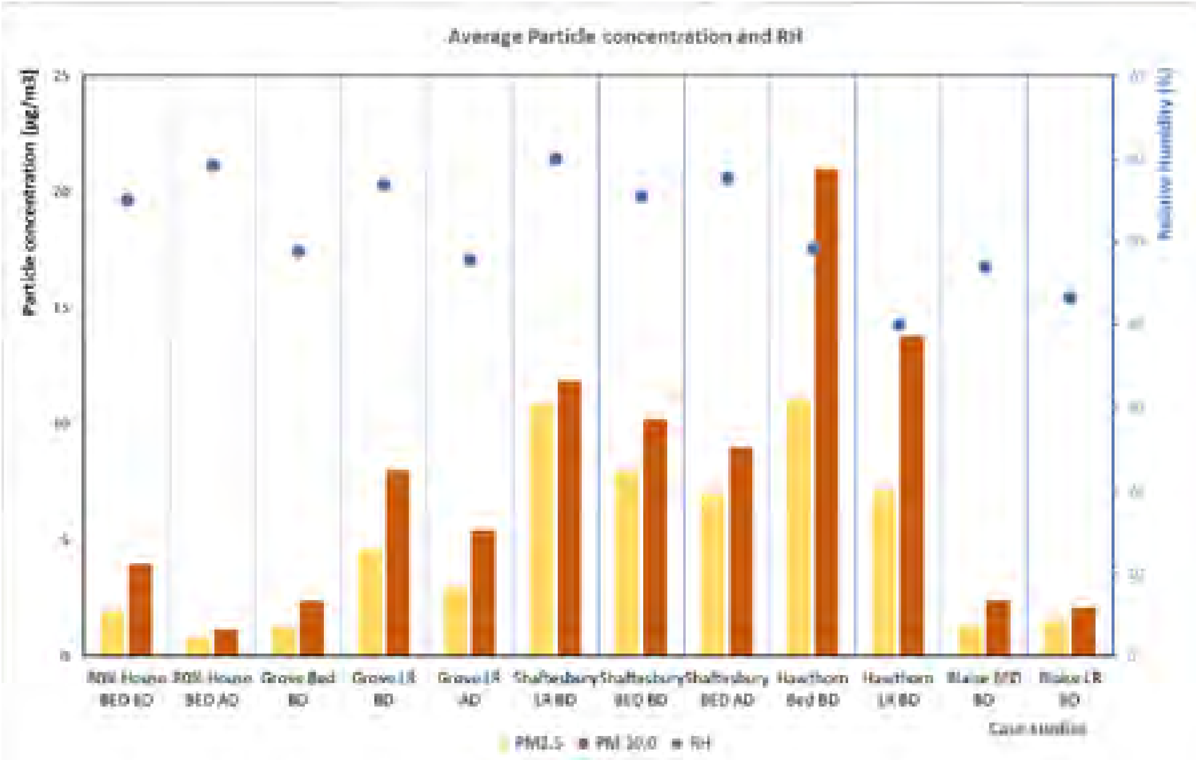


Figure 1. Spot measurements of RH and concentration of PM2.5 and PM10

3.3 Fungal tests: biomass quantification

This quantitative analysis can give an indication of the extent of fungal contamination and according to the Mycometer classification system, the levels can range from low (Class A+ and A), to average (Class B), high (Class C) and very high (Class D). The analysis of the samples collected indicated a very high risk of mould contamination in the living room of Grove Cottage. An elevated risk of mould contamination was also detected in the bedrooms of the properties on Hawthorn Road and Blaise Castle, indicating the need for further specialized fungal testing procedures to detect potential contamination sources and address the issues, if any. All other rooms tested were found to be within the range typically found in rooms where a good cleaning standard has been followed and without visual growth or moisture-related issues.

Table 1. Fungal levels for all the tested properties before and after depressurization

Property	FAI	Fungal Levels	Allergens
Hawthorn Bed BD	D	C	A
Hawthorn LR BD	D	B	A
Shaftesbury LR BD	B	A	A
Shaftesbury Bed BD	A	A	A
Shaftesbury Bed AD	B	A	A
Blaise Bed BD	A	C	C
Blaise LR BD	A	A	B
Grove LR BD	B	D	C
Grove LR AD	C	D	C
Grove Bed BD	A	C	C
80% House Bed BD	A	A	A
80% House Bed AD	A	A	A

3.4 Fungal tests: DNA analysis

DNA was collected by the team and analysed via PCR analysis by HouseTest ApS to detect the presence of 16 species and 3 targeted groups as described in the study by Holst, et al (2020). The analysis has shown that the total number of DNA copies of the 16 targeted species was elevated, particularly in the bedroom but also in the living room of the property at Hawthorn Road, as shown in Figure 2 and Table 2. Considering the cumulative outcomes of the quantification analysis, the elevated concentration of fungal copies in the property indicates that hidden sources of fungi may exist and supports the argument that further specialized fungal testing procedures may be needed to eliminate potential fungal-related risks.

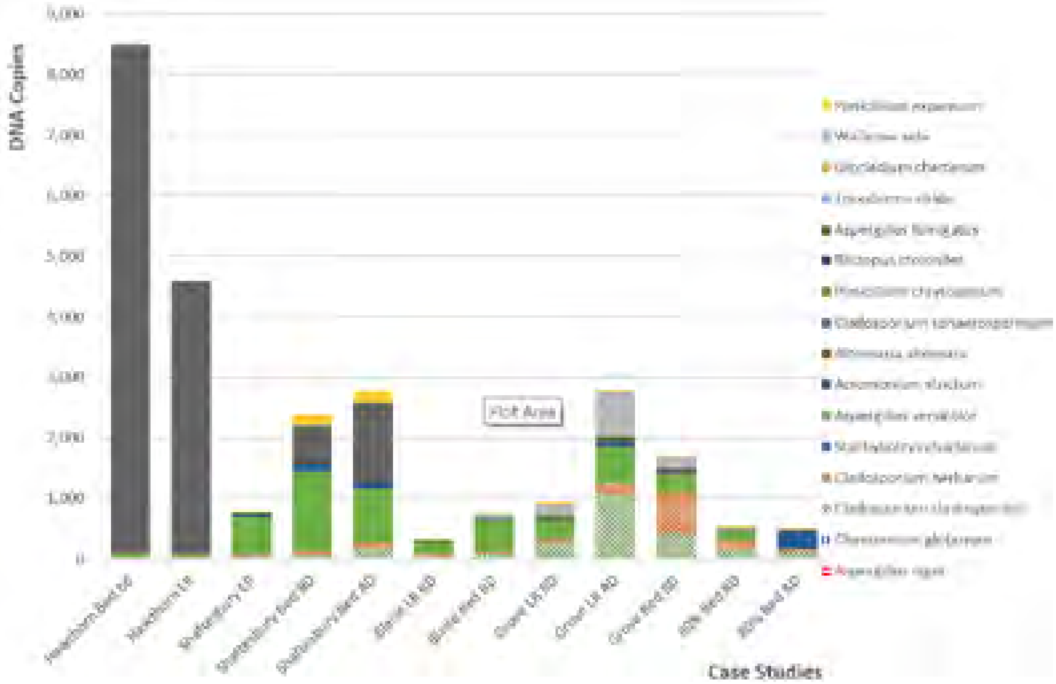


Figure 2. Difference in number of DNA copies for the 16 targeted species in the tested properties, with detail of species. The difference in number of DNA copies for the 16 targeted species before (BD) and after depressurization (AD) is shown for Shaftesbury Park, Grove cottage and the 80% house.

The noticeable difference between DNA copies in the living room of the property at Grove Cottage before and after depressurization (see Figure 2) also raises some concerns over the existence of a fungal contamination source in the room or in its surroundings. This increase of DNA copies may be associated with the aerosolisation of particles from locations such as air gaps inside the building fabric where fungal growth might have been initiated but would have been undetectable without implementing the depressurization test.

Table 2. Total number of DNA copies for the 16 species and 3 groups targeted via PCR from the air sampling in all tested properties.

Property	Total number of DNA Copies	
	16 targeted species	3 targeted groups
Hawthorn Bed	8,488	589
Hawthorn LR	4,604	378
Shaftesbury LR	798	2,482
Shaftesbury Bed BD	2,402	5,224
Shaftesbury Bed AD	2,786	2,809
Blaise LR BD	330	1,148
Blaise Bed BD	758	1,539

Grove LR BD	951	3,525
Grove LR AD	2,799	8,436
Grove Bed BD	1,704	2,575
80% House Bed BD	535	746
80% House Bed AD	501	568

The DNA extraction from the surface swabs (shown in Table 3) collected in all properties except the 80% property and the one located at Blaise Castle indicates that the tested surfaces have not been contaminated by fungi and that the background levels are unlikely to have been affected by the fungal activity on the surfaces. However, the samples from the property at Blaise Castle and the 80% property indicate that the loft in the former and bathroom in the latter property have been highly contaminated and may need treatment to avoid further fungal growth-related issues. It should be underlined that the contamination in the bathroom of the 80% house was confined near the plumbing leak and was discovered on time before affecting the background levels in the living room. On the contrary, the surface contamination in the loft at the property in Blaise Castle could be related to the contamination levels in the bedroom especially given that the dominant species in both the surface samples in the loft and the air samples in the bedroom were the same.

Table 3. Total number of DNA copies for the 16 species and 3 groups targeted via PCR for all the tested properties: results of surface test (swab)

Case study	Sample	*Total DNA copies 16 targeted species*	*Total DNA copies 3 targeted fungal groups*
Blaise	Sample 1: (Loft)	8,124	87,470
	Sample 2: (Loft)	94,237	936,426
80% House	Sample 1: (Bathroom, Water damage)	7,411,283	58,925,750
Grove	Sample 1: (Bathroom)	123	42
	Sample 2: (Hallway, past water damage)	26	19
	Sample 3: (Hallway, past water damage)	210	684
Hawthorn	Sample 1 (Loft Front rafter)	2	2
	Sample 2 (Loft Back rafter)	6	5
	Sample 3 (Bedroom Furniture)	59	158
	Sample 4 (Bedroom Furniture)	293	813
	Sample 5 (Loft Front rafter)	55	29
	Sample 6 (Loft Back rafter)	228	20
	Sample 7 (Bedroom Door Frame)	563	125
	Sample 8 (Bedroom Book shelf)	602	211

3.5 Hygrothermal performance assessment

The hygrothermal performance of the internal wall insulation systems in Hawthorn road and Shaftesbury Park was assessed via one-dimensional simulations. The results can be found in Table 4, showing condensation and mould growth risk at the wall-insulation interface, wood rot risk at the joist ends and freeze-thaw damage on the exterior surface.

In Hawthorn road, the hygrothermal assessment found the system installed to be relatively moisture safe; with higher mould growth and wood rot risk in case of more absorptive bricks.

In practice, moisture damage was found in the building inspection; however, the causes of this damage are not to be attributed to the malfunctioning of the wall insulation. Much of the cause is to be attributed to the floor retrofit - with a moisture-closed system - and the malfunctioning of the rainwater goods. The high thermal resistance of the wall insulation system might have exacerbated some of the issues, but the presence of cement pointing was found to have a higher impact in exacerbating the moisture damage.

Table 4. Summary of results from the hygrothermal performance assessment in Hawthorn road and Shaftesbury Park

	Condensation risk (wall-insulation interface)	Mould growth risk (wall-insulation interface)	Wood rot (behind joist ends)	Freeze-thaw damage (exterior surface)
Hawthorn road - Front (N)	Not likely	Likely (subject to brick type)	Likely (subject to brick type)	Not likely
Hawthorn road - Front (N) measured brick absorption	Not likely	Not likely	Not likely	Not likely
Shaftesbury park - Front (NW)	Not likely	Likely	Likely (subject to brick and timber type)	Not likely
Shaftesbury park - Rear (SE)	Not likely	Likely	Likely (subject to brick type)	Not likely
Shaftesbury park - Front (NW) intermediate floor		Likely (subject to brick type)		
Shaftesbury park - Rear (SE) intermediate floor		Not likely		

In Shaftesbury Park, the hygrothermal performance assessment identified high mould growth risk behind the wall insulation. A different wall insulation system was installed at the intermediate floor (i.e. dense woodfibre insulation); the analysis found this section of the wall at lower risk than the same wall insulated with aerogel, although some moisture risks might remain, depending on the materials found in the existing wall.
The detailed building inspection at the interface between aerogel and the existing wall was outside of the scope of this analysis, but no moisture issues were found behind the woodfibre insulation or in the adjacent indoor environments, suggesting that the insulation is functioning appropriately.

3.6 In-situ monitoring

Three properties were monitored for at least one month, for the analysis of internally insulated walls, lofts and ground floors.

In Hawthorn Road and in the 80% house, the results suggest that the internal wall insulation is working as expected. The 80% house has a ventilated cavity; no condensation was found in the cavity in the the period of analysis, but more data is needed to capture the behaviour in winter. The capillary-active insulation in Hawthorn Road did not experience condensation build up or mould growth risk at the tested location at the wall-insulation interface; more locations across the wall need to be monitored for a more complete picture.

Two insulated lofts were monitored; the data suggest that the loft is functioning as designed in the period under analysis, both in Shaftesbury Park and Hawthorn Road. However, the peak relative humidity in lofts is likely to occur in winter, which was not captured in this monitoring campaign. Longer-term monitoring is recommended.

Finally, one insulated suspended ground floor was monitored; the floor experienced high levels of relative humidity, which could lead to moisture issues if sustained; longer-term monitoring is recommended to evaluate moisture risk within the insulated ground floor.

4 Summary of case studies and recommendations

Hawthorn Road

- Exterior damage is likely to be caused by faulty rainwater goods and moisture-closed interventions to the ground floor.
- At the wall-insulation interface, the wall insulation was functioning as estimated in the hygrothermal performance assessment (i.e. low likelihood of condensation and mould growth) in the tested area, although the variability in moisture performance within the wall could not be captured; this would require the installation of additional sensors at the wall-insulation interface.
- When assessing the wall insulation system via simulations, the system was found to be relatively safe; however, the hygrothermal performance assessment does not consider the influence of other building elements (e.g. the floor) on the moisture content of the wall and the influence of poor maintenance (e.g. leaking rainwater goods).
- The loft was functioning as designed, although the peak relative humidity in lofts is usually expected to occur in winter and could not be captured (outside the timeframe of this monitoring campaign).
- Limited presence of fungal DNA copies on the surfaces, combined with high FAI suggest the possible presence of a point source (e.g. plants or pets) or a hidden mould source; further investigations are recommended on this (e.g. core drilling and further air and surface sampling).

Shaftesbury Park

- The building inspection, moisture content measurements and fungal tests found no areas of concern.
- The hygrothermal performance assessment identified possible mould growth risk behind the woodfibre insulation at the intermediate floor. However, no moisture issues were found in the adjacent indoor environments and the moisture content of joists and insulation were low, suggesting that the insulation is functioning adequately.
- The hygrothermal performance assessment identified high mould growth risk behind aerogel, but the interface between aerogel and the existing wall was outside of the scope of this analysis; this would require invasive analysis. However, no moisture issues were found in the adjacent indoor environments, suggesting that the insulation is functioning adequately.
- The loft was functioning as designed, although the peak relative humidity in lofts is expected to occur in winter and could not be captured (outside the timeframe of this monitoring campaign).
- Although the fungal levels and the moisture content of joists were low in the ground floor living room, the bottom of the ground floor experienced high relative humidity

levels within the timeframe of this monitoring campaign, suggesting that (i) the indoor environment is separated successfully from the building envelope (by a membrane), but (ii) further investigations are recommended to monitor the long-term moisture balance of the ground floor.

Blaise Castle Estate

- The building inspection found some areas of past moisture damage in the lower ground floor area.
- Surface fungal tests found high levels of DNA copies in the loft, which was reported to be at high relative humidity levels by the evaluator. The species identified were also found in the first-floor bedroom and, to a lesser extent, in the ground-floor living room.
- No mould was found in the loft insulation, treated with fungicides.
- Low levels of DNA copies from air sampling combined with high fungal and allergen levels in the bedroom suggest that there might be other species present in the environment outside those targeted in the PCR analysis or the quantitative analysis (of fungal and allergen levels) have overestimated the fungal activity due to a potential point source (e.g. pets, soil, plants); further tests are needed.

Grove Cottage

- The building inspection found some areas of past moisture damage adjacent to the suspended ground floor; the moisture content of floor joists near the damaged area was found to be low.
- Very high fungal levels were found in the living room; the increase of DNA copies after depressurisation combined with very high fungal levels in the air and low levels of DNA copies at surfaces suggest the presence of a hidden moisture source.
- DNA copies of Wallemia Sebi were found among the dominant species, suggesting that fungal growth might be due to water damage issues; the water damage might have increased water availability in the space underneath the floorboards and thus might have allowed mould activity. Further investigation is recommended.
- The likelihood of water reaching the suspended ground floor is high, as the airtightness membrane is only located under the ground floor insulation; a membrane between the insulation and the floorboards would have made the insulated ground floor more robust.

80% house

- The building inspection identified a plumbing leak in the bathroom and on the top of a built-in bookshelf in the living room; no other visual signs of mould or water damage were detected in the property.
- Low fungal and allergen levels were found in the property.
- The monitoring identified that the wall insulation was functioning as designed, without condensation build up inside the ventilated cavity after the wetting season (i.e. autumn and winter).

5 Lessons learned

Moisture issues are complex and depend on a combination of factors; this analysis on the moisture balance of buildings demonstrated that only a combination of diagnostic techniques was able to support a detailed assessment of these properties.

Some moisture damage is visible; however, some visual cues (e.g. damp patches) might disappear in the drying season (spring-summer), making the quality of this analysis time-dependent. Also, some moisture damage mechanisms (e.g. salt efflorescence, leaky gutters) can be spotted only under certain environmental conditions. Visual inspections are very important for a moisture assessment, but need to be combined with a number of techniques.

Infrared imaging was used to identify the moisture pathways and trace back to the moisture source, before opening up the wall; however, the technique works best when high temperature difference is found between the indoor and outdoor environments. Moisture content measurement of joists allows to identify whether there was some non-visible moisture damage; however, this required access to the floor space and only some of the joists were accessible, and not necessarily the most representative for moisture risk.

On the other hand, the biomass quantification of fungal levels allowed the team to characterise the moisture-related conditions of the indoor environment in a non-invasive and comprehensive way, suggesting whether the building needed further in-depth analysis. This test unveiled potential non-visible moisture issues and provided a better picture about the environmental conditions sustained in the tested environment than spot measurements of relative humidity, or PM, which only provided a snapshot in time. One drawback of this technique is the lack of benchmark; therefore, the interpretation of results is only based on the experience of the evaluator. Current efforts to provide benchmarks are in progress.

Even if no visible mould is detected in a room, growth might still exist - potentially due to a hidden mould source or the presence of dust, plants, pets ... The biomass quantification test carried out before and after depressurisation helped evaluating the likelihood of a hidden mould source, before carrying out more destructive tests (e.g., core drilling, lifting floorboards). In summary, the assessment of the fungal activity via biomass quantification was critical for the estimation of the building fabric damages and the detection of moisture related issues that could be invisible to the naked eye.

DNA analysis allowed to develop a better understanding of the sources of fungal contamination; some mould species primarily grow as a result of water damage, other grow as a response to sustained high relative humidity. Also, surface DNA analysis can identify those surfaces that are contaminated with the targeted species and reveal whether the contamination has affected the background levels of mould.

However, pinpointing the source or causes of mould require additional knowledge about the building (e.g. the location of the airtightness layer, the materials used), and a combination of other techniques can support this analysis. The measurement of ventilation rates allowed us to evaluate whether high fungal levels could be related to the lack of fresh air provision or if in-depth analysis is necessary. In-situ monitoring was used to understand the moisture balance within insulated building components (i.e. walls and ground floor) and in insulated lofts. At least one year of monitoring data is usually needed to obtain a full picture of moisture in building components; however, knowing the expected behaviour of the building components, the analysis can be reduced to those periods of expected higher moisture risk.

Finally the role of hygrothermal simulations was explored. The analysis focused on the standardised hygrothermal performance assessment, by means of one-dimensional simulations based on BS EN 15026:2007. These simulations can help us understand whether moisture balance is maintained, and can help designing low-risk retrofit strategies with iterative design, as shown in the results section. There are a number of limitations of these simulations:

- First, the one-dimensional analysis cannot consider complex geometries or building details; for example, the influence of the floor insulation on the moisture balance of the wall could not be assessed.
- Also, QODA noted that "there is not a clear set of moisture risk assessment criteria agreed upon within the industry yet, especially as different build-ups of materials and applications will require different criteria". This is currently being addressed by the UK Centre for Moisture in Buildings and its members.
- The assessment carried out by QODA considered construction imperfections as part of their models (e.g. imperfect airtightness); however, the assessment was based on the assumption that the building will be well maintained (e.g. gutters & pipes), which was not always the case.
- There is limited data availability on representative UK bricks and stones, as well as representative climate files.

The impact of the type of mortar in the brick wall was not considered in this one-dimensional study but was subsequently evaluated by means of two-dimensional hygrothermal simulations. These hygrothermal simulations, combined with visual inspections and interstitial monitoring of the building fabric, provided a picture of the potential, complex, moisture issues affecting one of the properties, Hawthorn Road. They allowed to evaluate the relative influence of cement pointing and insulation thickness on the spalling found via visual inspection. Spalling can be due to freeze-thaw or salt efflorescence; however, it was possible to run this analysis for the risk of freeze-thaw damage, due to the complexity of the salt efflorescence mechanism and the lack of suitable criteria.

6 Hawthorn road

In Hawthorn road, fungal tests (air sampling) were carried out at ambient pressure in two rooms with IWI. Surface swabs were collected in 8 areas, in the front bedroom and loft. Visual inspection was carried out, focusing on the ground floor/sleeper wall junction, the ground floor/external wall junction and the internally insulated wall. Additional inspections were carried out to check the functioning of MVHR, and understand the causes of moisture damage of the internally insulated wall. To this end, the absorption of bricks was estimated via Karsten tube measurements, and it was fed back into the hygrothermal simulations, and two-dimensional hygrothermal simulations were carried out (see the *Hygrothermal Risk Analysis Report* by Greengauge). Also, in-situ measurements of the loft space and the wall-insulation interface were carried out.

6.1 Building inspection

No visual signs of mould or water damage were detected inside the property, including in the tested rooms (living room and bedroom) and the loft. The absence of visible mould in the tested rooms was also verified by the team during a follow-up visual inspection of the property after one month from the first visit. However, dampness was reported by the residents on a sleeper wall under the stairs and surface damage was found on the front of the building.

There is significant surface damage evident in some areas of the north and west elevation at Hawthorn Road, near the ground floor level, and under the gutter on the west elevation. This part of the building is insulated internally, however other factors that are widely recognised to cause or contribute to such damage are also at work in this area. In particular, failed rainwater goods, which are directing significant amounts of rain onto parts of the façade, the presence of a solid ground floor, and re-pointing and other repair work using cementitious mortar. A detailed visual inspection and further analysis of the damage is available in the *Hygrothermal Risk Analysis Report* by Greengauge and summarised in section 6.6.

Regarding the ventilation of this property, the property is ventilated via MVHR. The flow rates from the MVHR seemed to be slightly imbalanced, with an average supply of 26.6 l/s and average extract of 18.8 l/s (in a three-bedroom house), measured with a rotating vane anemometer; the toilet extract seem to be clogged and allows an air flow rate of 0.4 l/s. These values are slightly lower than the minimum whole dwelling ventilation rate for a three-bedroom dwelling, 31 l/s (HM Government, 2021).

6.2 RH and particle count (spot measurements)

RH and particle counts were found to be within acceptable limits. However, the property was found to have higher PM10 concentrations compared to the other properties tested.

6.3 Fungal tests at ambient pressure

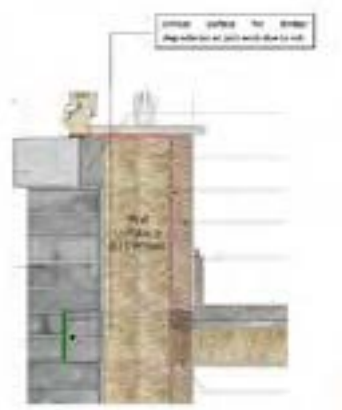
Typical levels of fungi were detected in the living room but high risk of mould contamination was detected in the tested bedroom under ambient pressure. While mould growth was not detected during the visual inspection of the property, the airborne levels found in the fungal biomass quantification tests indicate that a mould source was likely to exist especially in the bedroom. The species identification has also shown that the DNA copies of the targeted species were elevated compared to the other properties tested. The dominant fungal species in ambient air was Cladosporium Sphaerospermum, which may indicate contamination of surfaces such as wallpaper or woodwork.

Despite the high fungal concentration in indoor air, the surface contamination levels were very low in the 8 sampled locations (loft and bedroom), suggesting that the tested rooms and loft are in good conditions and that the tested surfaces are not contaminated by fungi. Still the hypothesis of the presence of other point sources of mould such as plants and pets, or a hidden mould source cannot be eliminated. Further investigation is recommended.

The allergens levels were found to correspond to values typically found in rooms without a mould growth source or with a good cleaning standard (according to Mycometer's classification system). However, the lack of visible signs of fungal growth or dampness and the low surface contamination levels throughout the property necessitate the conduction of further investigation for the detection of any potential fungal growth sources and the elimination of potential fungal-related risks.

6.4 Hygrothermal performance assessment

The findings of the hygrothermal performance assessment (see the Report by QODA) are summarised here. The analysis focused on the internally insulated front façade, which is north-facing.



- 15 mm lime plaster
- 200 mm sheep wool
- 1 mm VCL (variable, $s_{d,dry}$=3.4m)
- 15 mm lime plastersheep wool
- 200 mm sheep wool$_{,dry}$=3.4m)
- 1 mm VCL (variable, $s_{d,dry}$=3.4m)
- 60 mm woodfibre insulation board
- 25 mm air layer
- 15 mm gypsum board

The analysis found the relative humidity at the wall-insulation interface to be persistently higher than 80%, leading to high mould growth risk, apart from the case of Brick 3. This was the brick with the lowest water absorption coefficient of the three bricks tested, A_w=0.116 kg/($m^2s^{0.5}$), similar to the values measured in the property by means of Karsten tube testing.

Considering wood rot risk at 20% moisture content by mass and the moisture storage function of timber in the Fraunhofer IBP database, the respective relative humidity threshold was calculated. It was found to correspond to 86% for oak and 93% for oak, old. Again, the 86% relative humidity threshold was exceeded for all bricks except Brick 3; the 93% relative humidity threshold was exceeded for Brick 1 only (most absorptive, A_w=0.36 kg/($m^2s^{0.5}$)).

Lastly, the assessment against the risk of freeze-thaw deterioration indicated no high risk for the external face of the front elevation, as the analysis showed no occasions when the combination of 90% water content (compared with free water saturation) and 0^{O}C occurred.

This suggests that the current build up has low moisture risk, although there might be moisture issues if the material properties of the wall are different than those used in the analysis.

6.5 In-situ monitoring

In-situ monitoring of temperature and relative humidity was carried from the 31st March 2023 to the 7th June 2023.

One sensor was installed at the interface between the internal wall insulation and the existing wall, in an area protected from wind-driven rain. The data allowed to evaluate the interstitial moisture levels due to the vapour transfer between the indoor environment and the insulation, often considered an area of concern for "moisture open" (i.e. capillary active) insulation systems.

The results suggest that the internal wall insulation is working as expected, without condensation build up or mould growth risk at the wall-insulation interface. The data captured the period immediately after the wetting season (i.e. from March 2023), when peak relative humidity is usually found at the interface between wall and internal wall insulation (see Marincioni and Altamirano-Medina 2023). The data suggest limited moisture build up in the wetting season (maximum RH = 72.8%) as well as subsequent drying. Monitoring in different locations of the wall would provide a more complete picture.

Another sensor was installed in the loft space; the data suggest that the loft is functioning as designed in the period under analysis, with a monthly average relative humidity of 60% or lower, below the 75% threshold for monthly RH set out in the Approved Document F of the Building Regulations. However, the peak relative humidity in lofts is likely to occur in winter, which was not captured in this monitoring campaign. Longer-term monitoring is recommended.

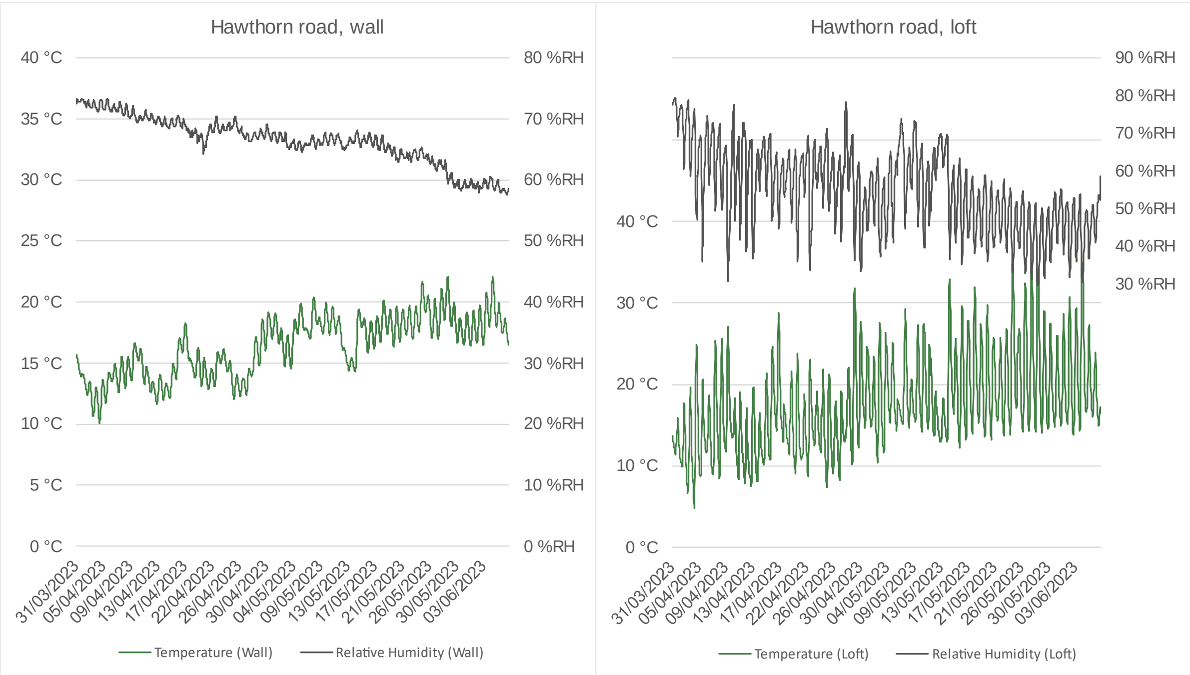


Figure 3 Temperature and relative humidity of internally insulated wall (left) and loft (right) in Hawthorn road

6.6 Detailed hygrothermal analysis of moisture damage

The findings of the detailed hygrothermal risk analysis of moisture damage (see the Report by Greengauge) are summarised here.

The damage visible at high level can be directly linked to observed defects that are unrelated to the IWI, i.e. inappropriate cement pointing, and failed rainwater goods. The presence of damage in areas that are outside the thermal envelope (i.e. the parapet) is supporting this observation.

At low level, the floor insulation is likely to be a key cause of salt crystallisation damage, exacerbated by inappropriate use of cement materials and, possibly, impermeable paint.

Figure 4 Damage near the gutters (left) and above the ground floor (right) on the west wall

Two-dimensional hygrothermal simulations indicated that with a brick thought to be similar to that used to build Hawthorn Road, the presence of cement pointing presents a greater risk of freeze-thaw damage than the thick IWI. However, the properties of the brick influences the relative influence of these two interventions on surface damage.

Combining these simulations with observations from site suggest that there are two types of damage occurring on the North elevation of Hawthorn Road

• Salt crystallisation damage near to ground level, as a result to rising damp (likely linked to the floor treatment), primarily exacerbated by inappropriate use of cement (and possibly impermeable paint).

• Freeze-thaw damage at high level as a result of faulty rainwater goods, primarily exacerbated by inappropriate cement pointing. The IWI may be increasing the risk, but to a lesser degree than the cement.

7 Shaftesbury Park

In Shaftesbury Park, fungal tests (air sampling) were carried out at ambient pressure in two rooms with IWI (bedroom and living room); the test was repeated in one of the rooms with IWI after depressurisation (bedroom). Visual inspection was carried out, focusing on the junction between the ground floor and the internally insulated wall, and between the intermediate floor and the internally insulated wall. The inspection included spot moisture content measurements of the joists that we could reach when lifting the floorboards. Also, in-situ measurements of the loft space and the suspended ground floor were carried out and analysed.

7.1 Building inspection

No visual signs of mould or water damage were detected inside the property and no major maintenance issues were identified. A missing window seal strip in the bedroom is expected to have affected the air infiltration in the bedroom on the 1st floor but is not expected to produce any major moisture-related issues in the room.

The maximum moisture content of the joists was under the moisture content threshold of 20% by mass set out in BS 5250:2021. It is worth noting that the moisture content was measured at the end of the wetting period (March 2023), representing the peak moisture content in the year however, only a small portion of the ground floor and intermediate floor joists was analysed.

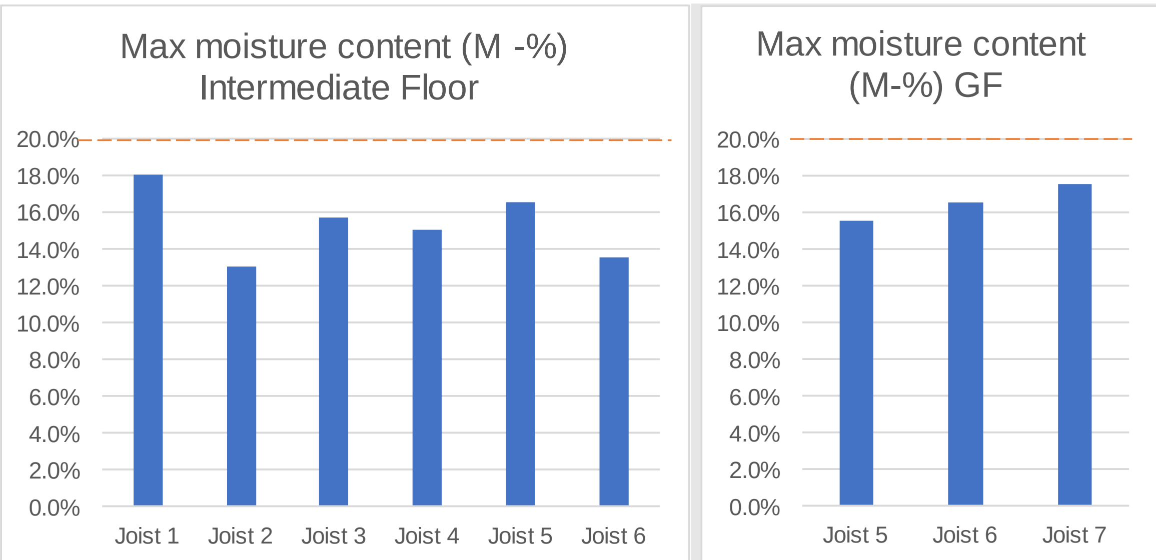


Figure 5 Maximum moisture content of the joists in the intermediate floor (left) and ground floor (right) and 20% threshold. The joists were counted from left to right.

Regarding the ventilation system, the property has passive stack ventilation; its inspection was beyond the scope and the timeframe of this project.

7.2 RH and particle count (spot measurements)

RH and particle counts were found to be within acceptable limits based on literature. The PM measurements also indicated that the ventilation system is maintaining good indoor air quality in the property and that the risk of mould growth is likely to be minimal.

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7.3 Fungal tests at ambient pressure

According to the fungal biomass quantification test, the levels of fungi and allergens in the bedroom and living room were found to be within the range typically found in rooms without visual growth or moisture-related issues (Class A, low mould contamination risk).

The species identification has shown that the dominant fungal species in ambient air was Aspergillus versicolor, which is often used as an indicator of high relative humidity in the indoor environment. However, the low readings found using the biomass quantification test indicate that the species identified exist only in small quantities within the room and should not have any significant impact to the building fabric or the occupant's health.

7.4 Fungal tests after depressurisation

According to the fungal biomass quantification test, the levels of fungi and allergens in the bedroom after depressurisation were found to be within the range typically found in rooms without visual growth or moisture-related issues (Class A, low mould contamination risk), with minimal change in DNA count after depressurisation. This result suggests either limited fungal activity in the building fabric elements connected to the tested room (i.e. internal wall insulation and intermediate floor), or limited interaction between those elements and the indoor environment (i.e. continuous airtightness layer). However, the airtightness layer was not continuous around the joist ends in the intermediate floor, suggesting limited fungal activity to be likely.

7.5 Hygrothermal performance assessment

The findings of the hygrothermal performance assessment (see the Report by QODA) are summarised here. The analysis focused on the internally insulated front and rear façades, which are facing north-west and south-east respectively.

The analysis considered the following build-ups (walls a and b):

- 265 mm solid brick (3 types, with different water absorption coefficients)
- 15 mm lime plaster
- 60 mm aerogel insulation blanket (*a*), or 60 mm composite woodfibre board (*b*)
- 1 mm VCL with s_d=15.7m (a), or s_d=0.5m (b),
- 15 mm gypsum board

The analysis of wall *a* found the relative humidity at the wall-insulation interface to be persistently higher than 80%, for both elevations leading to high mould growth risk, apart from the case of Brick 3 on the rear elevation. This was the brick with the lowest water absorption coefficient of the three bricks tested, A_w=0.116 kg/($m^2s^{0.5}$).

Considering wood rot risk at 20% moisture content by mass and the moisture storage function of timber in the Fraunhofer IBP database, the respective relative humidity threshold was calculated. It was found to correspond to 86% for oak and 93% for oak, old. The thresholds were exceeded in all cases except Brick 3, which only exceeded the 86% RH threshold on the front elevation and both thresholds on the rear elevation.

To reduce the risk of mould growth and wood rot at the critical area around the joist ends, the design considered 60mm of dense woodfibre board (a composite board with an integrated functional layer) rather than aerogel. The hygrothermal simulations showed a reduction of mould growth risk for this option on both front and rear elevations, compared with wall *a*. As the relative humidity was found to be fluctuating around 80%, the WUFI Biohygrothermal model was considered. On the rear façade, the model indicated low mould growth risk for all bricks considered; on the front façade, the risk was found to be low for all bricks apart from

Brick 2, a brick with a mid-range water absorption coefficient (A_w=0.183 kg/($m^2s^{0.5}$)), but with lowest water content at 80% RH and at free water saturation among the bricks considered. For a more detailed analysis of the moisture risk, measuring the material properties of bricks is recommended in this case.

Lastly, the assessment against the risk of freeze-thaw deterioration indicated no high risk for the external face of the front elevation, as the analysis showed no occasions when the combination of 90% water content (compared with free water saturation) and 0^{O}C occurred. The front elevation was considered to be the worst-case scenario for freeze-thaw damage.

In summary, the analysis found the aerogel-insulated wall (*a*) at higher risk than the same wall insulated with woodfibre, although some moisture risks might remain, depending on the materials found in the existing wall.

The hygrothermal performance assessment can help designing low-risk retrofit strategies. In this case, solutions with lower moisture risk (woodfibre insulation in this case) were used in areas considered to be more vulnerable to moisture (e.g. around joist ends), whereas higher-performance solutions with higher moisture risk (aerogel in this case) were used in less vulnerable areas of the wall.

7.6 In-situ monitoring

In-situ monitoring of temperature and relative humidity was carried from the 29th March 2023 to the 25th April 2023. One sensor was installed behind the insulation in the suspended ground floor. The relative humidity behind the floor insulation was found to have a monthly average of 81%, above the 75% threshold for monthly RH set out in the Approved Document F of the Building Regulations. Therefore, a more detailed analysis based on annual data is needed to evaluate the risk of mould growth; longer-term monitoring is recommended to evaluate moisture risk within the insulated ground floor.

Another sensor was installed in the loft space; the data suggest that the loft is functioning as designed in the period under analysis, with a relative humidity between 34 % and 86%. Also, the monthly average of the relative humidity was 64%, below the 75% threshold for monthly RH. However, the peak relative humidity in lofts is likely to occur in winter, which was not captured in this monitoring campaign; longer-term monitoring is recommended to evaluate moisture risk in the loft space.

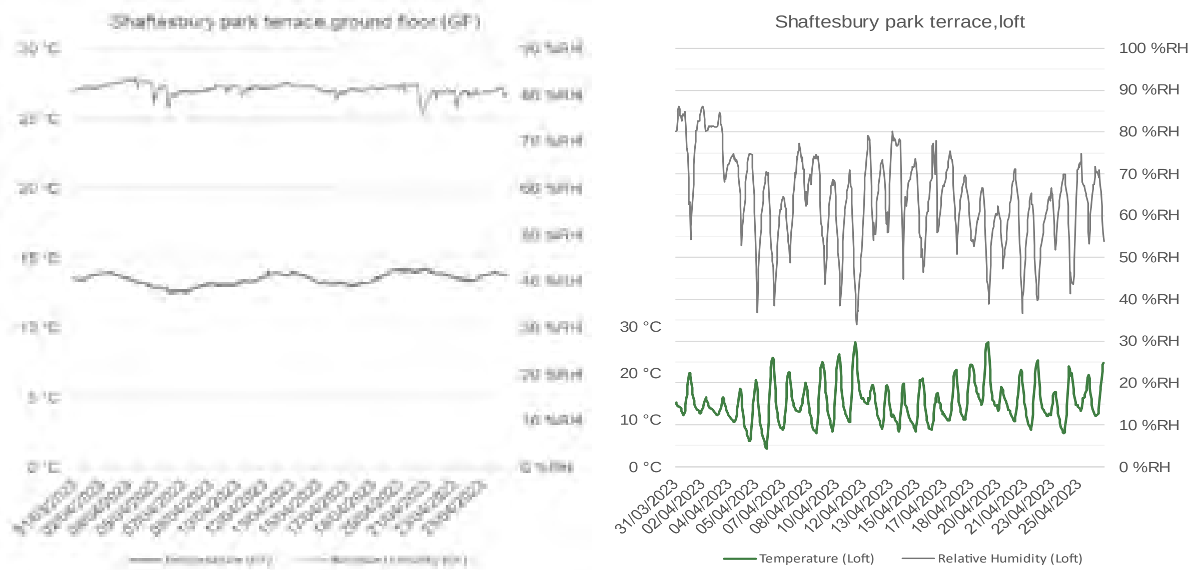

Figure 6 Temperature and relative humidity of suspended ground floor (left) and loft (right) in Shaftesbury park

8 Blaise Castle Estate

In Blaise Castle Estate, mould was measured at ambient pressure in two rooms with IWI. Surface swabs were collected in 2 areas, in the loft. Visual inspection was carried out, focusing on the loft, the bedroom, the living room and the areas that were reported to have sustained water damage.

8.1 Building inspection

No visual signs of mould or moisture damage were detected in the tested rooms (living room and bedroom) or in the loft. Signs of moisture damage were detected in the lower ground floor, which was caused by a leak in the waterproofing membrane in the balcony/flat roof above (see evaluator's report).

The property has MVHR, which was tested by the evaluator; the ventilation system was reported to be balanced (see evaluator's report).

8.2 RH and particle count (spot measurements)

RH and particle counts were found to be within acceptable limits based on literature. No indication of imbalanced ventilation was identified.

8.3 Fungal tests at ambient pressure

High mould contamination and allergen levels were detected in the bedroom of the property. The levels lie within the range typically found in rooms with an inadequate cleaning standard or potential fungal growth according to the Mycometer classification system. While mould growth was not detected during the visual inspection of the property, the airborne levels found in the fungal biomass quantification tests indicate that a mould source was likely to exist in the bedroom. On the other hand, a low risk of mould contamination and an average level of allergens were detected in the living room.

Compared to the other properties examined, the species identification revealed a lower quantity of DNA copies from the targeted species in the property. However, the high mould and allergen levels from the fungal biomass quantification test, indicates that the discrepancy the quantitative results and the species identification may be either a product of the overestimation of fungal contamination due to potential point sources like pets, soil, and plants or the underestimation of the contamination from the DNA results due to the low number of fungal targets. In any case, additional specialized tests may be necessary to pinpoint the presence of any potential sources of fungal growth.

Figure 7 Inspection of loft insulation under an optical microscope; the inspection found no mould growth in the analysed sample.

The surface contamination levels were measured in two locations in the loft (rafters), and were found to be high, in line with the fungal concentration in indoor air. Also, the dominant species in the surface DNA analysis was Aspergillus Versicolor, in agreement with those in ambient air. The test was combined with the analysis of loft insulation (i.e. blown cellulose) under a microscope, which found no traces of fungal contamination on the insulation, possibly due to anti-fungal treatments of the insulation (Figure 7).

The evaluator also identified sustained high levels of relative humidity in the loft, which is often occurring in combination with Aspergillus Versicolor, the dominant mould species found in this property.

9 Grove cottage

In Grove cottage, fungal tests (air sampling) were carried out at ambient pressure in one room with the suspended ground floor (living room) and one room under the roof (bedroom); the test was repeated in the ground floor room after depressurisation (living room). Surface swabs were collected in three areas, in areas with suspected fungal activity (i.e. bathroom and hallway). Visual inspection was carried out, focusing on the ground floor. The inspection included spot moisture content measurements of the joists that we could reach when lifting the floorboards.

9.1 Building inspection

No visual signs of mould were detected in the property. Signs of past water damage were identified in the hall outside the living room and the team was informed that they appeared as a result of plumbing leaks. Formation of salts has been observed on the lower parts of the walls in the hallway, but no visible signs of mould were detected in the room. Small patches of mould and dampness were identified in the bathroom/toilet on the ground floor but the extract ventilation seemed to be functioning in the bathroom. A damp smell was detected in the basement, but no major visual signs of water damage were observed.

Infrared imaging was used to collect further information on the area where the escape of water incident was reported (Figure 8). The picture (left) shows that the past water damage has indeed damaged the wall close to the ground floor; this corresponds to an area of higher heat transfer (as shown in the image on the right). This combination suggests that it is an area at high risk of mould growth and needs to be further investigated.

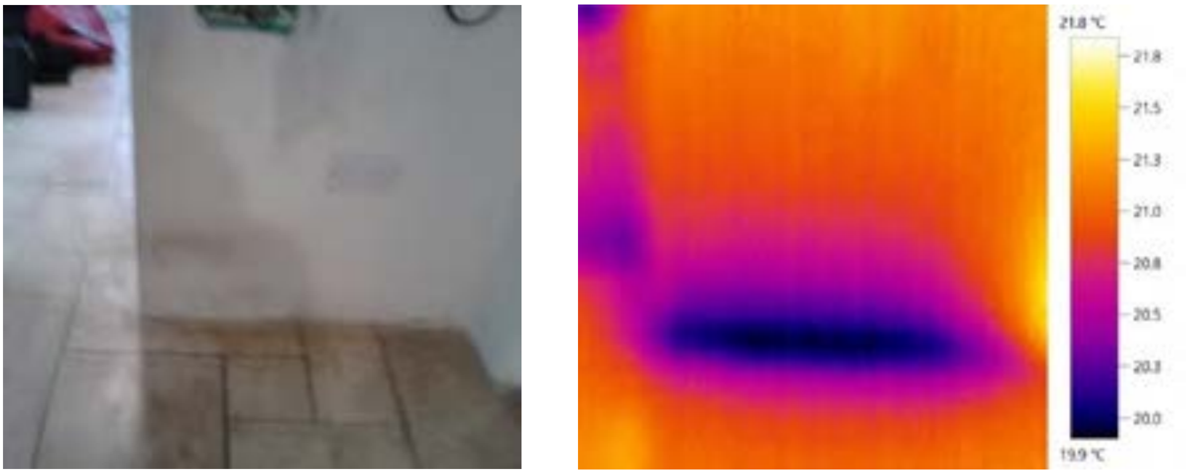

Figure 8 Photo (left) and Infrared image (right) of visible dampness in the hallway of Grove cottage

The maximum moisture content of two easy-to-access joists was measured in an area of the ground floor adjacent to the wall with visible dampness; the moisture content was found to be below the moisture content threshold of 20% by mass set out in BS 5250:2021. It is worth noting that the moisture content was measured at the end of the wetting period (March 2023), representing the peak moisture content in the year; however, only a small portion of the ground floor joists was analysed.

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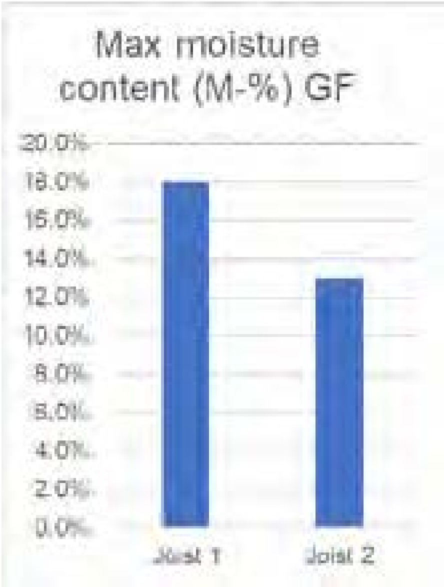

Figure 9 Maximum moisture content of the joists in the ground floor (right) and 20% threshold. The joists were measured from left to right.

9.2 RH and particle count (spot measurements)

RH and particle counts of the tested rooms were found to be within acceptable limits based on literature.

9.3 Fungal tests at ambient pressure

The fungal levels were found to be high in the bedroom and very high in the living room; allergen levels were also found to be high, in both locations. This suggests the presence of a mould source and/or allergen sources.

The samples collected in the living room found Aspergillus versicolor to be the dominant species (indicator of high relative humidity in the indoor environment), followed by Cladosporium cladosporides (flourishing under low temperatures and alternating wet and dry conditions), and Wallemia sebi (mould occurring in damp environments). These were in line with the surface samples obtained from the bathroom and hallway; although the contamination level was low, the samples showed the same dominant species, with Wallemia Sebi found in the hallway.

Similar dominant species were found in the bedroom, but with lower fungal levels than in the living room. Further analysis is needed to identify the causes for high fungal levels in the bedroom.

9.4 Fungal tests after depressurisation

Similarly to the fungal biomass quantification test at ambient pressure, the levels of fungi in the living room after depressurisation were found to be very high (Class D), with an increase of FAI (from class B to class C), and a marked increase in DNA count after depressurisation. This result, combined with the measured low air permeability, suggests fungal activity in the elements of the building envelope connected to the tested room (e.g. the suspended ground floor, which is located before the airtightness layer).

The samples collected were dominated by Cladosporium cladosporides, Aspergillus versicolor and Wallemia sebi, with a proportional increase of Cladosporium cladosporides and Wallemia sebi after depressurisation. The hypothesis of interstitial mould growth is supported by the elevated DNA copies of Wallemia Sebi, a species that - if found at high levels - indicates fungal growth due to water damage issues.

The findings from the fungal tests and visual inspection suggest that the levels in the living room might be connected to the past water damage in the hallway. The water damage might have increased water availability in the space underneath the floorboards and thus might have allowed mould activity. Further analysis is recommended.

10 80% House

In the 80% house, fungal tests (air sampling) were carried out at ambient pressure in one room that has an internally insulated wall and the solid ground floor (bedroom); the test was repeated after depressurisation. Surface swabs were collected in one area, where escape of water was identified, in the bathroom. Visual inspection was carried out, focusing on the junction between the ground floor and the walls. Also, in-situ measurements were collected from the ventilated cavity between insulation and the existing wall.

10.1 Building inspection

Signs of dampness were identified on the top of a built-in bookshelf in the living room as result of plumbing leaks, but no visible signs of mould were detected in the room. Visual signs of mould and dampness were identified around water pipes in the bathroom and on the corresponding ceiling one storey below the bathroom (living room).

Infrared imaging was used to detect the presence of hidden moisture damage signs in the property and to determine the extent of the leak. The visible signs of dampness in the living room were confirmed via thermal imaging (Figure 10) and further investigations revealed the presence of moisture damage due to a plumbing leak in the bathroom (Figure 11). Though invisible to the eye, the small but detectable temperature differences from the thermal imaging in Figure 11 showed the path of the moisture transfer in the wall.

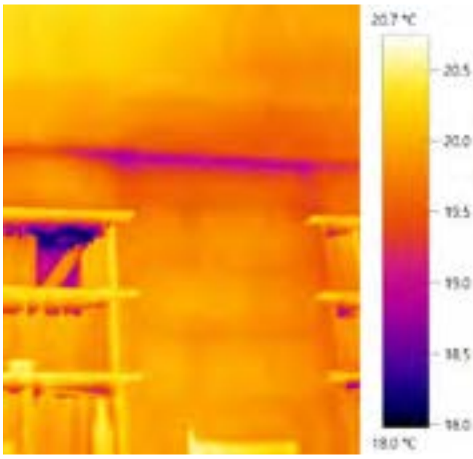

Figure 10: Infrared image of visible dampness in the living room of the 80% house.

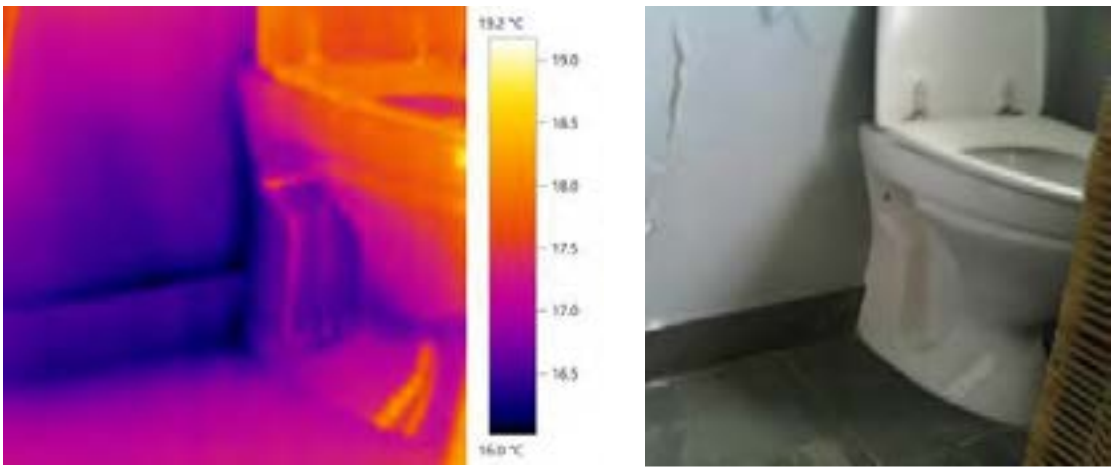

Figure 11: Infrared image (left) and photo (right) of visible dampness in the bathroom of the 80% house.

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No other visual signs of water damage or mould were detected in the property. The ventilation system installed in the property is MVHR (see the evaluator's report).

10.2 RH and particle count (spot measurements)

RH and particle counts were found to be within acceptable limits based on literature.

10.3 Fungal tests at ambient pressure

According to the fungal biomass quantification test, the levels of fungi and allergens in the tested bedroom were found to be within the range typically found in rooms without visual growth or moisture-related issues (Class A, low mould contamination risk).

The species identification in the indoor air has shown that the DNA copies of the targeted species were low compared to the other properties tested. On the other hand, the surface swab collected near the source of water damage (in the bathroom) showed a very high number of DNA copies, confirming high mould activity due to escape of water.

10.4 Fungal tests after depressurisation

According to the fungal biomass quantification test, the levels of fungi and allergens in the bedroom after depressurisation were found to be within the range typically found in rooms without visual growth or moisture-related issues (Class A, low mould contamination risk), with minimal change in DNA count after depressurisation. This result suggests limited fungal activity in the building fabric elements connected to the tested room (i.e. the elements located before the airtightness layer).

10.5 In-situ monitoring

In-situ monitoring of temperature and relative humidity was carried out in the cavity between the internal wall insulation – ventilated to the outdoor environment - and the existing wall, from the 23rd March 2023 to the 30th August 2023. The data suggest that the cavity is working as expected, without condensation build up inside the cavity after the wetting season (i.e. autumn and winter).

Figure 12: Temperature and relative humidity of wall cavity in the 80% house

The relative humidity in the vented cavity between the wall and the insulation was found to have a maximum monthly average of 81.8%. However, it is possible to expect higher levels of relative humidity in the cavity than in the indoor environment, if these cavities are not connected with the indoor environment and are slightly ventilated to the outside. The fungal test after depressurisation combined with the measured low air permeability of the building envelope suggested limited connection between the cavity (located after the airtightness layer) and the indoor environment.

11 References

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Appendix 6: Hawthorn Road: hygrothermal risk analysis report

Toby Cambray (Greengauge)

Hawthorn Road
Hygrothermal Risk Analysis Report

Author	TC
Date	25/7/2023
Revision	*0*
CHECK	*OdSC, VM*

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1 Summary

This report explores the surface damage observed at Hawthorn Road, its causes, and whether it is related the retrofit or not.

There is significant surface damage evident in some areas of the north elevation at Hawthorn Road. This part of the building is insulated internally, however other factors that are widely recognised to cause or contribute to such damage are also at work in this area. In particular, failed rainwater goods, which are directing significant amounts of rain onto parts of the façade, and re-pointing and other repair work using cementitious mortar.

The photographs in **Error! Reference source not found.** to **Error! Reference source not found.** show the damage observed, as well as the inappropriate use of cement a paint (possibly impermeable) on mortar joints and render. Although not evident in the photographs, on a previous visit rain was seen dripping from the gutter directly above the mossy area, and being blown onto the façade.

An extensive area of surface damage adjacent to the end of the gutter on the neighbouring house is likely to be due to freeze-thaw damage resulting in leakage or splashing from the neighbouring house, and/or leakage from failed parapet capping, and/or inappropriate render to the No. 10 side of the parapet, possibly exacerbated by the IWI.

Furthermore, there is a consistent pattern of damage near to the ground. On the most recent visit in June 2023, there was evidence of efflorescence (salt crystallisation) on the surface near to the ground. The tenants have also previously reported damp on an internal wall, near to the ground. This points to rising damp affecting walls. This could be a result of changes to the ground floor made as part of the retrofit. Faulty rainwater goods could be increasing ground moisture levels and therefore contributing to this problem, however the damage is not restricted to the area below the leak.

When used with solid masonry walls, Internal Wall Insulation reduces the average winter temperature of the masonry. The reduction in temperature can reduce the ability of the wall to dry after spells of rain, and increase the likelihood that the temperature at and near the surface will fall below freezing temperatures. Further more, the additional layers reduce drying to the inside. Hawthorn Road includes a relatively thick layer of IWI. This may therefore exacerbate the risks of damage to the brick surface.

The existing suspended timber floor was replaced with EPS and a concrete slab. This type of floor prevents evaporation from the ground that would be permitted by a suspended floor (assuming an exposed soil solum). If/when the water table is high enough, the lack of evaporation post-retrofit can lead to higher ground moisture levels, and increased absorption by the walls. Ground water contains dissolved salts in different concentrations, which will accumulate wherever the moisture evaporates. Where evaporation occurs on the surface, efflorescence can be seen; where the evaporation occurs below the surface, the growth of salt crystals within the pore structure can generate expansion forces that damage the material. In houses with a robust, complete DPC this is a less problematic, although masonry below DPC could be affected. On the bay window to a height of approx. 300mm there is a lime based render; this has been painted with unknown black material, and patched in places with a cement based material (primarily the edge). Much of the pointing also appears to have been painted; painting predates cement re-pointing.

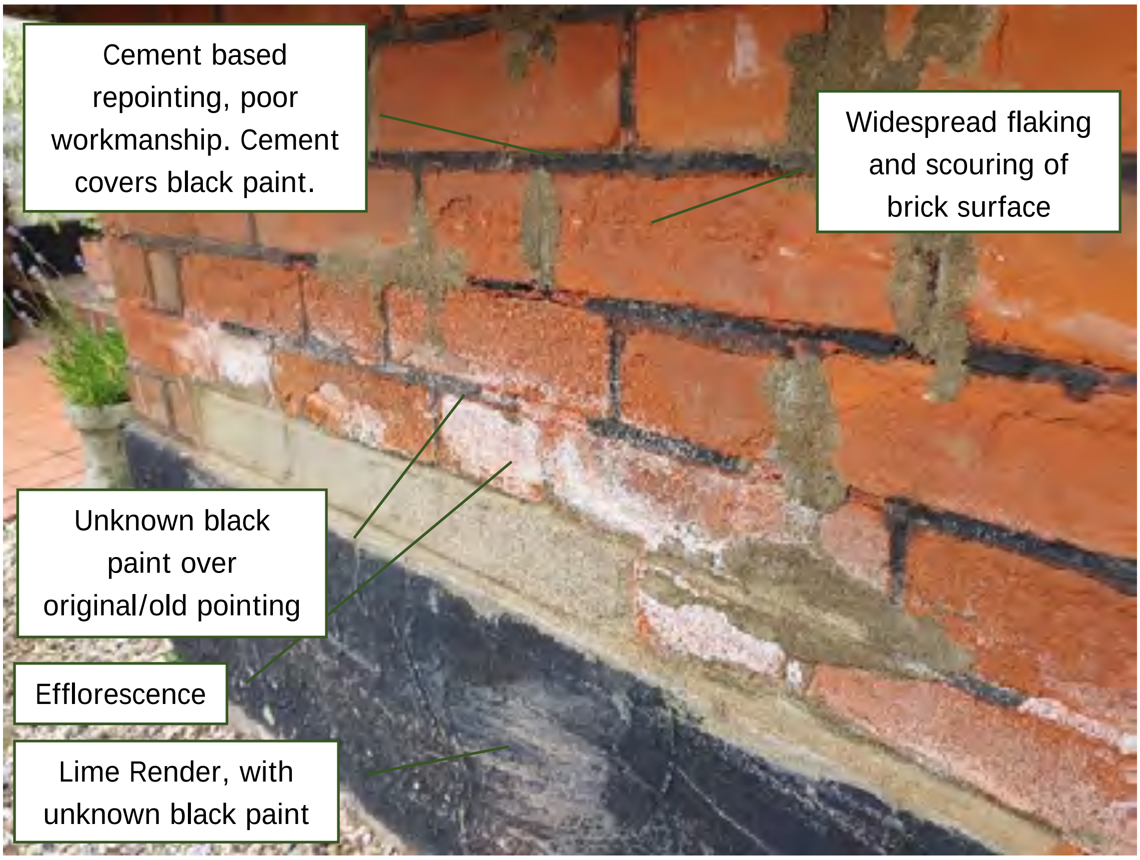
There are a number of mechanisms leading to damage in different areas of the elevation, and in some cases interacting.

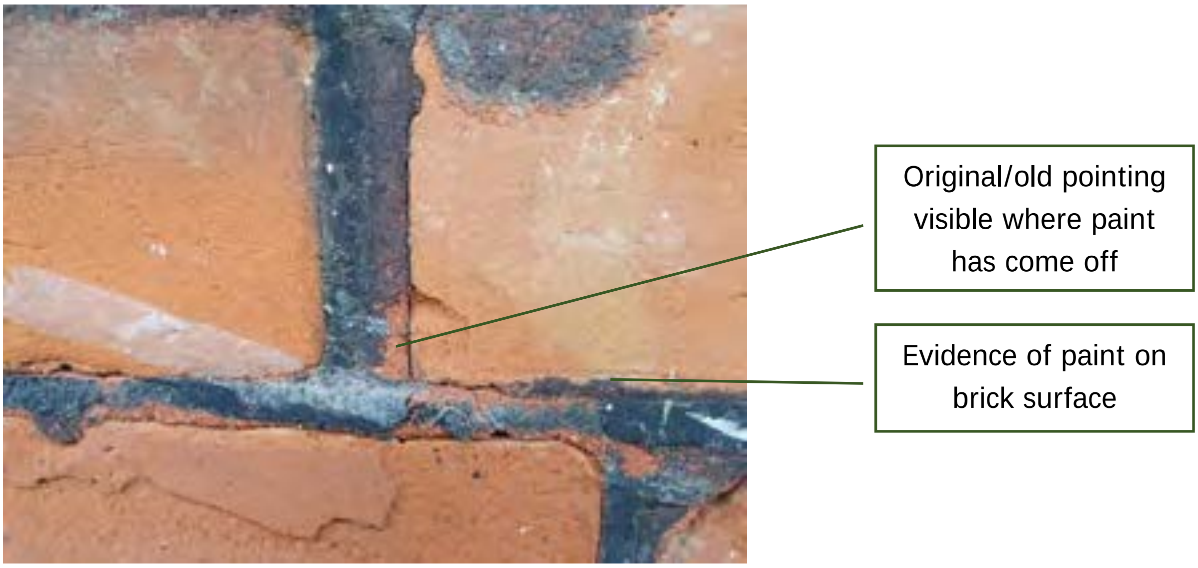
- The leaking rain water goods are depositing rain directly onto the side of the bay, leading to moss growth and elevating moisture levels for the entire height of the building at that corner.
- Failed or poorly designed rainwater goods on the neighbouring house are depositing rain onto the return wall at high level. The elevated moisture levels are likely leading to freeze-thaw damage.

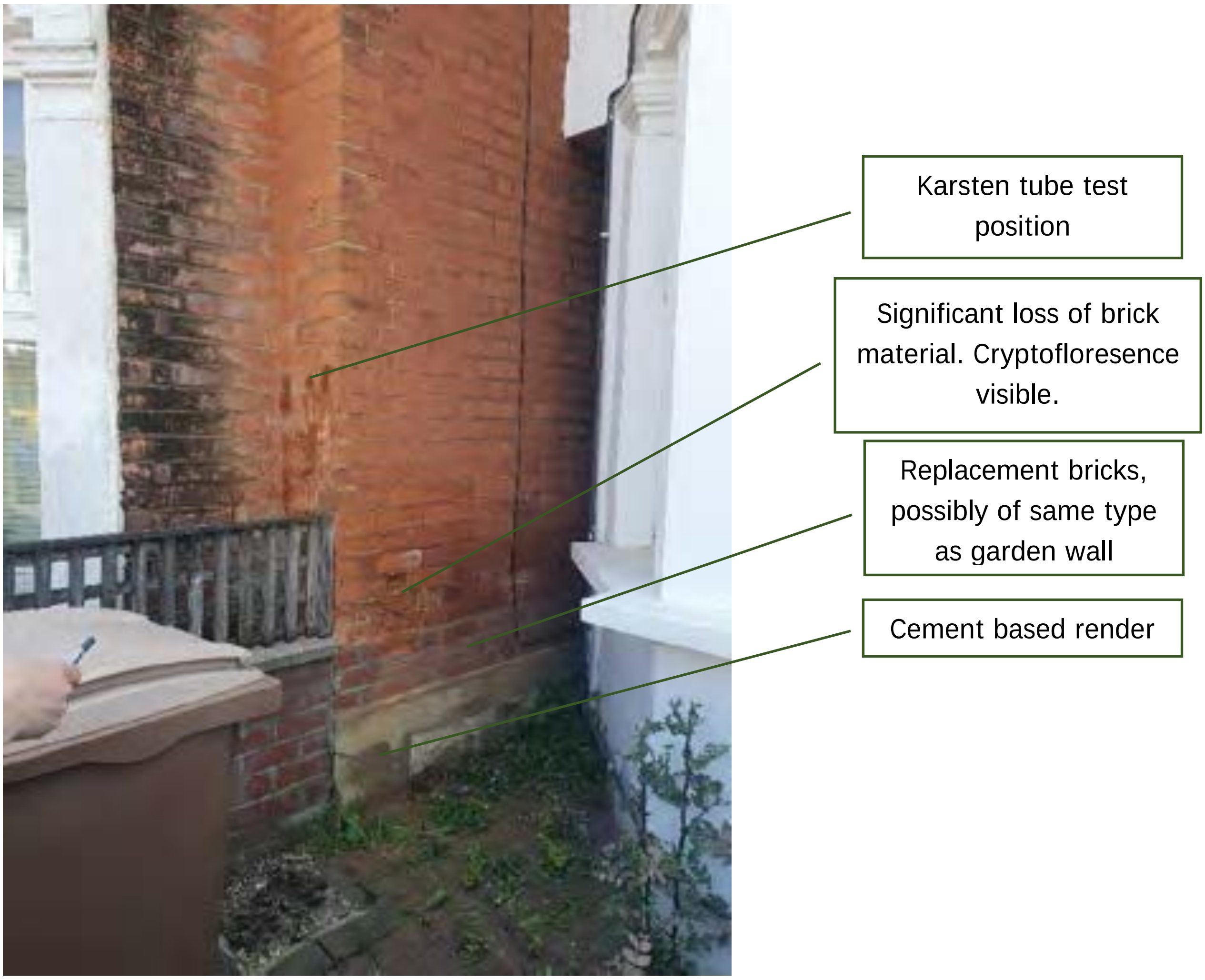
- There is rising damp, which is likely related to the floor retrofit. This is leading to salt crystallisation damage near to the ground.
- Vapour and capillary closed materials, i.e. cement based pointing is impairing drying and preventing lime mortar from fulfilling its sacrificial role
- Cement render and patch repairs, and possibly impermeable paint are impairing drying and exacerbating salt crystallisation damage
- Thick IWI is reducing temperatures precluding drying to inside, and impairing drying to outside, possibly exacerbating the above issues.

The damage can be considered in two main areas, with different mechanisms, although there will be some interaction. Firstly there is the rising damp which is driving salt crystallisation damage in a band near the ground; secondly there is freeze-thaw damage in the areas at high level. With respect to the retrofit interventions, the floor insulation is likely to have initiated rising damp and subsequent salt crystallisation damage. As well as adding moisture directly to the walls at high level, the faulty rainwater goods will increase ground moisture levels, exacerbating this further, although the damage is not focussed on the area below the leak.

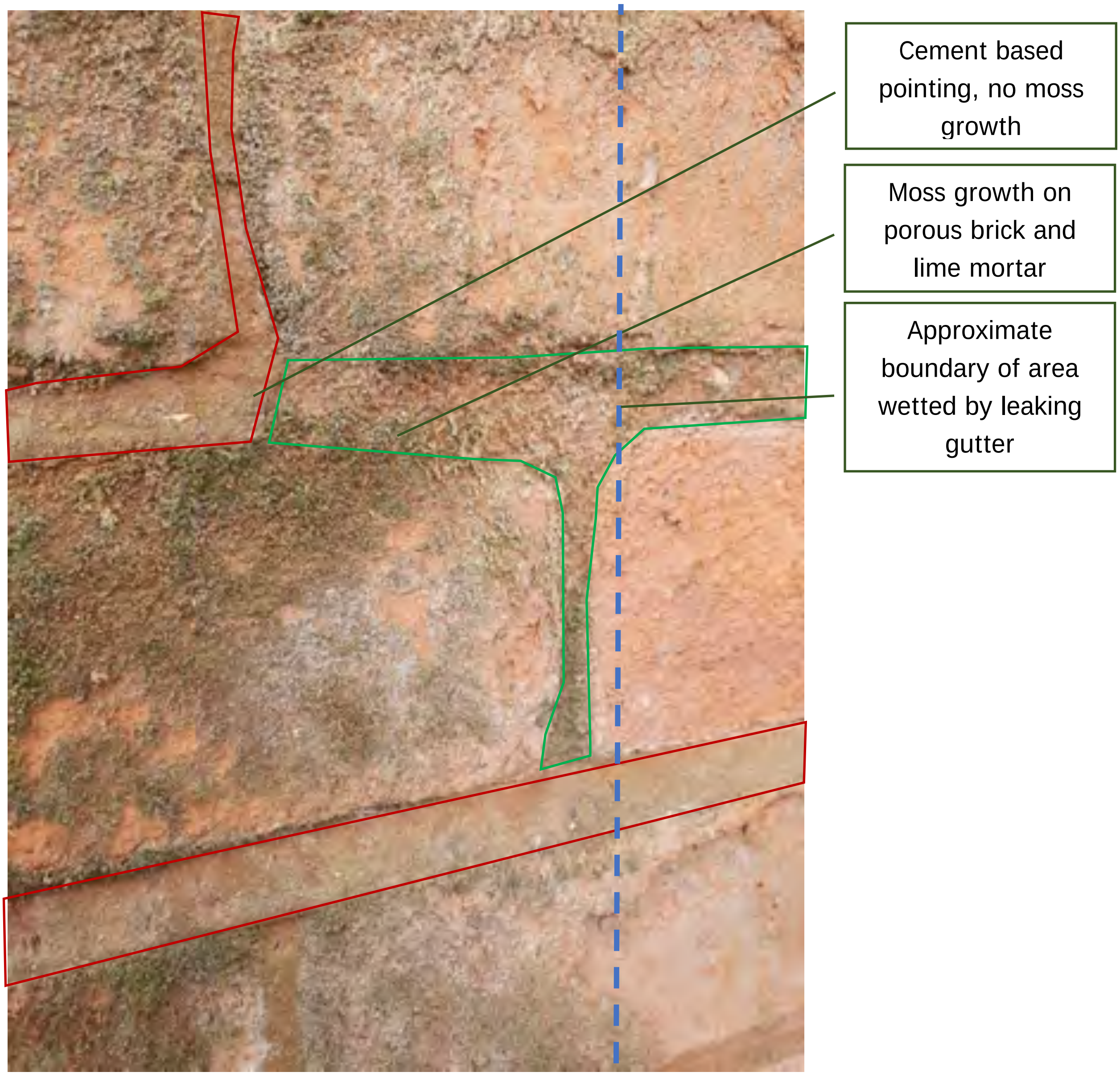
The IWI alone could in theory increase freeze-thaw risk however the simulations below indicate that there are more significant factors in this particular case. The IWI has an influence on drying and crystallisation behaviour associated with the rising damp, but again, other factors are likely to be more important.


Cement based repointing, poor workmanship. Cement covers black paint.
Widespread flaking and scouring of brick surface
Unknown black paint over original/old pointing
Efflorescence
Lime Render, with unknown black paint


Original/old pointing visible where paint has come off
Evidence of paint on brick surface


Karsten tube test position
Significant loss of brick material. Cryptofloresence visible.
Replacement bricks, possibly of same type as garden wall
Cement based render


Significant damage at high level. Maybe due to failure of neighbour's gutter, and/or parapet capping and inappropriate render. Flashing/splashback at end of gutter may be inadequate.
Replaced brickwork. Lack of moss likely due to low porosity of new bricks.
Original pointing painted or replaced with cement based mortar


Cement based pointing, no moss growth
Moss growth on porous brick and lime mortar
Approximate boundary of area wetted by leaking gutter

2 Simulation Exercise

2.1 Simulation setup

A simulation exercise was carried out to explore the relative influence of the IWI and cement pointing. A 2D section was modelled in Delphin, consisting of a 225mm thickness of brick, with a 10mm layer of lime bedding mortar. A 15mm thickness of gypsum plaster was represented internally. Models were created with and without the insulation layer (a similar specification to that at Hawthorn Road was simulated). A further set of permutations were simulated with the outer 11mm of lime mortar replaced with a cementitious material (concrete from the database) to reflect the inappropriate re-pointing. Three different types of brick were simulated.

A brick was selected from the Delphin database that was the closest match to material properties measured from a similar ‘soft red’ brick taken from a house of a similar age in another area of London. Furthermore, Karsten tube testing was undertaken to estimate the absorption coefficient in-situ. The Karsten tube tests suggest an A_w in the range of 0.10 to 0.16 $kg/m^{-2}s^{-0.5}$, although higher values were also observed these are likely to be due to sub-surface cracks. This value is higher than that found in the similar bricks that were tested in the lab.

As well as this similar brick, bricks with quite high and quite low absorption coefficients, were simulated. Some key hygrothermal properties for the materials used are given in Table 2.

Table 1 represents the main permutations simulated, each of which is allocated an identifying letter.

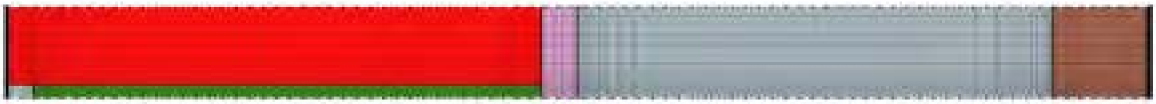
	Uninsulated		Insulated (200mm cellulose and 40mm woodfibre)	
	Lime mortar	Cementitious pointing	Lime mortar	Cementitious pointing
Brick 1	A	B	C	D
Brick 1, with WDR	E	F	G	H
Brick 2, with WDR	I	J	K	L
Brick 3, with WDR	M	N	O	P

Table 1: Permutations simulated and their IDs

	Notes	Density, kg/m^3	W_{Sat} kg/m^3	A_W $kg/m^2s^{0.5}$
Soft Red as measured	From an Edwardian House, Lewisham	~2020	249	0.062
Brick 1	Old Weinberg Berlin [529]	1967	240.1	0.06
Brick 2	Old Dresden ZD [492]	1619	361	0.381
Brick 3	Old Dresden ZF [494]	1976	169.4	0.02
Lime mortar (low cement ratio)	5:1:0.1 aggregate : lime : cement	1739	258.8	0.494
Concrete (to represent hard pointing)	[158]	2088	264	0.04
Gypsum Plaster	[81]	850	551	0.28
Cellulose insulation	[580] to approximate sheeps wool	55.2	780	0.56
Woodfibre	[435]	240	408	0.01

Table 2: Key properties of materiasl used in simulations

A climate file for Gatwick was used in the simulation, and internal conditions according to WTA 6.2 “Medium +5%” were used. The simulation orientation was North to reflect that of the wall with IWI at Hawthorn Road; the South elevation has EWI.



2.2 Results

2.2.1 Cases A – D

The first results presented are for cases A to D, i.e. those with the closely matching brick and no rain ingress. The four permutations compared are with/without insulation, and with/without cementitious pointing

Figure 1 shows the total moisture content of the arrangement in the first four simulations, over a period of 3.4 years. The simulations including an insulation layer (red and green lines) begin at a higher moisture content due to the additional material that can hold moisture. The simulation with insulation and concrete pointing has not reached a dynamic equilibrium, so the analysis that follows is likely to underestimate the long term risk in this arrangement.

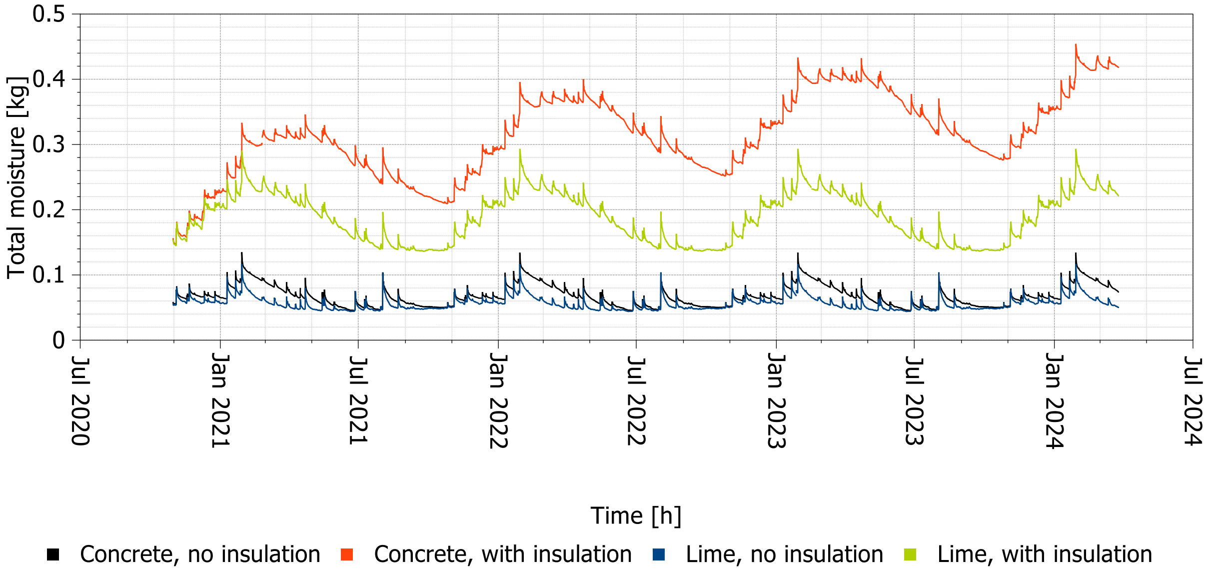


Figure 1: Total WMC, cases A-D

The moisture content and temperature of the outermost 1mm of brick were analysed to assess the risk of freeze-thaw damage. Freeze-thaw damage is a complex process that is difficult to fully represent. In this exercise, the number of risk events are counted for each scenario. A risk event occurs when the temperature drops from above to below zero degrees Celsius, while the moisture content remains above a threshold with respect to saturation. This is often selected to be 75%; not all pores need to be filled for damage to occur.

This approach does not take into account a number of important factors, including the pore-size dependency of the freezing temperature of water and the resistance of the material to freeze-thaw damage.

For the first four scenarios modelled, no freeze-thaw events occur. This is largely due to the northerly aspect of the wall, which receives little rain. In the simulated scenario, when weather events do wet the North facing wall, it is able to dry to below the risk threshold before the temperature falls below zero.

The potential for risk can nonetheless be explored. Table 3 shows the number of times the outermost 1mm of brick falls below 0°C in the last year of the simulation. The insulation has a strong effect on this, because the masonry is thermally isolated from the heated space; on the other hand the type of pointing has no influence.

All units: number of	Uninsulated	With insulation
Lime pointing	12	28
Concrete pointing	12	28

Table 3 - Freeze events, scenarios A-D

Table 4 shows the minimum observed temperatures which lead to the same conclusions.

All units: °C	Uninsulated	With insulation
Lime pointing	-7.8°C	-10.9°C
Concrete pointing	-7.8°C	-10.9°C

Table 4 - minimum brick temperature, scenarios A-D

Table 5 shows the number of times the outer 1mm of brick becomes saturated. The absence of insulation protects the wall from saturation because a warmer brick will dry faster. Also lime based mortar protects the brick from saturation, because its pore structure tends to draw water away from the brick. However, when there is insulation and cement pointing, there are 4 hours of the year when the brick approaches saturation (more than 75% of the fully saturated moisture content).

All units: hours	Uninsulated	With insulation
Lime pointing	0	0

Concrete pointing	0	4

Table 5 - number of saturation events, scenarios A-D

Table 6 shows the maximum moisture content (degree of saturation). This reveals more information than the simple count of threshold breaches. The cement pointed simulations have similar results, and happen to straddle the simple (and somewhat arbitrary) 75% threshold. This highlights a shortcoming of this simplified risk assessment protocol. Both lime pointed simulations have much lower peak moisture content, but the presence of insulation has a slightly greater influence.

All units: % (degree of saturation)	Uninsulated	With insulation
Lime pointing	48%	56%
Concrete pointing	74%	76%

Table 6 - maximum moisture content of brick surface, scenarios A-D

Table 7 shows the average moisture content (degree of saturation), which suggests yet another interpretation. With respect to the average moisture content, the insulation has a much more significant influence than the type of pointing, although the average level is far below that necessary to create a free-thaw risk. This suggests that the coincidence of cement pointing and insulation influences the peak moisture content most strongly.

All units: % (degree of saturation)	Uninsulated	With insulation
Lime pointing	1.1%	2.3%
Concrete pointing	1.0%	2.7%

Table 7 - average moisture content at brick surface, scenarios A-D

Wind driven rain was then added to the simulations to represent the fact that rain will penetrate into the brickwork where there is cracking between the pointing and brick or within the materials themselves. The difference was negligeable, and the statistics presented in Tables 1 to 5 are identical at the precision quoted. This is likely due to the fact that the elevation is north-facing, and received little wind driven rain.

2.3 South Facing

To verify this, a set of simulations was run with a hypothetical South orientation. The rear of 10 Hawthorn Road is externally insulated so this arrangement does not exist at this house in reality. Table 8 can be compared with Table 3; this indicates that the simulations without insulation see more occurrences with elevated moisture content, but where there is insulation there is no change.

All units: hours	Uninsulated	With insulation
Lime pointing	15	28
Concrete pointing	15	28

Table 8 - Freeze events, scenarios A-D

Table 9 shows the minimum observed temperatures, which are similar to the North-facing cases; the minimum temperature in situations with insulation is slightly higher.

All units: °C	Uninsulated	With insulation
Lime pointing	-7.8°C	-10.0°C
Concrete pointing	-7.8°C	-9.9°C

Table 9 - minimum brick temperature, scenarios A-D

Table 10 shows the number of times the outer 1mm of brick becomes saturated in a south facing scenario. While both lime pointed cases do not suffer saturation events, the insulated and cement pointed case has twice the number of saturation events, and the cement pointed but uninsulated case has one instance.

All units: Hours	Uninsulated	With insulation
Lime pointing	0	0
Concrete pointing	1	8

Table 10 - number of saturation events, scenarios A-D

Table 11 shows the maximum moisture content (degree of saturation). All scenarios are increased relative to the North facing example, but the increase is more pronounced with lime than cement pointing. None the less the peak content in the lime is still slightly below the threshold selected for frost risk.

All units: % (degree of saturation)	Uninsulated	With insulation
Lime pointing	71%	74%
Concrete pointing	80%	84%

Table 11 - maximum moisture content of brick surface, scenarios A-D

Table 12 shows the average moisture content (degree of saturation). The average is increased more dramatically with the cement pointing than with lime.

All units: % (degree of saturation)	Uninsulated	With insulation
Lime pointing	1.7%	2.6%
Concrete pointing	1.5%	3.0%

Table 12 - average moisture content at brick surface, scenarios A-D

2.4 Sensitivity to brick type

There is often uncertainty with respect to the selection of brick for simulation, due to practical problems with measuring the type of brick. In this case a brick of a similar age, and which is visually similar was used in simulation. Table 13 shows that when insulated the brick type does not influence the temperature strongly, although prior to insulation there is a stronger influence, due to the conductivity and thermal storage of the brick.

	Brick 2 (more porous)		Brick 3 (less porous)	
All units: hours	Uninsulated	With insulation	Uninsulated	With insulation
Lime pointing	21	30	13	28
Concrete pointing	21	30	13	27

Table 13 - Freeze events, scenarios A-D

Table 14 shows the minimum observed temperatures, which are similar to the main brick type explored.

	Brick 2 (more porous)		Brick 3 (less porous)	
All units: °C	Uninsulated	With insulation	Uninsulated	With insulation
Lime pointing	-9.4	-11.2	-7.6	-10.9
Concrete pointing	-9.5	-11.2	-7.7	-10.8

Table 14 - minimum brick temperature, scenarios A-D

Table 15 shows the number of times the outer 1mm of brick becomes saturated in a south facing scenario. It is significant that the more porous brick does not experience any saturation events; this is partly because the saturation threshold is defined as a fraction of the maximum water content; a given amount or water is therefore less likely to fill all the pores if there are more of them. Conversely the less porous brick is more likely to become saturated as there is less space to fill with water. This highlights a shortcoming of this approach, as the more dense brick is likely to be more resistant to frost damage.

	Brick 2 (more porous)		Brick 3 (less porous)	
All units: hours	Uninsulated	With insulation	Uninsulated	With insulation
Lime pointing	0	0	4	3
Concrete pointing	0	0	5	11

Table 15 - number of saturation events, scenarios A-D

Table 16 shows the maximum moisture content (degree of saturation). These results reflect the findings illustrated in Table 15.

	Brick 2 (more porous)		Brick 3 (less porous)	
All units: % (degree of saturation)	Uninsulated	With insulation	Uninsulated	With insulation
Lime pointing	27%	27%	81%	91%
Concrete pointing	30%	31%	92%	97%

Table 16 - maximum moisture content of brick surface, scenarios A-D

Table 17 shows the average moisture content (degree of saturation). The average is increased more dramatically with the cement pointing than with lime.

	Brick 2 (more porous)		Brick 3 (less porous)	
All units: % (degree of saturation)	Uninsulated	With insulation	Uninsulated	With insulation
Lime pointing	1.7%	2.3%	5.7%	8.6%
Concrete pointing	1.6%	2.5%	5.4%	9.5%

Table 17 - average moisture content at brick surface, scenarios A-D

3 Conclusions

The damage visible at high level can be directly linked to observed defects that are unrelated to the IWI, i.e. inappropriate cement pointing, and failed rainwater goods. The floor insulation is likely to be a key cause of salt crystallisation damage at low level, exacerbated by inappropriate use of cement materials and, possibly, impermeable paint.

The simulations indicate that with a brick thought to be similar to that used to build 10 Hawthorn Road, the presence of cement pointing presents a greater risk of freeze-thaw damage than the thick IWI. However, the properties of the brick influences the relative influence of these two interventions on surface damage.

Combining these simulations with observations from site suggest that there are two types of damage occurring on the North elevation of Hawthorn Road

- Salt crystallisation damage near to ground level, as a result to rising damp (likely linked to the floor treatment), primarily exacerbated by inappropriate use of cement (and possibly impermeable paint).
- Freeze-thaw damage at high level as a result of faulty rainwater goods, primarily exacerbated by inappropriate cement pointing. The IWI may be increasing the risk, but to a lesser degree than the cement.

Appendix 7: Shaftesbury Park Terrace: hygrothermal risk analysis report

Konstantinos Megagiannis (QODA)

QODA

80065 – CIBSE UKRI Retrofit Revisit

Shaftesbury - Hygrothermal Performance Assessment Report

QODA

Revision Summary

Issue	Document prepared			Document checked		
	Name	Signature	Date	Name	Signature	Date
v1	Konstantinos Megagiannis	KM	30/05/2023			

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Contents

QODA

1 Executive Summary

QODA Consulting was commissioned to assess the moisture-related risks of the installed internal wall insulation (IWI) at 26 Eversleigh Road, utilizing the WUFI Pro heat and moisture modelling software, in accordance with BS EN 15026.

The assessment of the mould growth risk showed that mould could be present in hidden cavities or air pockets between the pre-existing internal plaster and the IWI system, where indoor air can access in the front elevation and the rear elevation.

The assessment of the risk of deterioration of the timber joist ends due to rot illustrated the high possibility that timber degradation is likely to be occurring in the front and the rear elevations.

Lastly, the assessment against the risk of freeze-thaw deterioration indicated no high risk for the external face of the front and the rear elevation to suffer from spalling or face loss.

1.1 Disclaimer

QODA Consulting uses its reasonable endeavours to provide accurate and authoritative information in respect of this report. The Client accepts that the areas of hygrothermal assessment and proper measurement of all hygrothermal characteristics of building materials are emerging, but separate and related disciplines. Assumptions are adopted and assessments are therefore undertaken where large areas of uncertainty exist, namely in respect of, material properties, climate, care of construction and building usage. QODA Consulting's methodology is designed to deal with and limit uncertainty by simulating scenarios and using these simulations to provide recommendations. QODA Consulting does not provide any warranty of any kind with regard to the output of the simulations and resulting information. Such information should be used with care, by professionals who understand the implications of the information and are able to make their own assessment of the results.

2 Introduction

2.1 Aim of the report

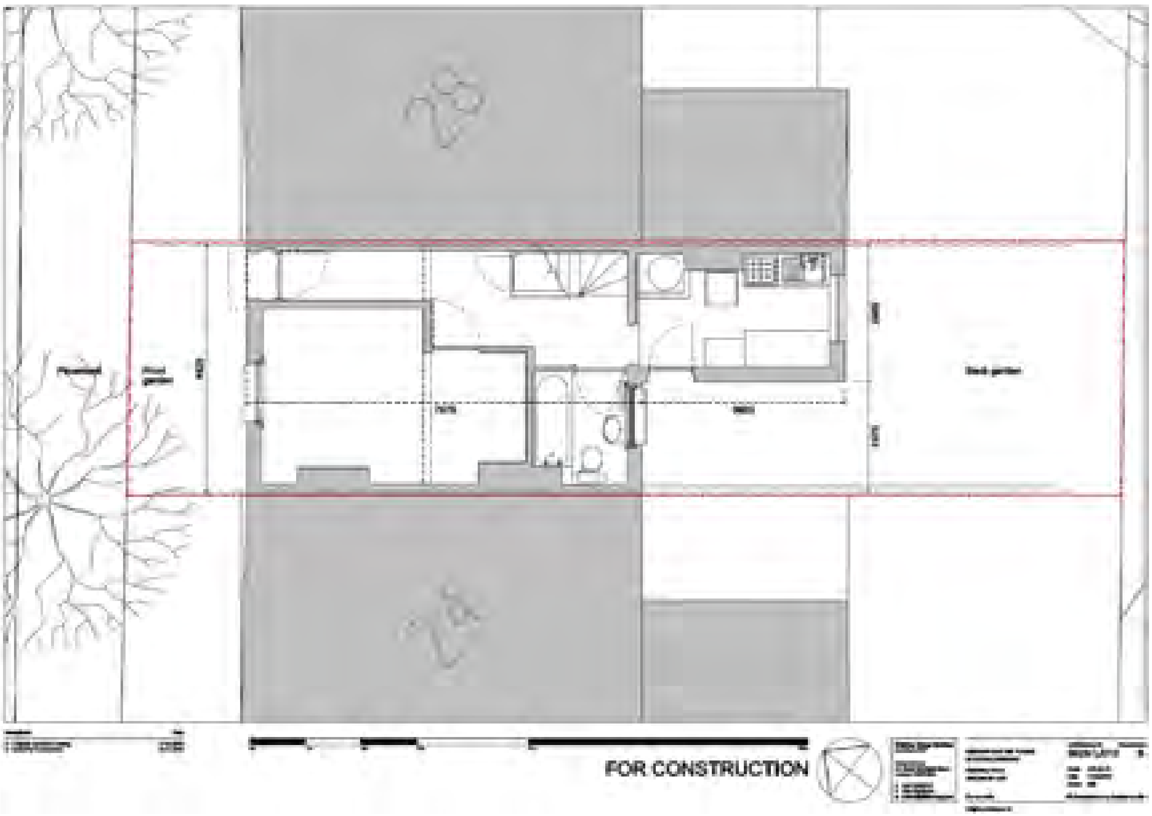
QODA Consulting was commissioned to undertake numerical modelling according to BS EN 15026 using the WUFI Pro heat and moisture modelling software, to understand the hygrothermal performance of the internal wall insulation (IWI) at 26 Eversleigh Road, SW11.

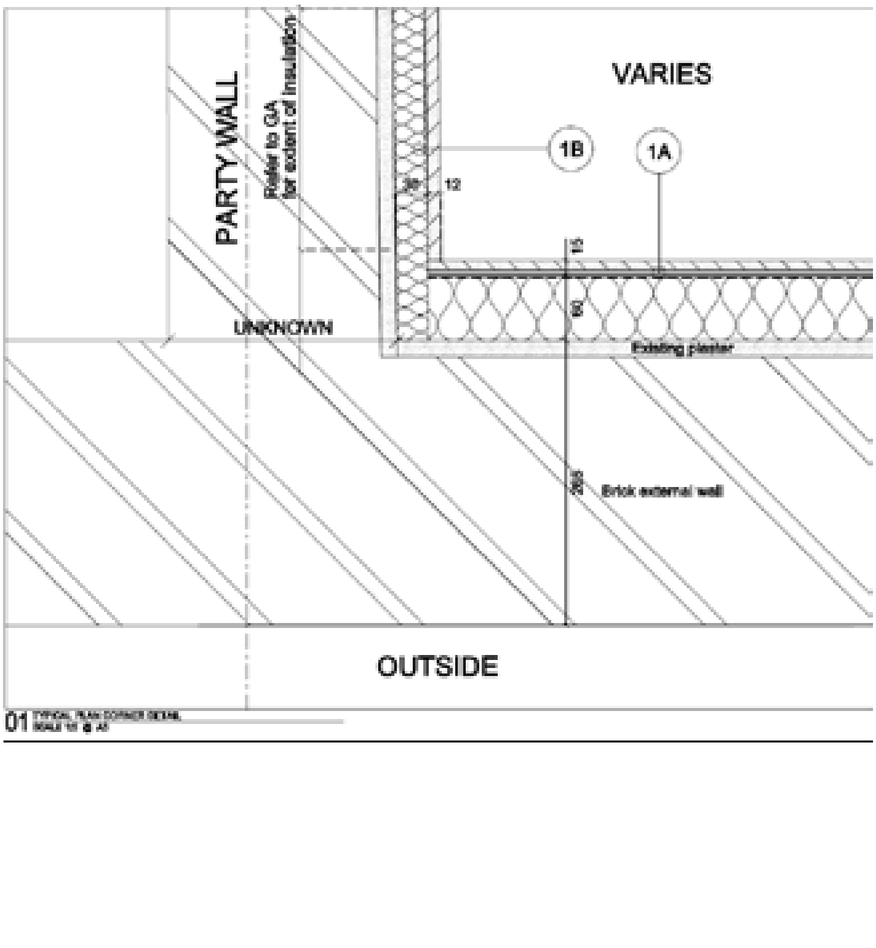
2.2 Context

The examined building - 26 Eversleigh Road - is a mid-terraced, two-storey, two-bedroom house on Peabody's Shaftesbury Park Estate in Wandsworth, SW11. It is one of many similar houses on the mixed-tenure estate which is in the Shaftsbury Park Estate Conservation Area. The house dates from approximately 1874. As shown in the provided plan drawing the front and rear elevations have a North-West and South-East orientation, respectively.

The property was retrofitted in 2012 as part of the 'Retrofit for the future' scheme, with the aim to improve energy efficiency and carbon consumption, with a target of an 80% reduction in carbon emissions. A whole-house approach to the improvement of the home was implemented, embracing the building fabric (insulation, air tightness and thermal bridging), the building services (heating, hot water, ventilation, fixed lighting and domestic appliances) and renewable energy systems (solar water heating and solar power).

The insulation strategy regarding the external walls included the installation of Spacethem aerogel-based lining boards internally, except for the single-storey kitchen wing at the rear, which was insulated externally. This study is focused on the internal wall insulation (IWI).


FOR CONSTRUCTION


VARIES
PARTY WALL
Refer to GA for extent of insulation
1B
1A
12
15
UNKNOWN
Existing plaster
Brick external wall
OUTSIDE

3 Methodology

3.1 Assessment method

The British Standard BS 5250:2021 Code of Practice for Management of Moisture in Buildings suggests that modelling as specified in standards such as BS EN ISO 13788 and BS EN 15026 is an appropriate method to assess and manage moisture risks.

BS EN ISO 13788 uses the 'Glaser' method, a steady state 1D vapour diffusion model with constant material properties and boundary conditions. This has been the common method to assess the moisture balance of a building component by considering vapour diffusion as the only moisture movement transport. However, this method does not allow for the capillary moisture transport in the component, nor for its sorption capacity, both of which reduce the risk of damage in case of condensation. Furthermore, since the method only considers steady-state transport under heavily simplified boundary conditions, it cannot reproduce individual short-term events or allow for rain and solar radiation. The approach also misses out that some materials are hygroscopic (i.e. liquid water stored in pores), some materials can start wet from built-in water or rain ingress during construction, and material properties are affected by moisture content.

On the other hand, BS EN 15026 is a standard that defines the practical application of hygrothermal simulation software used to predict one-dimensional transient heat and moisture transfer in multi-layer building envelope components subjected to non-steady climate conditions on either side. It specifies the equations for heat and moisture transport and storage, which are coupled (meaning that one affects the other). The transient models covered in this standard take account of heat and moisture storage, latent heat effects, and liquid and convective transport under realistic boundary and initial conditions, therefore providing more detailed and accurate information on the risk of moisture problems within building components and on the design of remedial treatment. This is the "dynamic" approach implemented in WUFI Pro 6.5, which is the software tool used in this study.

Even so, numerical simulations, such as WUFI, also have limitations in regard to how accurately they can model reality. As it is one-dimensional, it is not ideal for bridged structures with more complex geometry. Moreover, there is limited ability to simulate the microclimate at the project's site. More limitations are listed of this in the Caveat and Content section at the end of this report. Lastly, even if construction imperfections have been part of our models, the assessment assumes that the building will be well maintained (e.g., gutters & pipes).

3.2 Assessment risk criteria

There is not a clear set of moisture risk assessment criteria agreed upon within the industry yet, especially as different build-ups of materials and applications will require different criteria. The following criteria are used for the analysis of this WUFI modelling work:

- Assessment of the risk of mould growth

Studies have shown that moulds can germinate and grow if the relative humidity (RH) at a surface rises above 80% (BS 5250).

- Assessment of risk of decay in timbers in contact with the masonry.

Persistent timber moisture contents in excess of 20 % (by mass) can lead to deterioration due to rot (BS 5250).

- Assessment of risk of deterioration due to freezing and thawing

A threshold of 90% water content when temperatures are below 0ºC has been selected to assess the risk of the exterior face of the brick deteriorating due to surface spalling or face loss as a result of the freeze-thaw action.

3.3 Selection of materials

Whilst the relevant material properties of modern construction materials are reasonably consistent and well understood (e.g. gypsum plasterboard and polyisocyanurate insulation), there is currently a lack of properly tested data for existing bricks, stones, and plasters in the UK. Furthermore, no measurements of the hygrothermal properties of the construction materials of this building have been conducted. Therefore, the author has picked out a number of different materials to test a range of hygrothermal properties that are likely to match the properties of the existing construction materials of this building. This 'bracketing' approach is considered best practice in the context of missing information and in this study, it has been implemented to the materials that are believed to be the most influential in terms of the hygrothermal behaviour of each build-up. More specifically, 3 different bricks have been tested in the simulation of the front elevation and rear elevation build-ups.

Front Elevation:

	WUFI Material	**Water Absorption Coef. A-value (kg/m²√s)**	**Reference Water Content, w_{80} (kg/m³)**	**Free Water Saturation, w_f (kg/m³)**
Brick 1	Solid Brick, historical	0.36	4.5	230
Brick 2	Solid Brick ZC	0.183	3.1	188
Brick 3	Solid Brick ZM	0.116	5	264

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Spacetherm Wallboard is a high-performance laminate which consists of Spacetherm Aerogel insulation blanket bonded to foil-faced plasterboard. The physical properties of the Spacetherm Wallboard, as detailed in the product's datasheet, are presented below:

PHYSICAL PROPERTIES	RESULT
Spacetherm Wallboard panel sizes	2400 x 1200mm
Thickness: Plasterboard	12.5mm
Thickness: Aerogel	5, 10, 15, 20mm*
Vapour Control Layer	78.5 MNs/g
K-Factor: Aerogel	0.015W/mK
K-Factor: Plasterboard	0.190W/mK
Reaction to Fire: Plasterboard	A2, s1, d0
Reaction to Fire: Aerogel	Class C-s1, d0 (EN 13501-1)

To simulate Spacetherm Wallboard in WUFI, 3 different materials from the WUFI database with edited properties, as appropriate, have been used. In the following table, the properties that have been edited to match the materials of Spacetherm Wallboard are shown in red:

WUFI Material	**Thermal Conductivity (W/mK)**	**Buk density (kg/m^3)**	**Porosity (m^3/m^3)**	**Specific Heat Capacity (J/kgK)**	**Water Vapour Diffusion Resistance Factor (-)**
Aspen Aerogels – Spaceloft Grey	0.015	146	0.92	1000	4.7
Vapour Control Layer	0.5	1900	0.001	1000	15700
Gypsum Board	0.190	850	0.65	850	8.3

4 Numerical models: Inputs

4.1 Materials

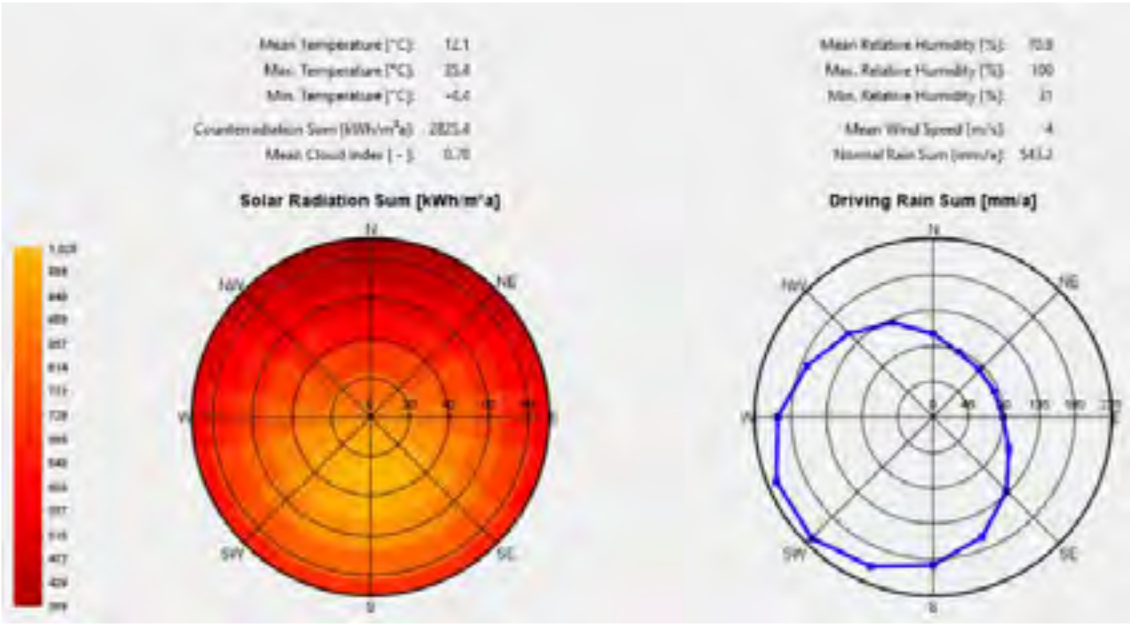
Materials				Hygrothermal Properties					
Layer	**WUFI Material**	**Source**	**Thickness (mm)**	**Bulk Density (kg/m3)**	**Porosity (m3/m3)**	**Heat Capacity (J/KgK)**	**Thermal Conductivity (W/mk)**	**Vapour Diffusion Resistance Factor (-)**	**Water Absorption Coef. A-value (kg/m²√s)**
1	Solid Brick, historical	Fraunhofer IBP	265	1800	0.31	850	0.6	15	0.36
	Solid Brick ZC	MASEA	265	1985	0.28	836	0.908	23	0.183
	Solid Brick ZM	MASEA	265	1720	0.35	937	0.547	19	0.116
2	Lime Plaster (for salt extraction, A-value: 10.2 kg/m2h0.5)	Fraunhofer IBP	15	1600	0.33	850	0.7	12	0.17
3	Spacetherm Aerogel	Fraunhofer IBP - edited	60	146	0.92	1000	0.015	4.7	0.0004
4	Intergrated Vapour Control Layer (sd - 15.7m)	Fraunhofer IBP - edited	1	1900	0.001	1000	0.5	15700	-
5	Gypsum Board	Fraunhofer IBP	15	850	0.65	850	0.19	8.3	0.287

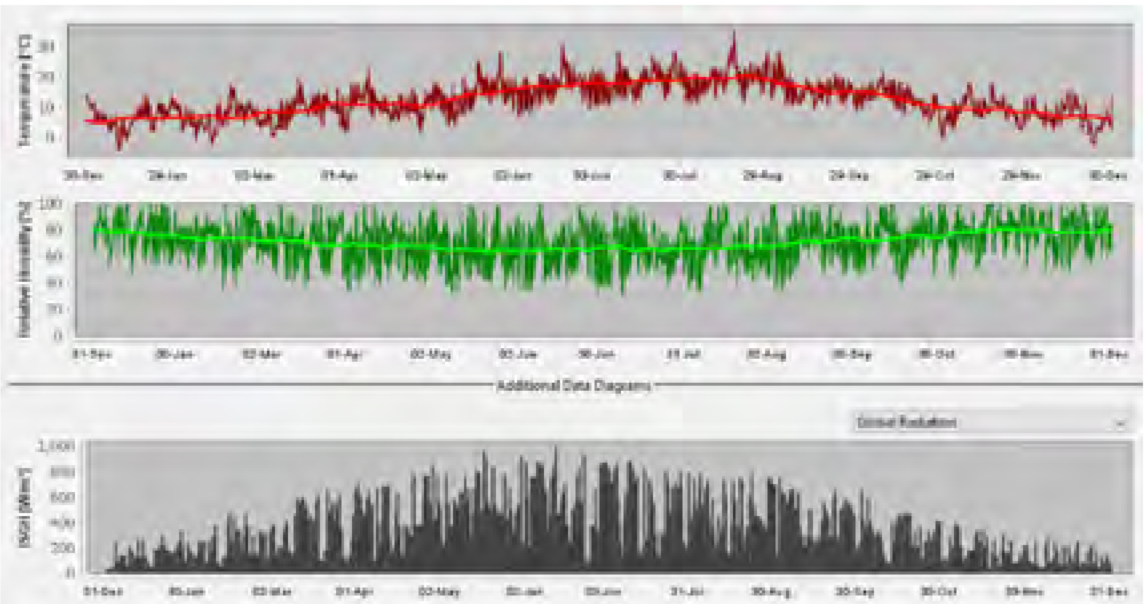
4.2 Initial Conditions

To realistically estimate the initial conditions of the build-up, a simulation for 5 years pre-retrofit was conducted in the relevant orientations. The water content of the brick and the plaster at the end of this simulation was used as an initial water content in the following simulations post-retrofit.

4.3 External climate

For this simulation, a synthetic weather file for a "Design Reference Year" is created for the project's location, following the procedure set out in BS 15026. The "Design Reference Year" is constructed to cause the most severe conditions likely to occur once every 10 years. A summary of the weather data included in the synthetic weather file for a "Design Reference Year" is displayed below.

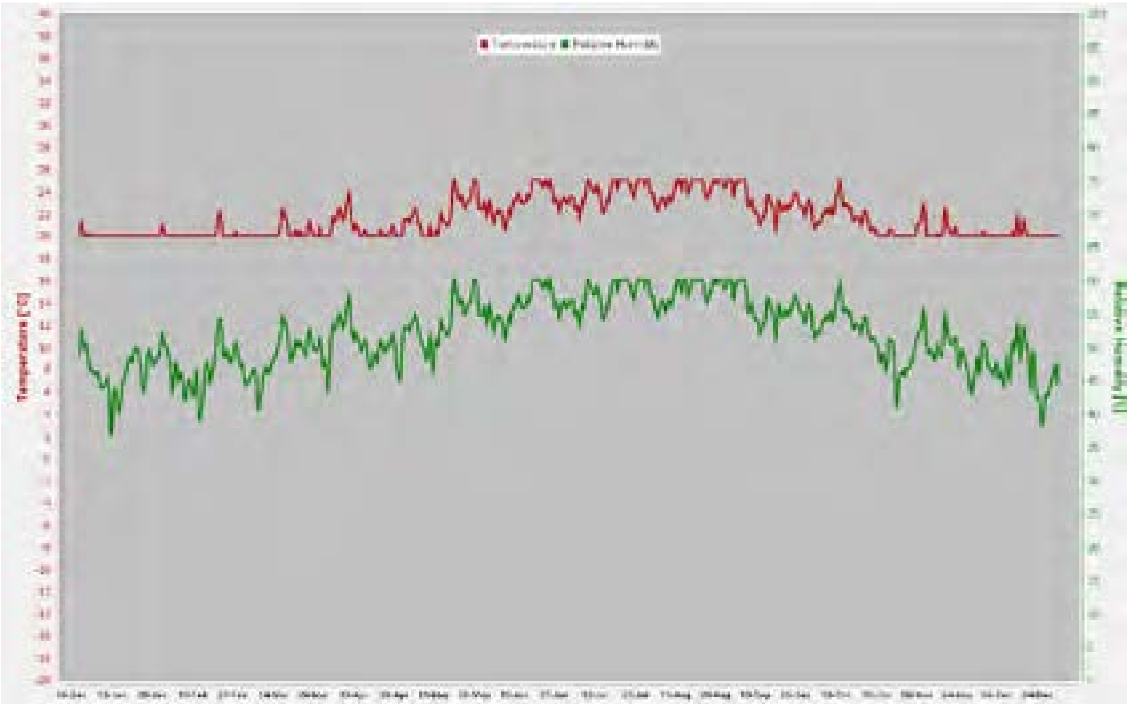




4.4 Indoor climate

BS EN ISO 15026 suggests that indoor conditions will vary between a medium to a high internal moisture load. Normal internal moisture load is typically considered with RH levels between 40 and 60%. High internal moisture load reaches higher RH levels and can be due to a combination of high levels of internal activities (cooking, showering, etc.) and a lack of adequate ventilation.

In this study, internal conditions are modelled as "Medium Moisture Load" in accordance with Annex C of BS EN 15026.



4.5 As-Built In-Situ Conditions

Issues such as liquid water penetration, air leakage due to construction faults and existing dampness should also be considered when assessing risks, as no 'perfect' build-up exists. The presence of an imperfect airtightness layer has been simulated with the addition of a moisture source based on an envelope infiltration of 5 q50 ($m^3/(m^2h)$) onto the wall build-up.

4.6 Other WUFI Model Parameters

Below, some additional information regarding the cases modelled is listed:

- A 1-hour time increment was chosen for all WUFI models.
- A 10-year total modelling period was used on all the WUFI models (with a 1st October start date).

5 Results and Analysis

5.1 Assessment against mould growth

To assess the risk of mould growth the relative humidity levels at the inner face of the brick for each modelling case were assessed against the threshold of 80% RH. The two graphs in this page display the relative humidity levels at this location for the front and the rear elevation, respectively.

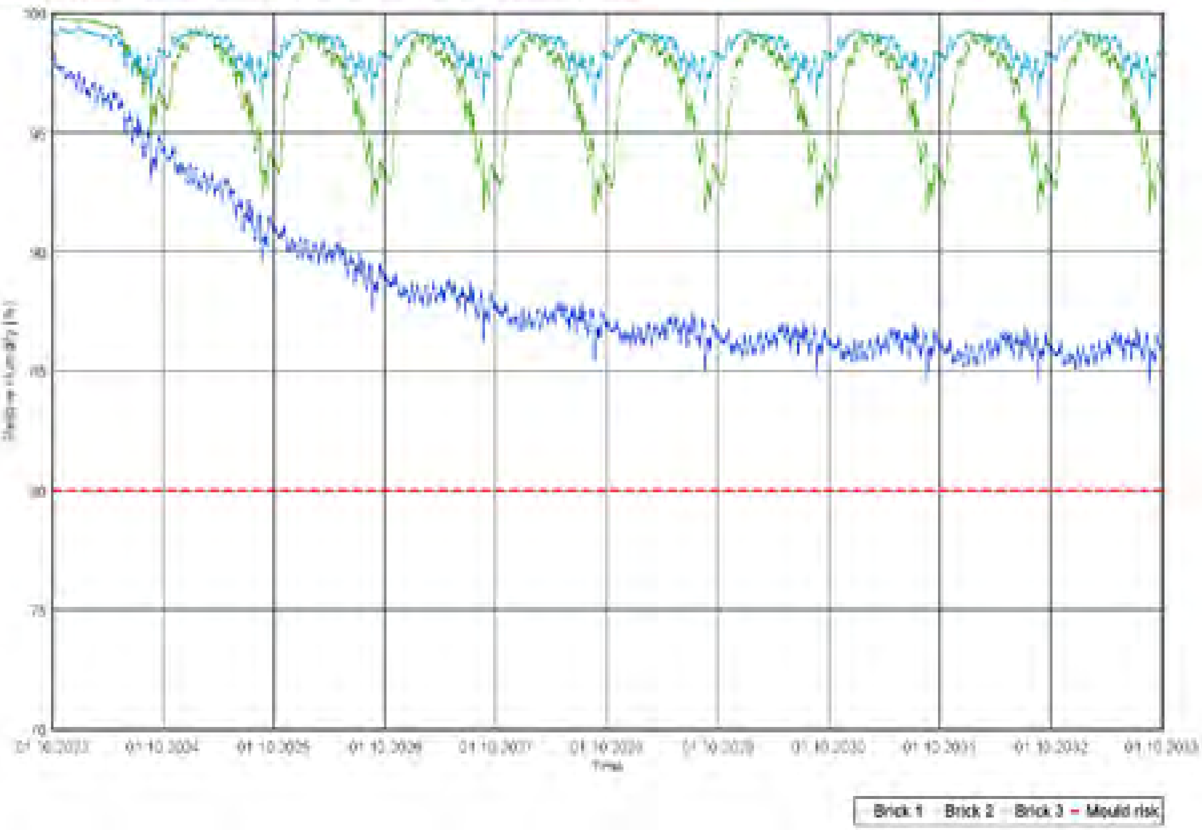
In the front elevation, the relative humidity levels at this critical surface remain above the threshold of 80% RH regardless of the brick type throughout the simulation period. However, the type of brick and its hygrothermal properties impact significantly on the fluctuation of the relative humidity levels. More specifically, the relative humidity levels on this surface in the Brick 1 modelling case (most absorbent brick) exceed 95% RH throughout the simulation period whilst in the Brick 2 modelling case (less absorbent brick) the RH levels fluctuate between 92% and 99%. On the other side, in the modelling cases with Brick 3 (least absorbent brick), a decrease in the RH levels is observed until an equilibrium state is reached in the fifth year of the simulation period at around 87% RH.

This shows that regardless of the brick type, mould might be present in hidden cavities or air pockets where indoor air can access between the pre-existing internal plaster and the Spacetherm Wallboard. The risk of mould growth in these areas would be lower, if the existing brick has an absorptivity equivalent to this of Brick 3.

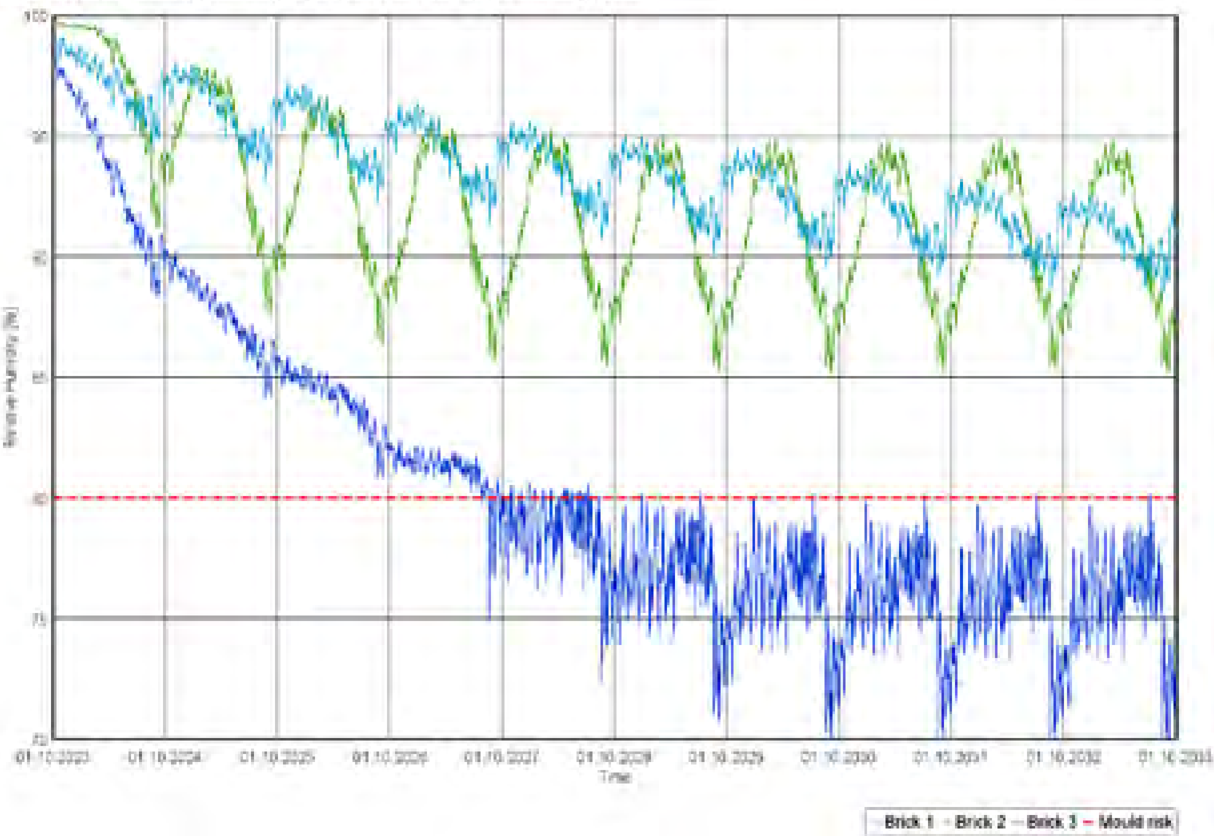
In the rear elevation, the relative humidity levels at the critical surface are relatively lower compared to the front elevation, not exceeding 95% RH in the modelling cases related to Brick 1 and Brick 2 but also staying above 85% once an equilibrium state is reached. The relative humidity levels decrease dramatically in the case of Brick 3 reaching levels below the threshold of 80% once an equilibrium state is reached, 4 years after the start of the simulation.

The analysis of the rear elevation shows that mould might be present, as in the case of the front elevation if the existing brick has a water absorption similar to this of Brick 2 or worse. If the existing brick is less absorptive (similar to Brick 3), it is likely that mould growth has not occurred. However, it should be noted that it is still likely that mould has grown during the drying out of the existing wall post-retrofit until an equilibrium was reached.

Front elevation: Relative Humidity at the the inner side of pre-existing plaster



Rear elevation: Relative Humidity at the the inner side of pre-existing plaster



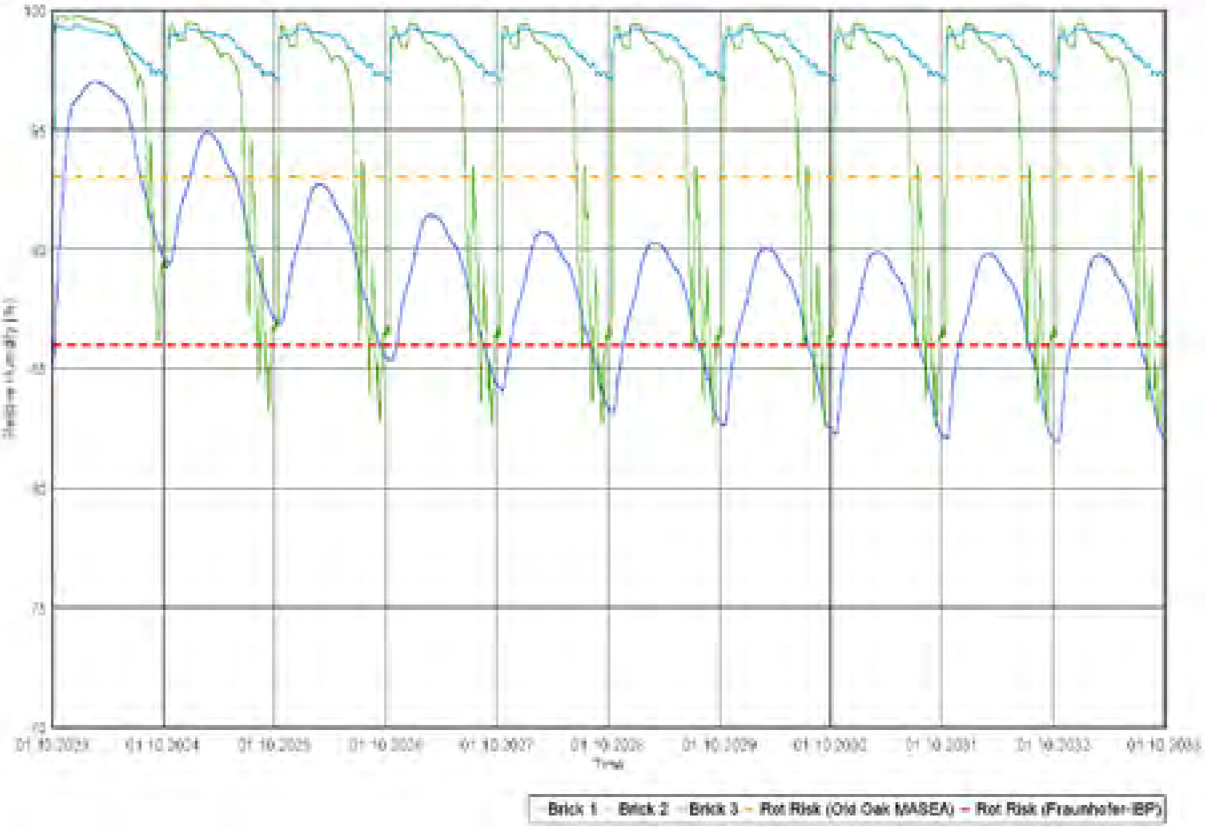
5.2 Assessment against timber rot risk

To assess the risk of timber joist degradation due to rot the relative humidity levels at the end of the timber joists which are embedded in the external wall case were assessed for each modelling against the threshold of 20% mass. Please note that it is assumed that timber joist ends are embedded in a depth of 100mm. To conduct this assessment, it was necessary to convert the water content as mass percentage to relative humidity levels. As there is uncertainty on the timber type of the joist conversion was conducted for 2 timber types that their hygrothermal properties were available in the WUFI database. More specifically, by using the moisture storage function and the porosity of each timber type, it was calculated that the 20% mass threshold corresponds to 86% RH for Oak (Fraunhofer IBP database) and 93% RH for Oak, Old (MASEA database).

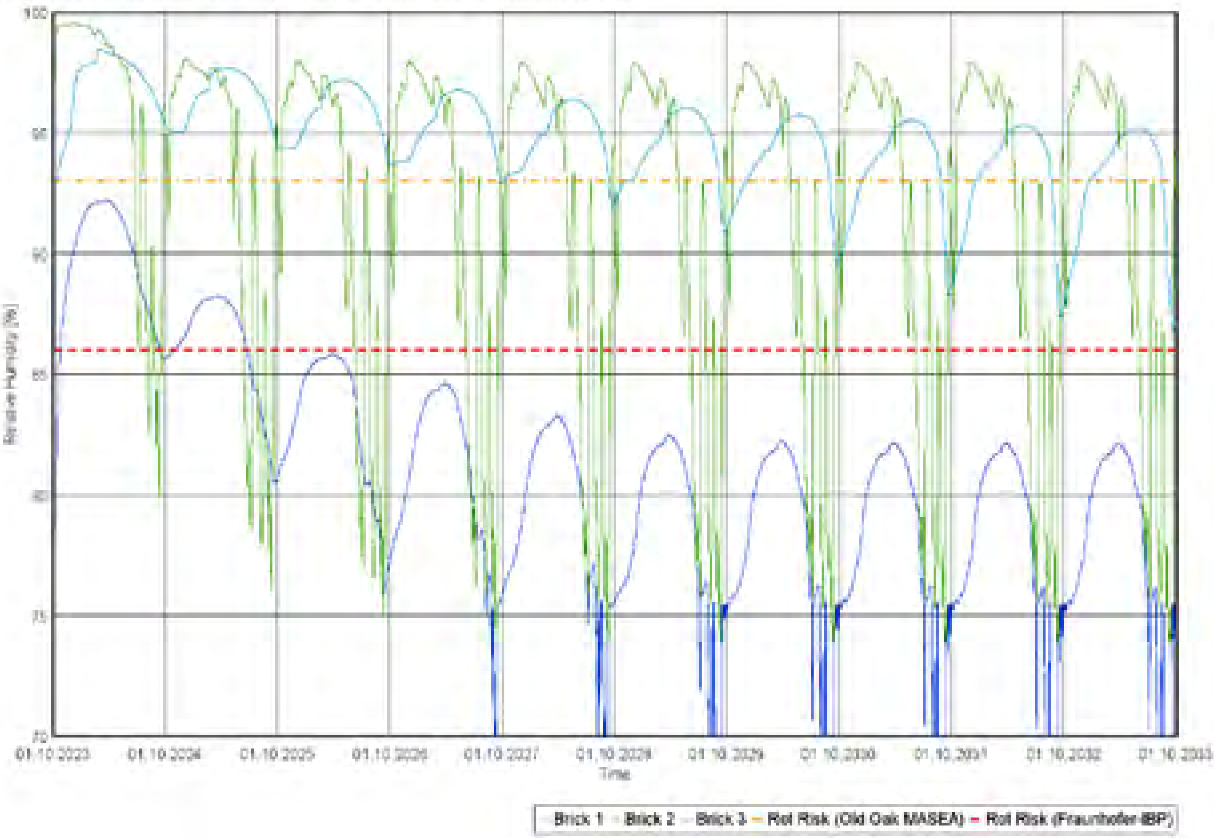
In the front elevation, the threshold of 20% is exceeded in all cases regardless of the brick type with the only exception being the combination of a brick type with low absorption, such as Brick 3, and a timber type with high moisture storage function, such as Oak, Old (MASEA).

In the rear elevation, a brick type with low absorption, such as Brick 3, would prevent the risk of decay due to rot in the timber joist ends, regardless of the timber type.

Front elevation: Relative Humidity at the the position of the timber joist end



Rear elevation: Relative Humidity at the the position of the timber joist end



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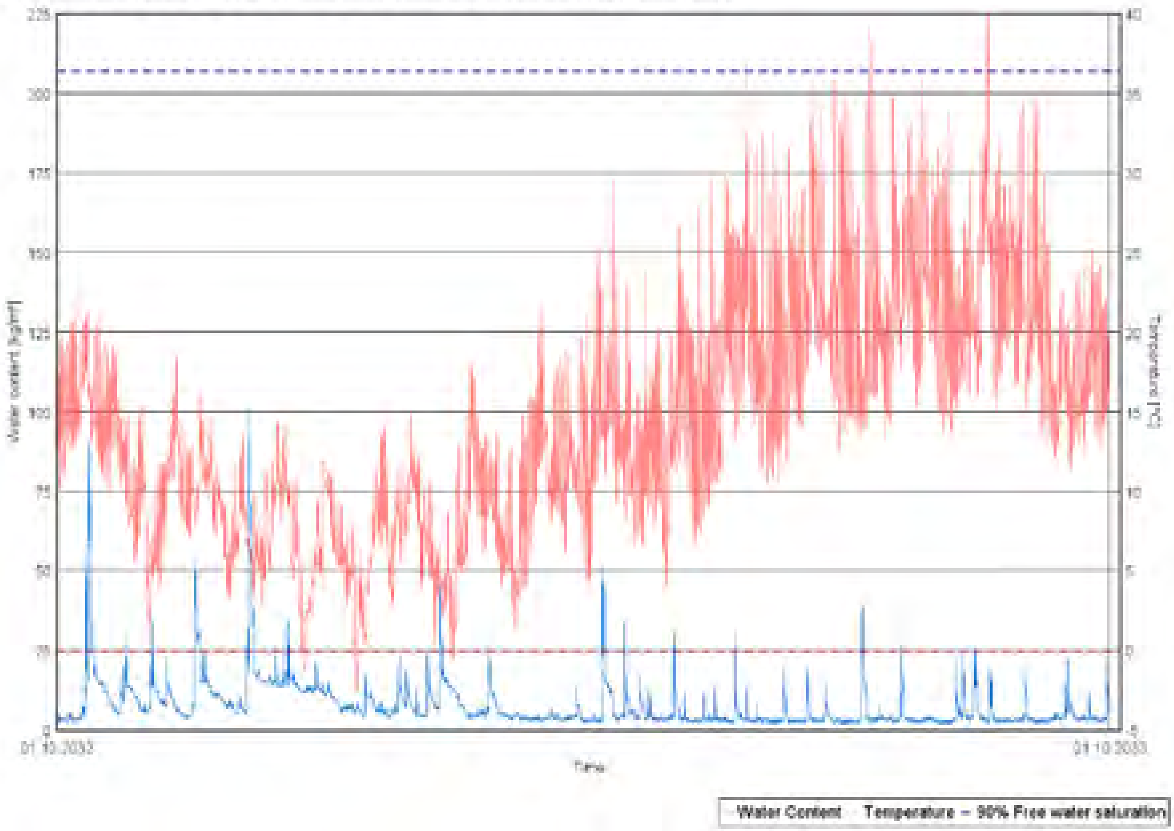
5.3 Assessment against freeze-thaw deterioration

The analysis to assess the risk of freeze-thaw deterioration analysis is based on the moisture content and the temperature of the external face of the brick. More specifically, the moisture content and the temperature of a 10mm thick sliver were analysed for each brick type with and without the dry lining, in order to determine how many freeze-thaw cycles it will undergo (i.e., how many times the water content of the silver will exceed the 90% free water saturation threshold while, at the same time, its temperature will be lower than 0 ºC).

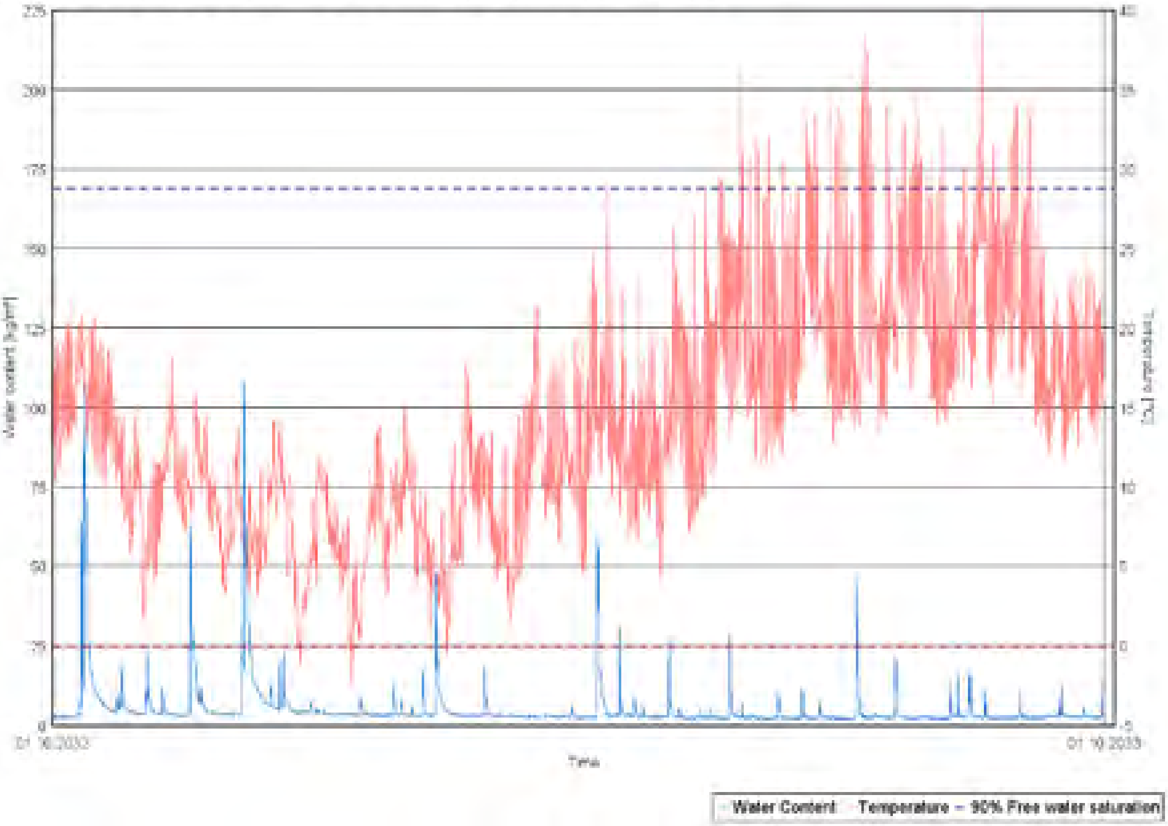
To conduct this assessment in the front elevation (North-West orientation), graphs with the water content of the external 10mm thick brick sliver and its temperature for each brick type for 1 year once the build-up has reached an equilibrium phase were plotted. These graphs show that there is no occasion where the two conditions mentioned above are met, therefore no freeze-thaw cycles would be expected to occur.

Since no freeze-thaw cycles would be expected to occur in the front elevation, it can be assumed that no such risk exists in the rear elevation, as well, as due to its South-East orientation it experiences higher temperatures and lower wind-driven rain, comparatively.

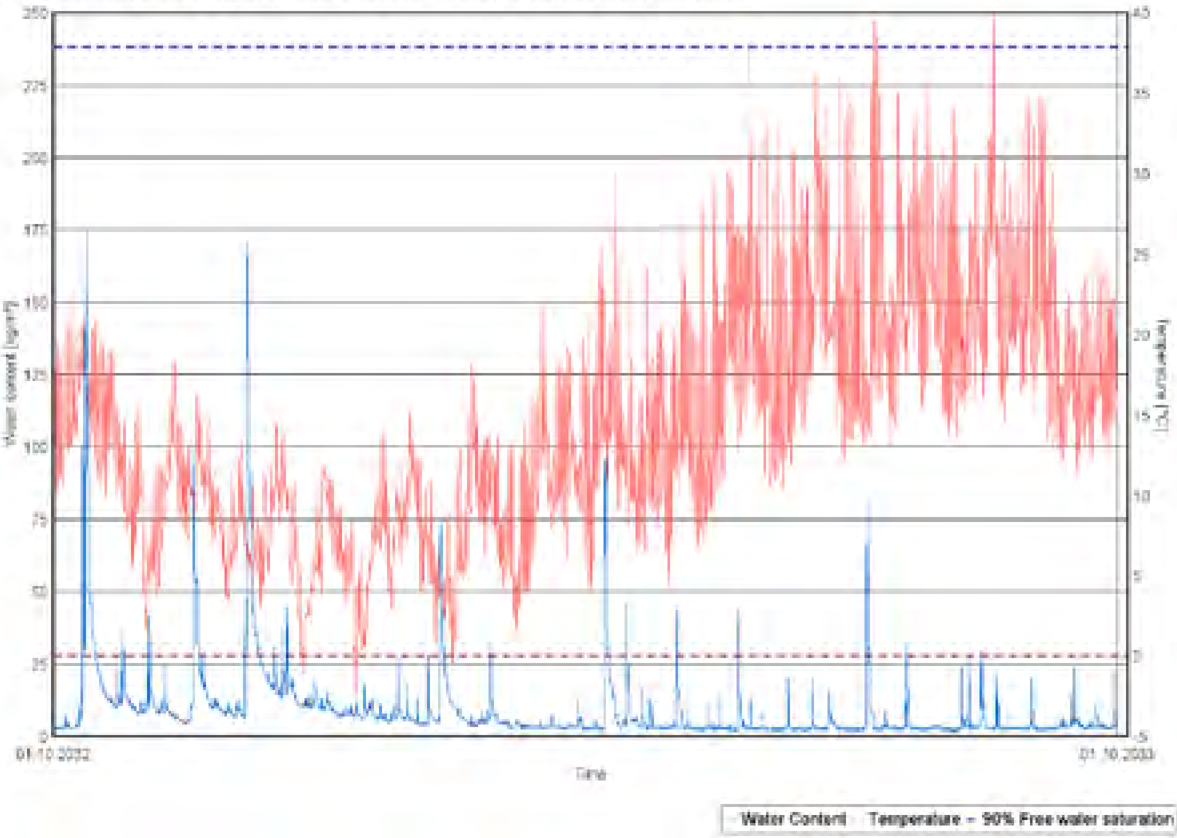
Front Elevation - Brick 1: Water Content and Temerature of external face (10mm thick)



Front Elevation - Brick 2: Water Content and Temerature of external face (10mm thick)



Front Elevation - Brick 3: Water Content and Temperature of external face (10mm thick)



6 Conclusions

The analysis of the internal wall insulation (IWI) system at 26 Eversleigh Road was based on the assessment of the risks against mould growth, degradation of the embedded timber joist ends within the wall due to rot, and deterioration of the external face of the bricks due to freeze-thaw cycles utilising numerical modelling according to BS EN 15026.

The assessment of the mould growth risk showed that mould could be present in hidden cavities or air pockets between the pre-existing internal plaster and the IWI system, where indoor air can access in the front elevation and the rear elevation.

The assessment of the risk of deterioration of the timber joist ends due to rot illustrated the high possibility that timber degradation is likely to be occurring in the front and the rear elevations.

Lastly, the assessment against the risk of freeze-thaw deterioration indicated no high risk for the external face of the front and the rear elevation to suffer from spalling or face loss.

7 Caveat and Context

The results presented in this analysis have been produced by WUFI Pro which is a one-dimensional software and therefore not ideal for bridged structures with more complex geometry. Also, the impact of the type of mortar in the brick wall has not been taken into account in this study.

In regard to the assessment of each modelling case, there is not a clear set of moisture risk assessment criteria agreed upon within the industry yet, especially as different build-ups of materials and applications will require different criteria. Therefore, the criteria used by the author are based on guidance from the Fraunhofer Insitut and from the relevant bibliography.

Furthermore, the simulations are based on synthetic climate data and not measured climatological data for the project's location.

Lastly, even if construction imperfections have been part of our models (imperfect airtightness), the assessment is based on the assumption that the building will be well maintained (e.g. gutters & pipes). Prolonged unmanaged water ingress will exceed the ability of the build-up to manage moisture.

8 References

- BS 5250. (2021). Management of moisture in buildings — Code of practice.

- Fraunhofer IBP. (2013, June 13). Criteria for Evaluating Hydrothermal Performance. Retrieved from WUFI - Wiki

- Little J., Ferraro C., & Arregi B. (2015). Historic Environment Scotland Technical Paper 15: Assessing risks in insulation retrofits using hygrothermal software tools. Edinburgh: Historic Environment Scotland

<u>Condensation risk assessment, moisture modelling and existing standards</u>

A number of existing standards and guidelines relating to insulation and the assessment and control of moisture risks are relevant to this project. These are outlined below:

- BEIS Retrofit Internal Wall Insulation – Guide to Best Practice, 2021

The Department for Business, Energy & Industrial Strategy recently released new guidance concerning internal wall insulation relating to Retrofit.

This guide can be used to assess: viability of internal wall insulation or systems, the design of internal wall insulation, and the selection of materials including hygrothermal aspects. It also provides information on best practice for internal wall insulation.

- BS 5250:2021 Management of moisture in buildings — Code of practice

Recommendations and guidance on avoiding problems with high moisture levels and condensation in buildings. Recommendations given are based on common forms of construction in the UK.

It gives guidance on the risks associated with excessive humidity in buildings, notably mould growth and condensation, which can endanger the health and well-being of building occupants and the integrity of the building fabric. It describes the principal sources of water vapour, its transportation and deposition and provides guidance on how to manage those risks during the design, construction and operation of buildings.

- BS EN ISO 13788:2012 Hygrothermal performance of building components and building elements. Internal surface temperature to avoid critical surface humidity and interstitial condensation. Calculation methods.

Gives calculation methods for the internal surface temperature of a building component or building element below which mould growth is likely, given the internal temperature and relative humidity - the method can also be used to assess the risk of other internal surface condensation problems. Also looks at the method for assessment of the risk of interstitial condensation due to water vapour diffusion and the time taken for water, from any source, in a layer between two high vapour resistance layers to dry out and the risk of interstitial condensation occurring elsewhere in the component during the drying process. Uses the 'Glaser' method, a steady state 1D vapour diffusion model with constant material properties.

This method is used in BS 5250:2011 and is the common method to assess the moisture balance of a building component by considering vapour diffusion transport in its interior. However, this method does not allow for the capillary moisture transport in the component, nor for its sorption capacity, both of which reduce the risk of damage in case of condensation. Furthermore, since the method only considers steady-state transport under heavily simplified boundary conditions, it cannot reproduce individual short-term events or allow for rain and solar radiation. The approach also misses out that: some materials are hygroscopic (i.e. liquid water stored in pores), some materials can start wet from built in water or rain ingress during construction, material properties are affected by moisture content and that 2D and 3D flows can be important.

- BS EN 15026:2007 Hygrothermal performance of building components and building elements. Assessment of moisture transfer by numerical simulation

Standard defining the practical application of hygrothermal simulation software used to predict one-dimensional transient heat and moisture transfer in multi-layer building envelope components subjected to non-steady climate conditions on either side. Specifies the equations for heat and moisture transport and storage, which are coupled (meaning that one affects the other). This is the "dynamic" approach implemented in WUFI.

The transient models covered in this standard take account of heat and moisture storage, latent heat effects, and liquid and convective transport under realistic boundary and initial conditions, therefore providing more detailed and accurate information on the risk of moisture problems within building components and on the design of remedial treatment.

Appendix 8: Hawthorn Road: hygrothermal risk analysis report

Konstantinos Megagiannis (QODA)

QODA

80065 – CIBSE UKRI Retrofit Revisit

Hawthorn Road - Hygrothermal Performance Assessment Report

QODA

Revision Summary

Issue	Document prepared			Document checked		
	Name	Signature	Date	Name	Signature	Date
v1	Konstantinos Megagiannis	KM	21/08/2023			

Contents

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1 Executive Summary

QODA Consulting was commissioned to assess the moisture-related risks of the installed internal wall insulation (IWI) at 10 Hawthorn Rd, utilizing the WUFI Pro heat and moisture modelling software, in accordance with BS EN 15026.

The assessment of the mould growth risk showed that mould could be present in hidden cavities or air pockets between the pre-existing internal plaster and the IWI system, where indoor air can access in the front elevation and the rear elevation.

The assessment of the risk of deterioration of the timber joist ends due to rot illustrated the high possibility that timber degradation is likely to be occurring in the front elevation.

Lastly, the assessment against the risk of freeze-thaw deterioration indicated no high risk for the external face of the front and the rear elevation to suffer from spalling or face loss.

1.1 Disclaimer

QODA Consulting uses its reasonable endeavours to provide accurate and authoritative information in respect of this report. The Client accepts that the areas of hygrothermal assessment and proper measurement of all hygrothermal characteristics of building materials are emerging, but separate and related disciplines. Assumptions are adopted and assessments are therefore undertaken where large areas of uncertainty exist, namely in respect of, material properties, climate, care of construction and building usage. QODA Consulting's methodology is designed to deal with and limit uncertainty by simulating scenarios and using these simulations to provide recommendations. QODA Consulting does not provide any warranty of any kind with regard to the output of the simulations and resulting information. Such information should be used with care, by professionals who understand the implications of the information and are able to make their own assessment of the results.

2 Introduction

2.1 Aim of the report

QODA Consulting was commissioned to undertake numerical modelling according to BS EN 15026 using the WUFI Pro heat and moisture modelling software, to understand the hygrothermal performance of the internal wall insulation (IWI) at 10 Hawthorn Rd, London N8 7NA, UK.

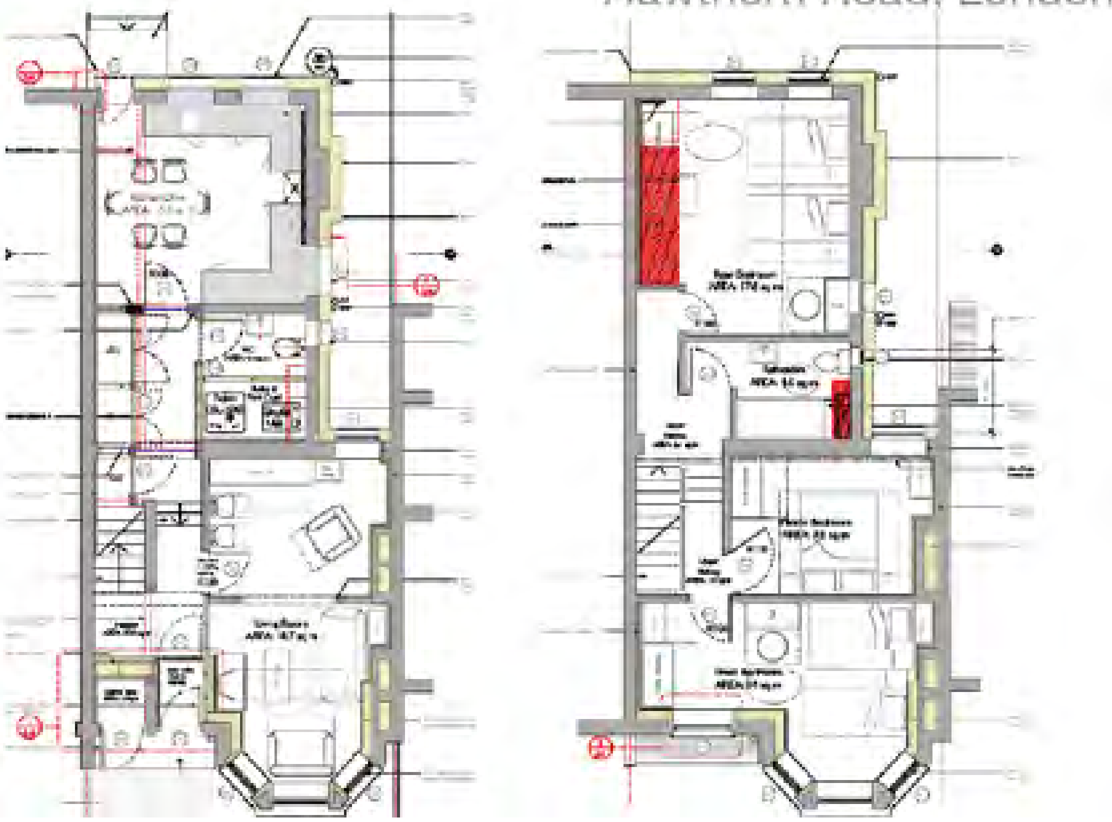
2.2 Context

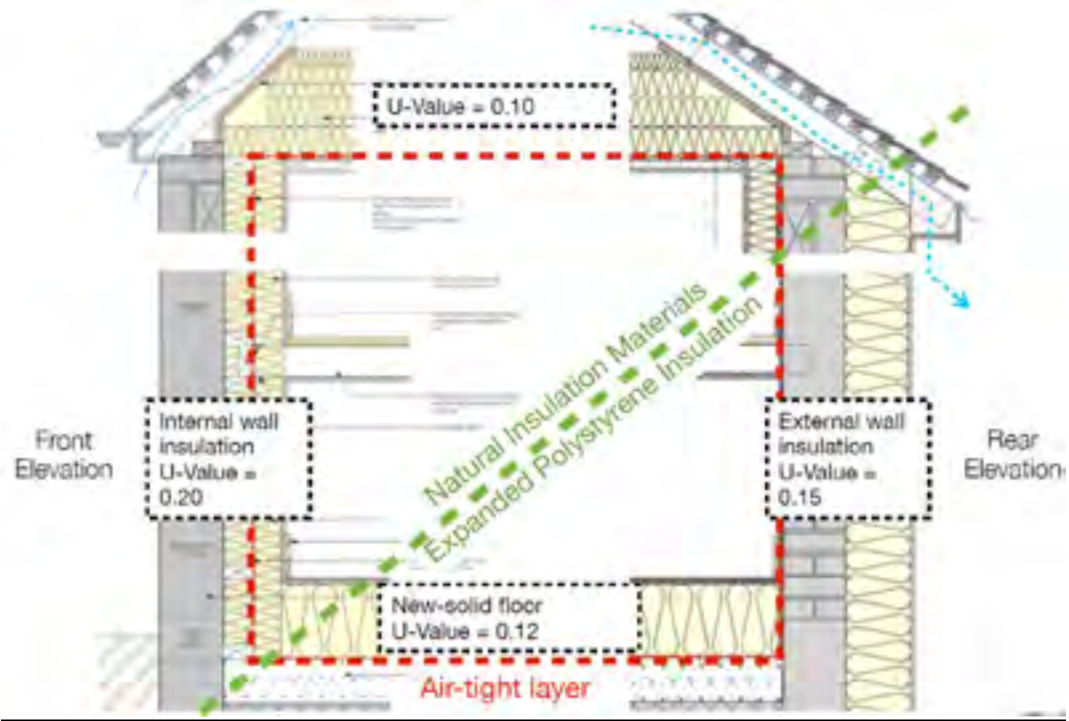
The examined building, an Edwardian terrace house near Alexandra Palace, London, was built as two flats, and is being combined into one 3-bedroom house. It has 225mm solid brickwork walls with timber floors and tiled/slated roofs, with 102mm thick party walls and a two storeys back extension.

The property was retrofitted in 2010 as part of the 'Retrofit for the future' scheme, with the aim to improve energy efficiency and carbon consumption, with a target of an 80% reduction in carbon emissions. A whole-house approach to the improvement of the home was implemented, embracing the building fabric (insulation, air tightness and thermal bridging) and the building services (heating, hot water, ventilation)

The insulation strategy regarding the external walls' insulation is external at the rear of the house and internal at the front of the house driven largely by external appearance and its location in Campsbourne Cottages Conservation Area. This study will be focusing on the analysis of the internal wall insulation of the North-oriented front façade.

Hawthorn Road, London





3 Methodology

3.1 Assessment method

The British Standard BS 5250:2021 Code of Practice for Management of Moisture in Buildings suggests that modelling as specified in standards such as BS EN ISO 13788 and BS EN 15026 is an appropriate method to assess and manage moisture risks.

BS EN ISO 13788 uses the 'Glaser' method, a steady state 1D vapour diffusion model with constant material properties and boundary conditions. This has been the common method to assess the moisture balance of a building component by considering vapour diffusion as the only moisture movement transport. However, this method does not allow for the capillary moisture transport in the component, nor for its sorption capacity, both of which reduce the risk of damage in case of condensation. Furthermore, since the method only considers steady-state transport under heavily simplified boundary conditions, it cannot reproduce individual short-term events or allow for rain and solar radiation. The approach also misses out that some materials are hygroscopic (i.e. liquid water stored in pores), some materials can start wet from built-in water or rain ingress during construction, and material properties are affected by moisture content.

On the other hand, BS EN 15026 is a standard that defines the practical application of hygrothermal simulation software used to predict one-dimensional transient heat and moisture transfer in multi-layer building envelope components subjected to non-steady climate conditions on either side. It specifies the equations for heat and moisture transport and storage, which are coupled (meaning that one affects the other). The transient models covered in this standard take account of heat and moisture storage, latent heat effects, and liquid and convective transport under realistic boundary and initial conditions, therefore providing more detailed and accurate information on the risk of moisture problems within building components and on the design of remedial treatment. This is the "dynamic" approach implemented in WUFI Pro 6.5, which is the software tool used in this study.

Even so, numerical simulations, such as WUFI, also have limitations in regard to how accurately they can model reality. As it is one-dimensional, it is not ideal for bridged structures with more complex geometry. Moreover, there is limited ability to simulate the microclimate at the project's site. More limitations are listed of this in the Caveat and Content section at the end of this report. Lastly, even if construction imperfections have been part of our models, the assessment assumes that the building will be well maintained (e.g., gutters & pipes).

3.2 Assessment risk criteria

There is not a clear set of moisture risk assessment criteria agreed upon within the industry yet, especially as different build-ups of materials and applications will require different criteria. The following criteria are used for the analysis of this WUFI modelling work:

- Assessment of the risk of mould growth

Studies have shown that moulds can germinate and grow if the relative humidity (RH) at a surface rises above 80% (BS 5250).

- Assessment of risk of decay in timbers in contact with the masonry.

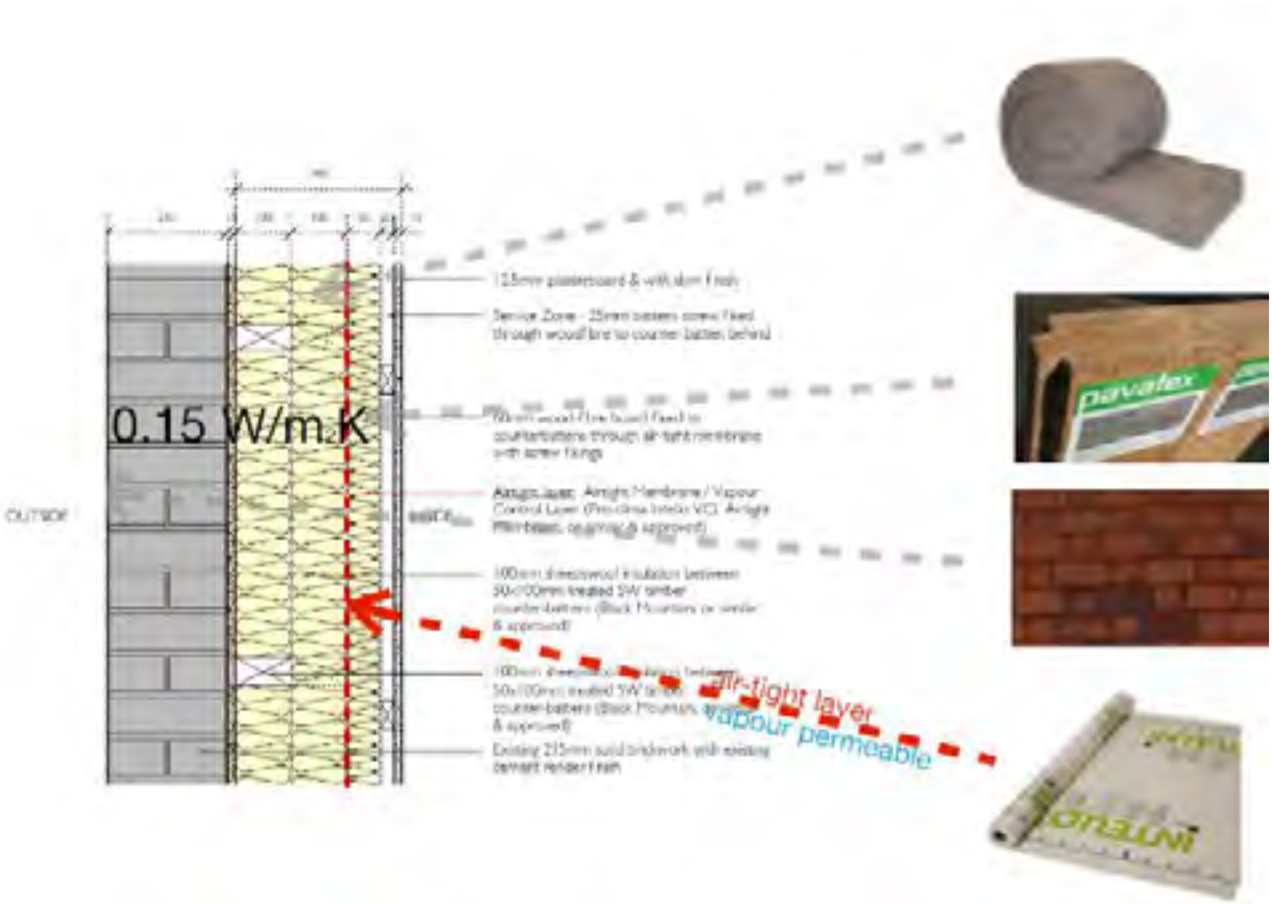
Persistent timber moisture contents in excess of 20 % (by mass) can lead to deterioration due to rot (BS 5250).

- Assessment of risk of deterioration due to freezing and thawing

A threshold of 90% water content when temperatures are below 0ºC has been selected to assess the risk of the exterior face of the brick deteriorating due to surface spalling or face loss as a result of the freeze-thaw action.

3.3 Selection of materials

The IWI system that this study focused on is presented below:



Whilst the relevant material properties of modern construction materials are reasonably consistent and well understood (e.g. gypsum plasterboard and polyisocyanurate insulation), there is currently a lack of properly tested data for existing bricks, stones, and plasters in the UK. Furthermore, no measurements of the hygrothermal properties of the construction materials of this building have been conducted. Therefore, the author has picked out a number of different materials to test a range of hygrothermal properties that are likely to match the properties of the existing construction materials of this building. This 'bracketing' approach is considered best practice in the context of missing information and in this study, it has been implemented to the materials that are believed to be the most influential in terms of the hygrothermal behaviour of each build-up. More specifically, 3 different bricks have been tested in the simulation of the front elevation build-up.

Front Elevation:

	WUFI Material	**Water Absorption Coef. A-value (kg/m²√s)**	**Reference Water Content, w_{80} (kg/m³)**	**Free Water Saturation, w_f (kg/m³)**
Brick 1	Solid Brick, historical	0.36	4.5	230
Brick 2	Solid Brick ZC	0.183	3.1	188
Brick 3	Solid Brick ZM	0.116	5	264

To simulate the sheepwool insulation, the *thermalan iso / swisswool iso / tirowool iso* material from the Fraunhofer database has been used. This is the only material in the WUFI database for a sheepwool insulation and given that the exact product used in this project is unknown, its default values in terms of its hygrothermal properties have been used in our analysis, as shown in the following table.

WUFI Material	**Thermal Conductivity (W/mK)**	**Buk density (kg/m³)**	**Porosity (m³/m³)**	**Specific Heat Capacity (J/kgK)**	**Water Vapour Diffusion Resistance Factor (-)**
thermalan iso / swisswool iso / tirowool iso	0.036	26.2	0.978	1650	1.8

To simulate the sheepwool insulation, the *Wood-fibre Insulation Board* material from the Fraunhofer database has been used.

WUFI Material	**Thermal Conductivity (W/mK)**	**Buk density (kg/m³)**	**Porosity (m³/m³)**	**Specific Heat Capacity (J/kgK)**	**Water Vapour Diffusion Resistance Factor (-)**
Wood-fibre Insulation Board	0.042	155	0.981	1400	3

4 Numerical models: Inputs

4.1 Materials

Materials				**Hygrothermal Properties**					
Layer	**WUFI Material**	**Source**	**Thickness (mm)**	**Bulk Density (kg/m3)**	**Porosity (m3/m3)**	**Heat Capacity (J/KgK)**	**Thermal Conductivity (W/mk)**	**Vapour Diffusion Resistance Factor (-)**	**Water Absorption Coef. A-value (kg/m²√s)**
1	Solid Brick, historical	Fraunhofer IBP	225	1800	0.31	850	0.6	15	0.36
	Solid Brick ZC	MASEA	225	1985	0.28	836	0.908	23	0.183
	Solid Brick ZM	MASEA	225	1720	0.35	937	0.547	19	0.116
2	Lime Plaster (for salt extraction, A-value: 10.2 kg/m2h0.5)	Fraunhofer IBP	15	1600	0.33	850	0.7	12	0.17
3	thermalan iso / swisswool iso / tirowool iso	Fraunhofer IBP	100	26.5	0.978	1650	0.036	1.8	0.000342
4	thermalan iso / swisswool iso / tirowool iso	Fraunhofer IBP	100	26.5	0.978	1650	0.036	1.8	0.000342

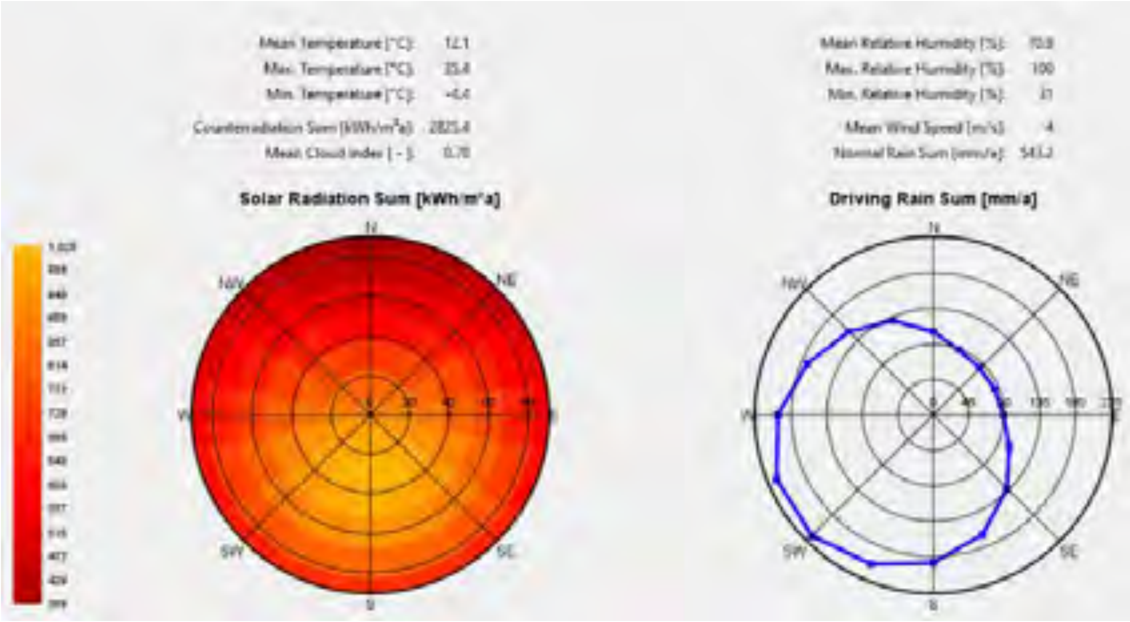
5	INTELLO PLUS (ETA)	Fraunhofer IBP	1	110	0.086	2500	2.4	3400 (variable)	-
6	Wood-fibre Insulation Board	Fraunhofer IBP	60	155	0.981	1400	0.042	3	0.007
7	Air Layer 25 mm; without additional moisture capacity	Fraunhofer IBP	25	1.3	0.999	1000	0.155	0.51	-
8	Gypsum Board	Fraunhofer IBP	15	850	0.65	850	0.19	8.3	0.287

4.2 Initial Conditions

To realistically estimate the initial conditions of the build-up, a simulation for 5 years pre-retrofit was conducted in the relevant orientations. The water content of the brick and the plaster at the end of this simulation was used as an initial water content in the following simulations post-retrofit.

4.3 External climate

For this simulation, a synthetic weather file for a "Design Reference Year" is created for the project's location, following the procedure set out in BS 15026. The "Design Reference Year" is constructed to cause the most severe conditions likely to occur once every 10 years. A summary of the weather data included in the synthetic weather file for a "Design Reference Year" is displayed below.


Mean Temperature [°C]: 12.1
Max. Temperature [°C]: 35.4
Min. Temperature [°C]: -4.4
Counterradiation Sum [kWh/m²a]: 2825.4
Mean Cloud Index [-]: 0.70
Max. Relative Humidity [%]: 100
Mean Wind Speed [m/s]: 4
Solar Radiation Sum [kWh/m²a]
Driving Rain Sum [mm/a]
N
NE
NW
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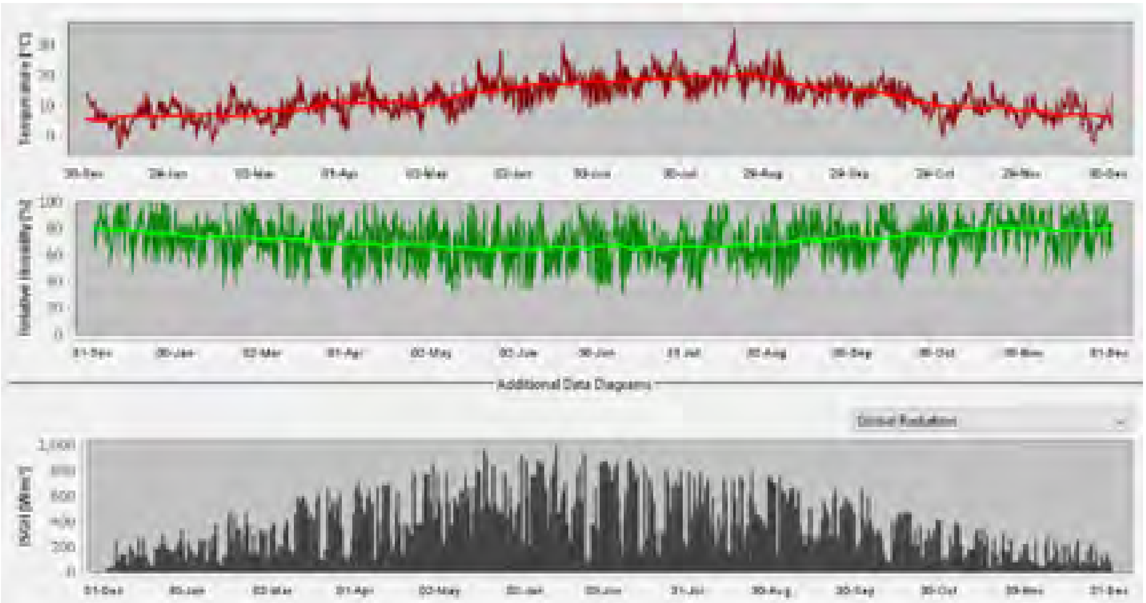
Temperature [°C]
Relative Humidity [%]
Additional Data Diagrams
Global Radiation

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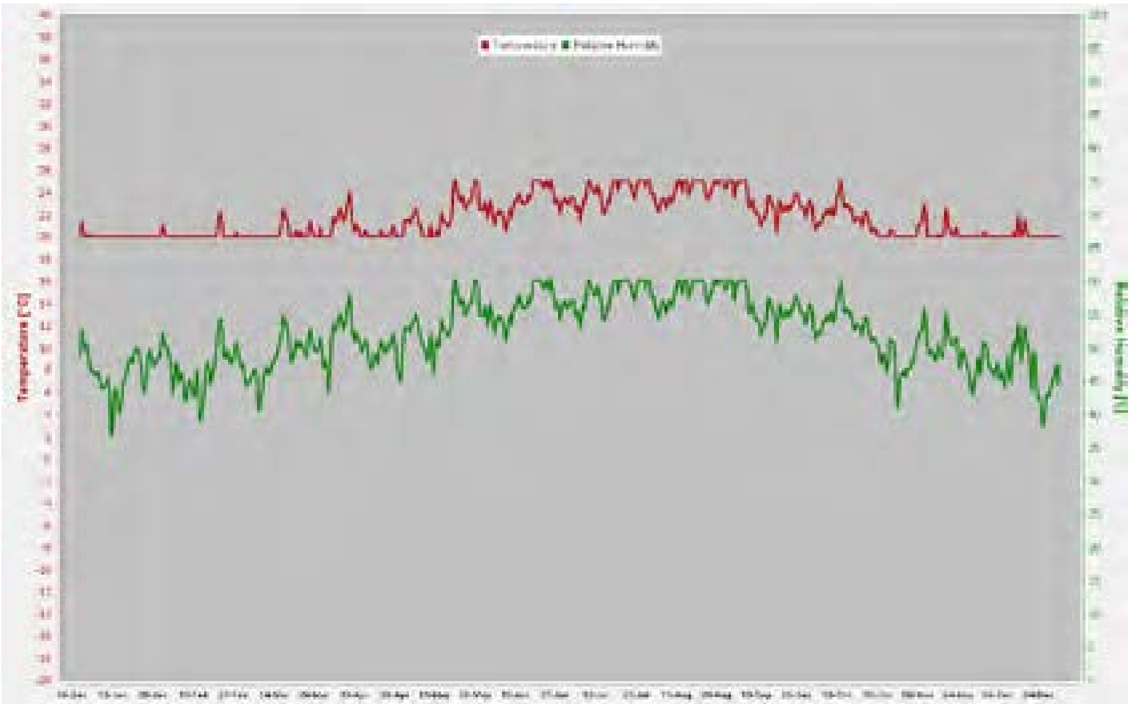
4.4 Indoor climate

BS EN ISO 15026 suggests that indoor conditions will vary between a medium to a high internal moisture load. Normal internal moisture load is typically considered with RH levels between 40 and 60%. High internal moisture load reaches higher RH levels and can be due to a combination of high levels of internal activities (cooking, showering, etc.) and a lack of adequate ventilation.

In this study, internal conditions are modelled as "Medium Moisture Load" in accordance with Annex C of BS EN 15026.



4.5 As-Built In-Situ Conditions

Issues such as liquid water penetration, air leakage due to construction faults and existing dampness should also be considered when assessing risks, as no 'perfect' build-up exists. The presence of an imperfect airtightness layer has been simulated with the addition of a moisture source based on an envelope infiltration of 5 q50 ($m^3/(m^2h)$) onto the wall build-up.

4.6 Other WUFI Model Parameters

Below, some additional information regarding the cases modelled is listed:

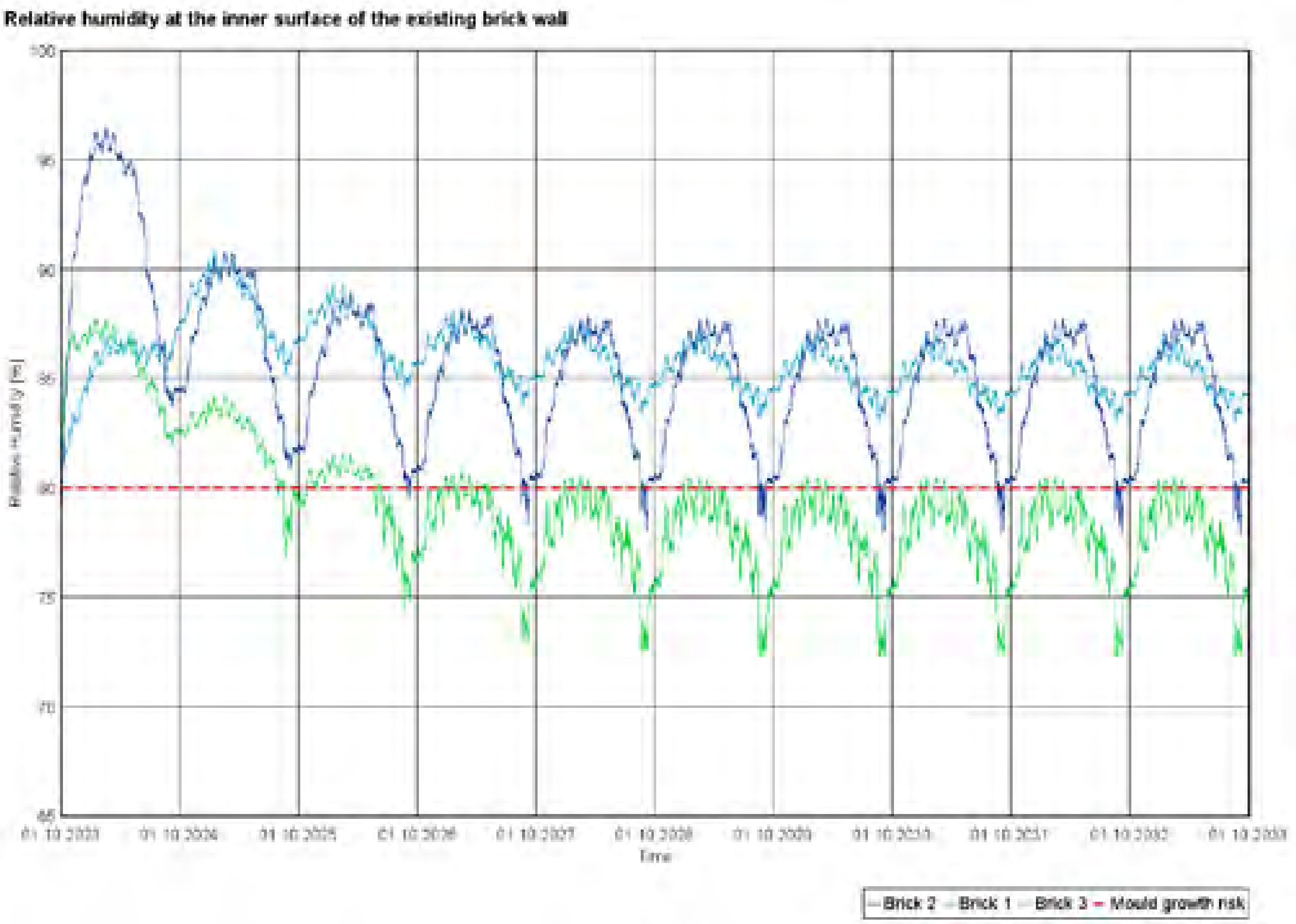
- A 1-hour time increment was chosen for all WUFI models.
- A 10-year total modelling period was used on all the WUFI models (with a 1st October start date).

5 Results and Analysis

5.1 Assessment against mould growth

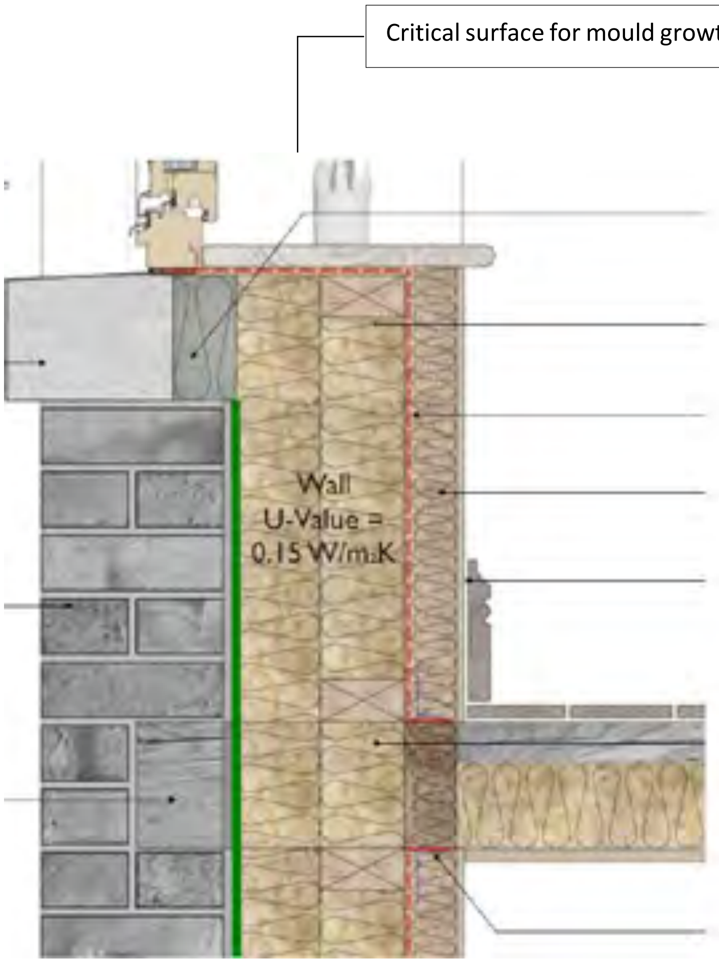
To assess the risk of mould growth, the relative humidity levels at the inner face of the existing brick wall were assessed against the threshold of 80% RH for each modelling case. The graph in this page displays the relative humidity levels at this critical surface.

The relative humidity levels at this critical surface remain above the threshold of 80% RH in the modelling cases related to Brick 1 and Brick 2. More specifically, the relative humidity levels on this surface in the Brick 1 modelling case (most absorbent brick) fluctuates around 85% RH throughout the simulation period, once an equilibrium state is reached, whilst in the Brick 2 modelling case (less absorbent brick) the RH levels fluctuate between 80% and 87%.



On the other side, in the modelling case related to Brick 3 (least absorbent brick), a decrease in the RH levels is observed until an equilibrium state is reached with fluctuations between approximately 73-80% RH.

The results show that mould might be present in hidden cavities or air pockets between the pre-existing internal plaster and the sheepwool insulation where indoor air can access, if the existing brick has a water absorption similar to this of Brick 2 or worse. Nevertheless, if the existing brick is less absorptive (similar to Brick 3), it is not likely that mould growth has occurred.



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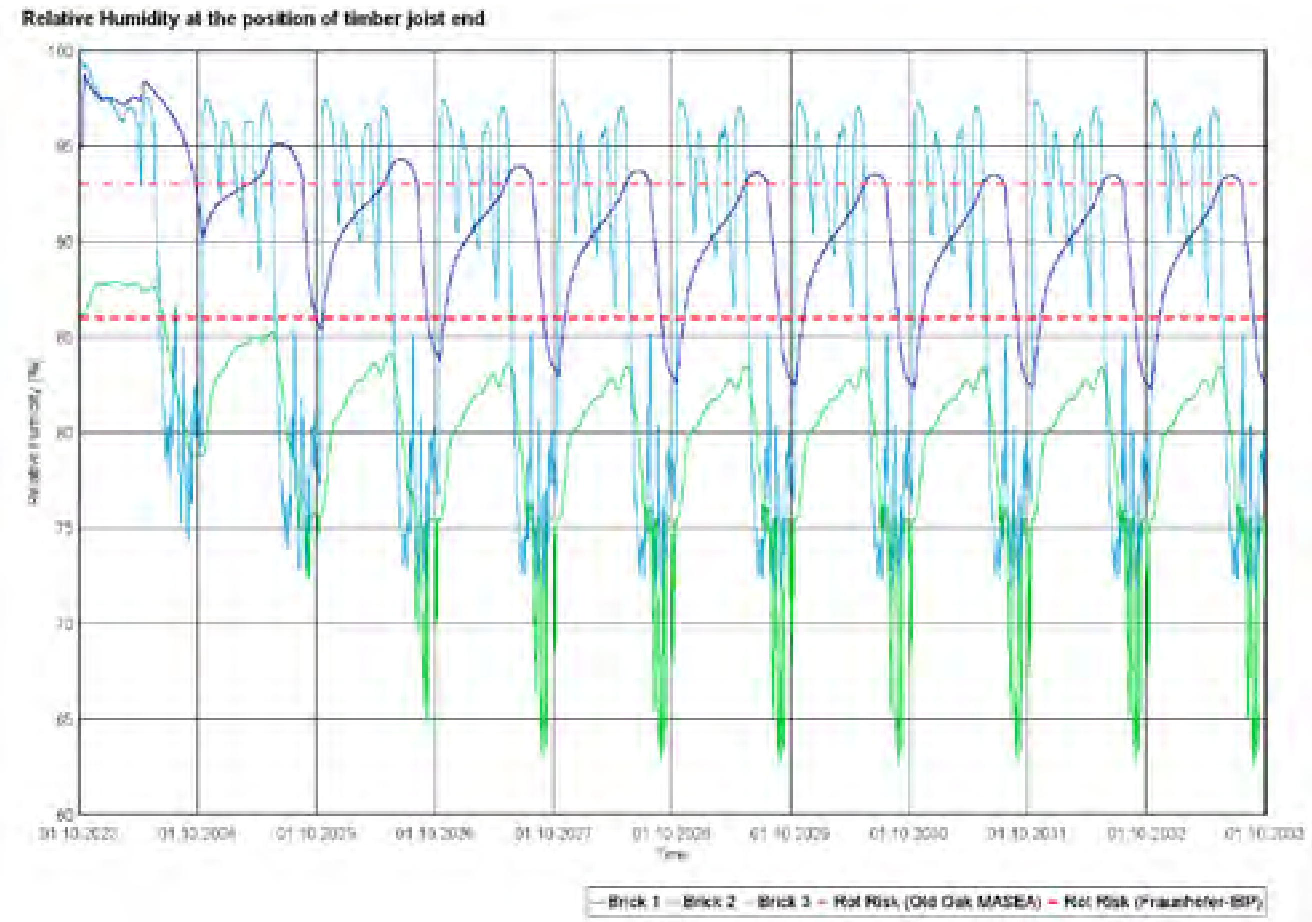
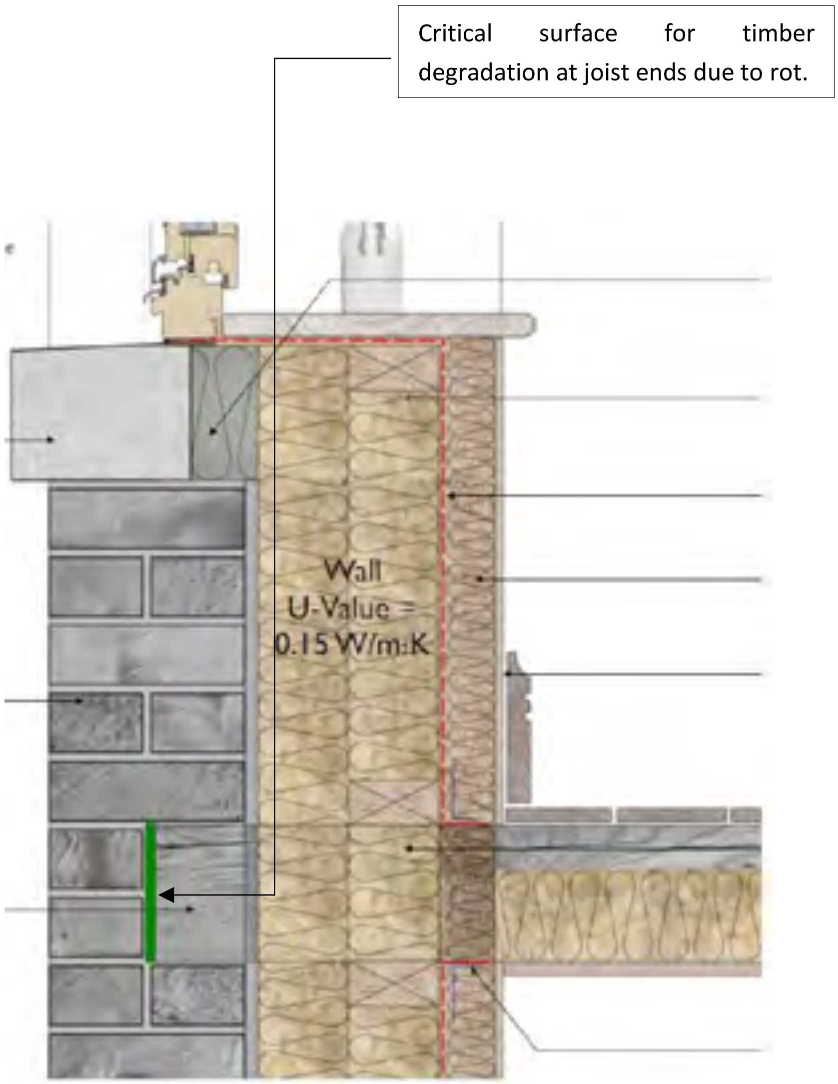
5.2 Assessment against timber rot risk

To assess the risk of timber joist degradation due to rot, the relative humidity levels at the end of the timber joists which are embedded in the external wall were assessed for each modelling against the threshold of 20% mass. Please note that it is assumed that timber joist ends are embedded in a depth of 100mm. To conduct this assessment, it was necessary to convert the water content as mass percentage to relative humidity levels. As there is uncertainty on the timber type of the joist conversion was conducted for 2 timber types that their hygrothermal properties were available in the WUFI database. More specifically, by using the moisture storage function and the porosity of each timber type, it was calculated that the 20% mass threshold corresponds to 86% RH for Oak (Fraunhofer IBP database) and 93% RH for Oak, Old (MASEA database).



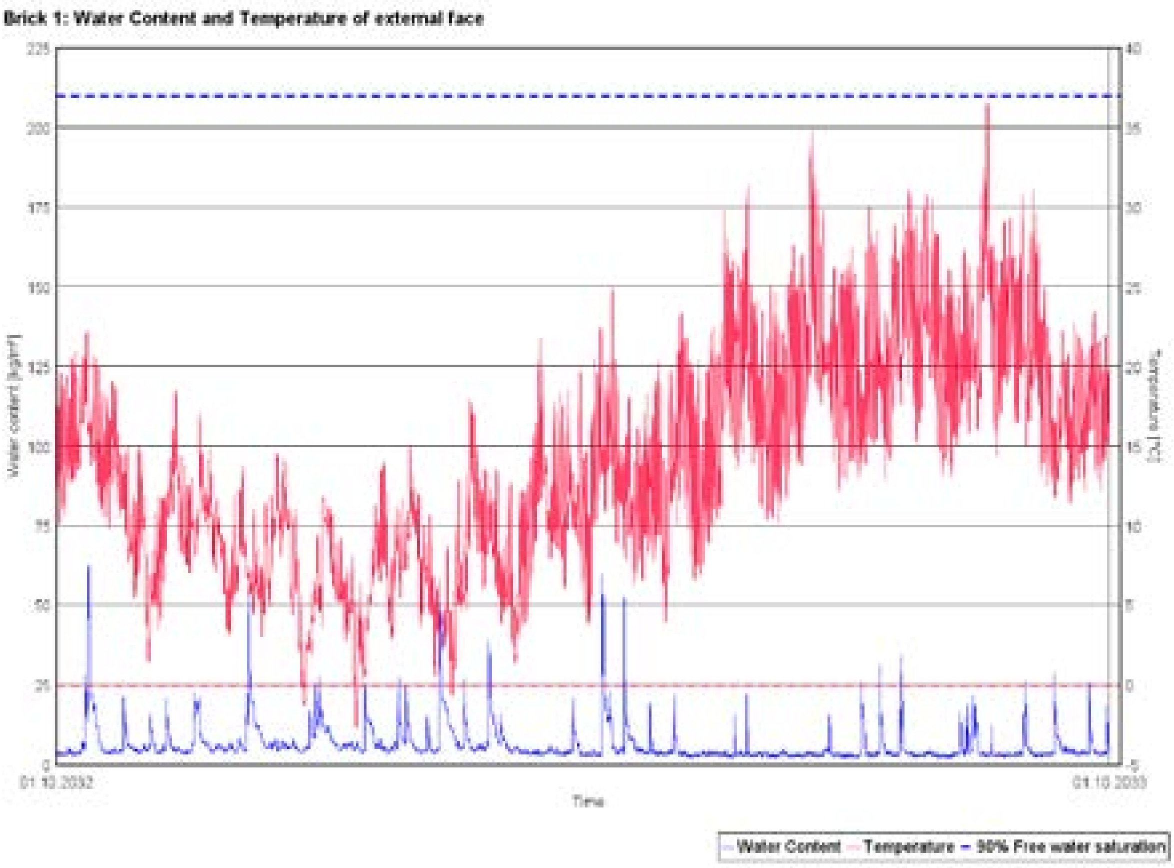
In the modelling case related to Brick 1, the threshold of 20% is exceeded for significant time periods regardless of the timber type. In the modelling case related to Brick 2, the threshold of 20% is not exceeded only with a timber type with high moisture storage function, such as Oak, Old (MASEA). The modelling case related to Brick 3 showed that a brick type with low absorption, such as Brick 3, would prevent the risk of decay due to rot in the timber joist ends, regardless of the timber type.



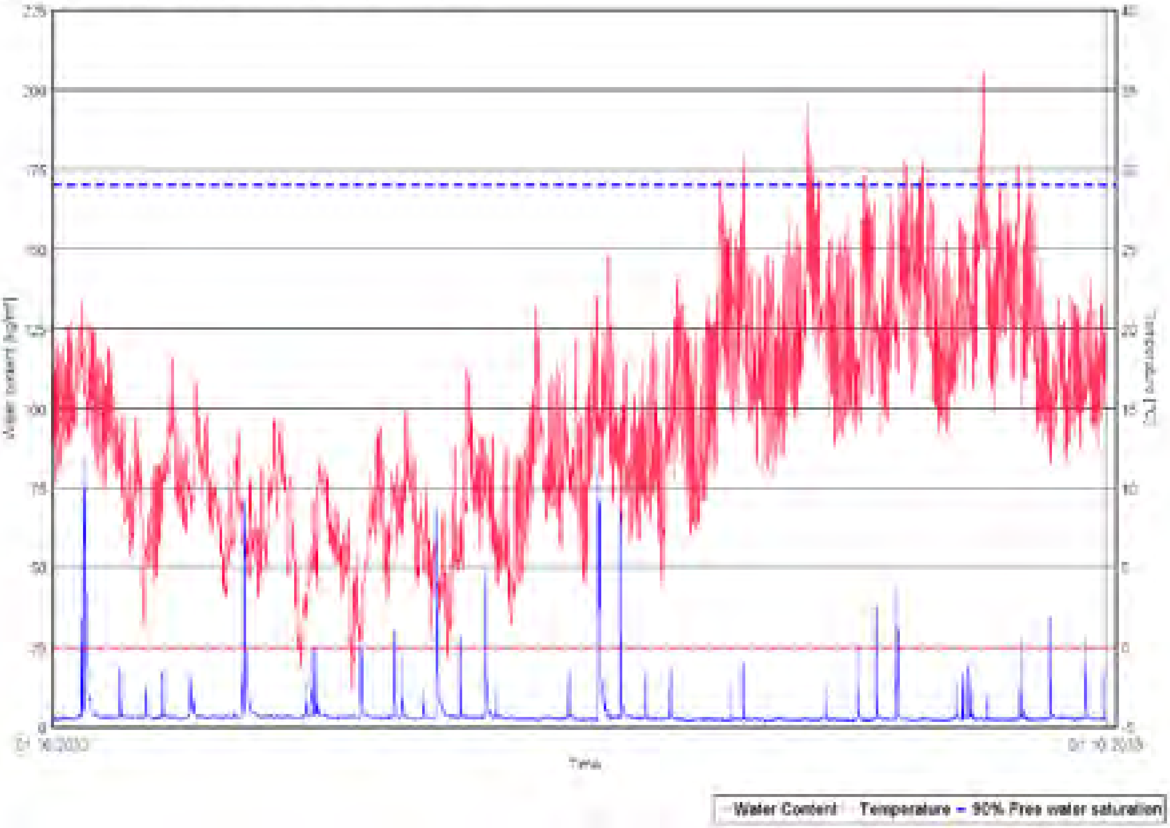
5.3 Assessment against freeze-thaw deterioration

The analysis to assess the risk of freeze-thaw deterioration analysis is based on the moisture content and the temperature of the external face of the brick. More specifically, the moisture content and the temperature of a 10mm thick sliver were analysed for each brick type, in order to determine how many freeze-thaw cycles it will undergo (i.e., how many times the water content of the silver will exceed the 90% free water saturation threshold while, at the same time, its temperature will be lower than 0 ºC).

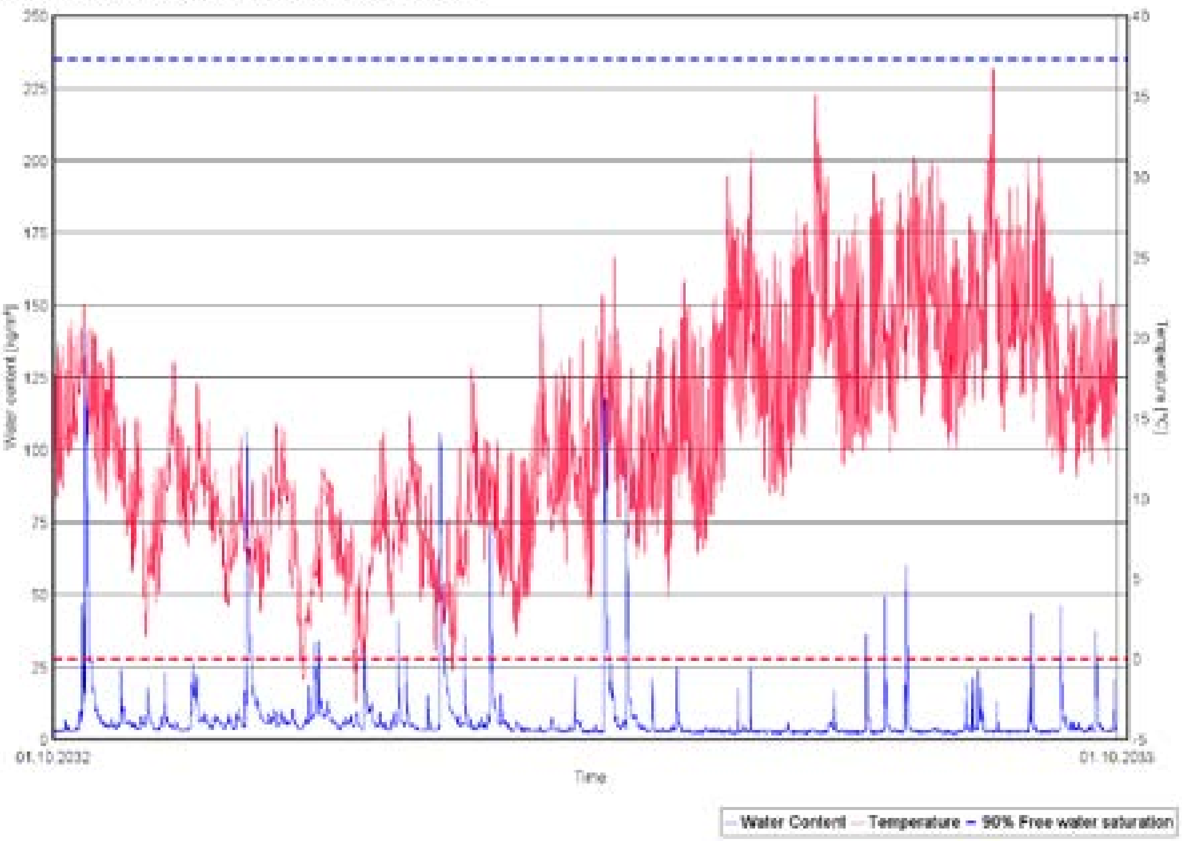
To conduct this assessment, graphs with the water content of the external 10mm thick brick sliver and its temperature for each brick type for 1 year once the build-up has reached an equilibrium phase were plotted. These graphs show that there is no occasion where the two conditions mentioned above are met, therefore no freeze-thaw cycles would be expected to occur.



Brick 2: Water Content and Temperature of external face



Brick 3: Water Content and Temperature of external face



6 Conclusions

The analysis of the internal wall insulation (IWI) system at 10 Hawthorn Rd was based on the assessment of the risks against mould growth, degradation of the embedded timber joist ends within the wall due to rot, and deterioration of the external face of the bricks due to freeze-thaw cycles utilising numerical modelling according to BS EN 15026.

The assessment of the mould growth risk showed that mould could be present in hidden cavities or air pockets between the pre-existing internal plaster and the IWI system, where indoor air can access in the front elevation and the rear elevation. However, if the existing brick has low absorption (similar to Brick 3 in this study), the risk of mould growth is significantly lower.

The assessment of the risk of deterioration of the timber joist ends due to rot illustrated the high possibility that timber degradation is likely to be occurring in the front elevation. This risk is also directly related to the absorptivity of the brick, as a brick type with low absorption, such as Brick 3, would prevent the risk of decay due to rot in the timber joist ends, regardless of the joist timber type.

Lastly, the assessment against the risk of freeze-thaw deterioration indicated no high risk for the external face of the front and the rear elevation to suffer from spalling or face loss.

7 Caveat and Context

The results presented in this analysis have been produced by WUFI Pro which is a one-dimensional software and therefore not ideal for bridged structures with more complex geometry. Also, the impact of the type of mortar in the brick wall has not been taken into account in this study.

In regard to the assessment of each modelling case, there is not a clear set of moisture risk assessment criteria agreed upon within the industry yet, especially as different build-ups of materials and applications will require different criteria. Therefore, the criteria used by the author are based on guidance from the Fraunhofer Insitut and from the relevant bibliography.

Furthermore, the simulations are based on synthetic climate data and not measured climatological data for the project's location.

Lastly, even if construction imperfections have been part of our models (imperfect airtightness), the assessment is based on the assumption that the building will be well maintained (e.g. gutters & pipes). Prolonged unmanaged water ingress will exceed the ability of the build-up to manage moisture.

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8 References

- BS 5250. (2021). Management of moisture in buildings — Code of practice.

- Fraunhofer IBP. (2013, June 13). Criteria for Evaluating Hydrothermal Performance. Retrieved from WUFI - Wiki

- Little J., Ferraro C., & Arregi B. (2015). Historic Environment Scotland Technical Paper 15: Assessing risks in insulation retrofits using hygrothermal software tools. Edinburgh: Historic Environment Scotland

<u>Condensation risk assessment, moisture modelling and existing standards</u>

A number of existing standards and guidelines relating to insulation and the assessment and control of moisture risks are relevant to this project. These are outlined below:

- BEIS Retrofit Internal Wall Insulation – Guide to Best Practice, 2021

The Department for Business, Energy & Industrial Strategy recently released new guidance concerning internal wall insulation relating to Retrofit.

This guide can be used to assess: viability of internal wall insulation or systems, the design of internal wall insulation, and the selection of materials including hygrothermal aspects. It also provides information on best practice for internal wall insulation.

- BS 5250:2021 Management of moisture in buildings — Code of practice

Recommendations and guidance on avoiding problems with high moisture levels and condensation in buildings. Recommendations given are based on common forms of construction in the UK.

It gives guidance on the risks associated with excessive humidity in buildings, notably mould growth and condensation, which can endanger the health and well-being of building occupants and the integrity of the building fabric. It describes the principal sources of water vapour, its transportation and deposition and provides guidance on how to manage those risks during the design, construction and operation of buildings.

- BS EN ISO 13788:2012 Hygrothermal performance of building components and building elements. Internal surface temperature to avoid critical surface humidity and interstitial condensation. Calculation methods.

Gives calculation methods for the internal surface temperature of a building component or building element below which mould growth is likely, given the internal temperature and relative humidity - the method can also be used to assess the risk of other internal surface condensation problems. Also looks at the method for assessment of the risk of interstitial condensation due to water vapour diffusion and the time taken for water, from any source, in a layer between two high vapour resistance layers to dry out and the risk of interstitial condensation occurring elsewhere in the component during the drying process. Uses the 'Glaser' method, a steady state 1D vapour diffusion model with constant material properties.

This method is used in BS 5250:2011 and is the common method to assess the moisture balance of a building component by considering vapour diffusion transport in its interior. However, this method does not allow for the capillary moisture transport in the component, nor for its sorption capacity, both of which reduce the risk of damage in case of condensation. Furthermore, since the method only considers steady-state transport under heavily simplified boundary conditions, it cannot reproduce individual short-term events or allow for rain and solar radiation. The approach also misses out that: some materials are hygroscopic (i.e. liquid water stored in pores), some materials can start wet from built in water or rain ingress during construction, material properties are affected by moisture content and that 2D and 3D flows can be important.

- BS EN 15026:2007 Hygrothermal performance of building components and building elements. Assessment of moisture transfer by numerical simulation

Standard defining the practical application of hygrothermal simulation software used to predict one-dimensional transient heat and moisture transfer in multi-layer building envelope components subjected to non-steady climate conditions on either side. Specifies the equations for heat and moisture transport and storage, which are coupled (meaning that one affects the other). This is the “dynamic” approach implemented in WUFI.

The transient models covered in this standard take account of heat and moisture storage, latent heat effects, and liquid and convective transport under realistic boundary and initial conditions, therefore providing more detailed and accurate information on the risk of moisture problems within building components and on the design of remedial treatment.

Appendix 9: Results from fungal testing and visual inspection

Dr Valentina Marincioni (UKCMB) and
Spyros Efthymiopoulos (UKCMB)

RESULTS FROM FUNGAL TESTING AND VISUAL INSPECTION

Results summary table and appendices

v.2

Prepared by:

Spyros Efthymiopoulos

Checked by:

Dr Valentina Marincioni

Table 1: Summary of visual inspection, fungal testing and RH and particle concentration results

Property Location	Room	Depressurization test	Risk estimation based on fungal biomass quantification	Dominant Fungal species (>10%)	Visual Inspection, ventilation assessment and infrared imaging	RH and particle concentration measurements	Swab testing/ Dominant species	Fungal testing findings
Hawthorn	Bed	BD	Risk is deemed to be high (Class C).	Cladosporium sphaerospermum (98.48%)	No visual signs of mould or water damage were detected inside the property, including in the tested rooms (living room and bedroom) and the loft, although the occupants reported water damage on the sleeper wall. The flow rates from the MVHR seemed to be slightly imbalanced, with an average supply of 26.6 l/s and average extract of 18.8 l/s (in a three-bedroom house), measured with a rotating vane anemometer; the toilet extract seem to be clogged and allows an air flow rate of 0.4 l/s. Water damage on the external front façade has been detected. Further analysis of the damage is available in the report.	RH and particle counts were found to be within acceptable limits. However, the property was found to have markedly higher PM10 concentrations compared to the other properties tested.	Sample 1 (Loft Front rafter) Surface contamination level: Low Dominant species: Cladosporium cladosporides (75.86%) Wallemia sebi (13.34%) Sample 2 (Loft Back rafter) Surface contamination level: Low Dominant species: Cladosporium cladosporides (25.59%) Aspergillus versicolor (15.64%) Cladospo sphaerospermum (18.4%) Penicillium chrysogenum (11.13%) Penicillium expansum (12.66%) Wall Sample 3 (Bedroom Furniture) Surface contamination level: Low Dominant species: Aspergillus versicolor (13.22%) Cladosporium cladosporides (31.7%) Cladospori (18.19%) Cladosporium sphaerospermum (11.78%) Wallemia sebi (14.3%) Sample 4 (Bedroom Furniture) Surface contamination level: Low Dominant species: Aspergillus versicolor (14.73%) Cladosporium cladosporides (17.74%) Cladospo (29.75%) Tricoderma viride (12.54%) Wallemia sebi (12.89%) Sample 5 (Loft Front rafter) Surface contamination level: Low Dominant species: Cladosporium sphaerospermum (29.36%) Wallemia sebi (53.58%) Sample 6 (Loft Back rafter) Surface contamination level: Low Dominant species: Cladosporium cladosporides (42.76%) Wallemia sebi (40.78%) Sample 7 (Bedroom Door Frame) Surface contamination level: Low Dominant species: Cladosporium cladosporides (37.79%) Cladosporium herbarum (52.62%) Sample 8 (Bedroom Book shelf) Surface contamination level: Low Dominant species: Cladosporium cladosporides (30.41%) Cladosporium herbarum (56.71%)	An elevated risk of mould contamination was detected in the property. While mould growth was not detected during the visual inspection of the property, according to the Mycometer classification system the airborne levels indicate that a mould source was likely to exist especially in the bedroom. The species identification has also shown that the DNA copies of the targeted species were elevated compared to the other properties tested. However, the surface sampling in both the bedroom and loft did not indicate fungal contamination on the tested surfaces. The absence of visible mould in the tested rooms was also verified by the team during a follow-up visual inspection of the property after one month from the first visit. On the other hand, the allergens levels corresponded to values typically found in rooms without a mould growth source or with a good cleaning standard according to Mycometer's classification system. However, the concentration of PM10 was found to be high compared to the other properties tested, which might indicate the presence of particles other than allergens where spores can be suspended from. Further tests may be needed to determine whether potential hidden mould sources exist.
Hawthorn	LR	BD	Risk is deemed to be medium (Class B).	Cladosporium sphaerospermum (97.26%)				

Shaftesbury	LR	BD	Risk is deemed to be minor (Class A).	Aspergillus versicolor (79.32%)	No visual signs of mould or water damage were detected inside the property and no major maintenance issues were identified. A missing window seal strip in the bedroom is expected to have affected the air infiltration in the bedroom on the 1st floor but is not expected to produce any moisture-related issues in the room.	RH and particle counts were found to be within acceptable limits based on literature.	Results haven't been retrieved	The levels of fungi were found to be within the range typically found in rooms without visual growth or moisture-related issues (Class A) according to Mycometer's classification system. The air quality measurements also indicate that the ventilation system is maintaining good indoor air quality in the property and that the risk of mould growth is likely to be minimal.
Shaftesbury	Bed	BD	Risk is deemed to be minor (Class A).	Aspergillus versicolor (54.45%) Cladosporium sphaerospermum (24.97%)				
Shaftesbury	Bed	AD	Risk is deemed to be minor (Class A).	Aspergillus versicolor (32.48%) Cladosporium sphaerospermum (47.23%)				
Blaise	LR	BD	Risk is deemed to be medium (Class B).	Cladosporium cladosporides (15.01%) Cladosporium herbarum (13.46%) Aspergillus versicolor (54.63%)	No visual signs of mould or moisture damage were detected in the tested rooms (living room and bedroom) and in the loft. Signs of moisture damage were detected in the lower ground floor and are likely to have been caused by the proximity of the flue and vapour from the boiler to the balcony, combined with a gap on the VCL membrane (see evaluator's report).	RH and particle counts were found to be within acceptable limits based on literature.	*Sample 1 (Loft):* *Surface Contamination Level: High* *Dominant species:* *Aspergillus versicolor (95.21%)* *Sample 2 (Loft):* *Surface Contamination Level: High* *Dominant species:* *Aspergillus versicolor (99.4%)* *Samples analysed via microscopy:* *No traces of fungal contamination were found on the blown insulation collected from the loft*	The fungal levels were found to be medium-to-high – within the range typically found in rooms with an inadequate cleaning standard or potential fungal growth. As the Aspergillus versicolor species is often treated as an indoor moisture indicator, its dominance in the samples analysed via PCR indicates that despite the low RH spot measurements, the rooms may be prone to fungal growth. However, the number of DNA copies of the species in the samples suggest that fungal growth is likely not to be extensive and that further specialized tests might be needed to identify potential fungal growth sources, if any. No indication of ventilation faults or water damage-related issues were observed during the physical inspection in the tested rooms. In the loft, although no traces of fungal contamination were found on the blown insulation (possibly treated with fungicides), the fungal contamination level of the rafters seems to be high; this is in agreement with the high RH levels detected (see evaluator's report).
Blaise	Bed	BD	Risk is deemed to be high (Class C).	Cladosporium cladosporides (10.82%), Aspergillus versicolor (68.73%)				
Grove	LR	BD	Risk is deemed to be high (Class C).	Cladosporium cladosporides (29.55%) Aspergillus versicolor (34.49%) Wallemia sebi (18.40%)	No major visual signs of mould were detected in the property. Signs of past water damage were identified in the hall outside the living room and the team was informed that they appeared as a result of plumbing leaks. Formation of salts has been observed on the lower parts of the hall's walls, but no visible signs of mould were detected in the room. Small patches of mould and dampness were identified in the bathroom/toilet on the ground floor but the extract ventilation seemed to be functioning in the bathroom. A damp smell was detected in the basement, but no major visual	RH and particle counts were found to be within acceptable limits based on literature..	*Sample 1: Bathroom* *Surface Contamination Level: Low* *Dominant species:* *Aspergillus versicolor (17.9%) Cladosporium cladosporides (46.17%) Cladosporium sphaerospermum (23.48%)* *Sample 2: Hallway (past water damage)* *Surface Contamination Level: Low* *Dominant species:* *Cladosporium cladosporides (16.45%) Cladosporium sphaerospermum (12.33%) Wallemia sebi (44.57%)* *Sample3: Hallway (past water damage)* *Surface Contamination Level: Low* *Dominant species:* *Aspergillus versicolor (40.62%) Cladosporium sphaerospermum (17.4%) Wallemia sebi (14.69%)*	The fungal levels were found to be high -to-very high. This might be attributed to interstitial mould or mould growing at inaccessible locations. In fact the hypothesis of interstitial mould growth could be further supported by (a) the elevated DNA copies of the Aspergillus versicolor and Wallemia Sebi species (both species that if found in high levels indicate fungal growth due to water damage issues) and (b) the fact that higher concentration of the dominant species were detected after the depressurisation test. While a hypothesis regarding the reason behind the high fungal levels in the bedroom is yet to be formed, the team assumes that the levels in the living room might be connected to the past water damage in the hallway. The water damage might have affected water availability in the space
Grove	LR	AD	Risk is deemed to be high (Class C).	Cladosporium cladosporides (38.51%) Aspergillus versicolor (21.24%) Wallemia sebi (26.78%)				
Grove	Bed	BD	Risk is deemed to be high (Class C).	Cladosporium cladosporides (24.88%) Cladosporium herbarum (40.25%) Aspergillus versicolor (17.25%) Wallemia sebi (11.09%)				

					signs of water damage were observed.			underneath the floorboards and thus might have allowed the flourishing of mould.
80% House	Bed	BD	Risk is deemed to be minor (Class A).	Cladosporium cladosporides (28.34%) Cladosporium herbarum(29.31%) Aspergillus versicolor (27.34%)	No major visual signs of mould or water damage were detected in the property. Signs of dampness were identified on the top of a built-in bookshelf in the living room as result of plumbing leaks, but no visible signs of mould were detected in the room. Visual signs of mould and dampness were identified around the burst pipes connected to the bathroom/toilet. Infrared imaging was used to determine the extent of the leak.	RH and particle counts were found to be within acceptable limits based on literature.	*Sample 1: Bathroom (Water damage)* *Surface Contamination Level: Very High* *Dominant species:* *Aspergillus versicolor (99.31%)*	The levels of fungi were found to be within the range typically found in rooms without visual growth or moisture-related issues (Class A) according to Mycometer's classification system. The air quality measurements also indicate that the ventilation system is maintaining good indoor air quality in the property and that the risk of mould growth is likely to be minimal. The swab testing has shown a high fungal contamination of the surfaces affected by the plumbing leak in the bathroom and necessitates the implementation of remediations.
80% House	LR	AD	Risk is deemed to be minor (Class A).	Cladosporium cladosporides (23.29%) Cladosporium herbarum (11.20%) Acremonium strictum (54.88%)				

Abbreviations: Bed – Bedroom, LR – Living room, BD – Before depressurisation, AD – After depressurisation

Brief species description

Aspergillus versicolor is one of the most common species in the world and has often been used as an indicator of relative humidity in the indoor environment. Spores of the species can naturally be found in the indoor environment and are among the first species to grow when damp-related problems issues appear**.**

Acremonium strictum often appears in soil and dead plants in nature but could also indicate fungal contamination on surfaces such as concrete, plaster, wallpaper or woodwork, if found in high concentration indoors.

Cladosporium cladosporides can be found in higher concentrations outdoors during the summer and early autumn months but can also be deposited on house dust and flourish under low temperatures and alternating wet and dry conditions.

Cladosporium herbarum can be found in higher concentrations outdoors during the summer and early autumn months. Its spores may cause allergic reactions and if found in high concentrations indoors, they may indicate contamination of surfaces such as wallpaper or woodwork.

Cladosporium sphaerospermum can be found in higher concentrations outdoors during the summer and early autumn months. High indoor concentration of the species may indicate contamination of surfaces such as wallpaper or woodwork.

Wallemia sebi is one of the most frequent occurring moulds in damp environments according to HouseTest ApS. High airborne concentration of its spores may cause allergic reactions and discomfort to the occupants.

Appendix A – Percentage of Fungal Species

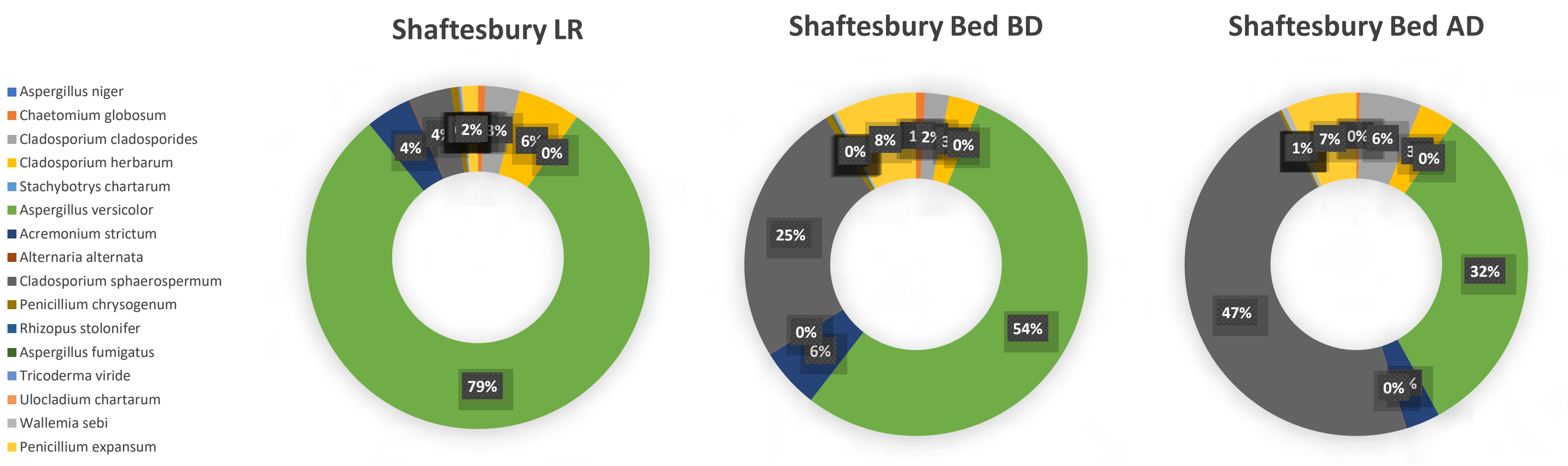
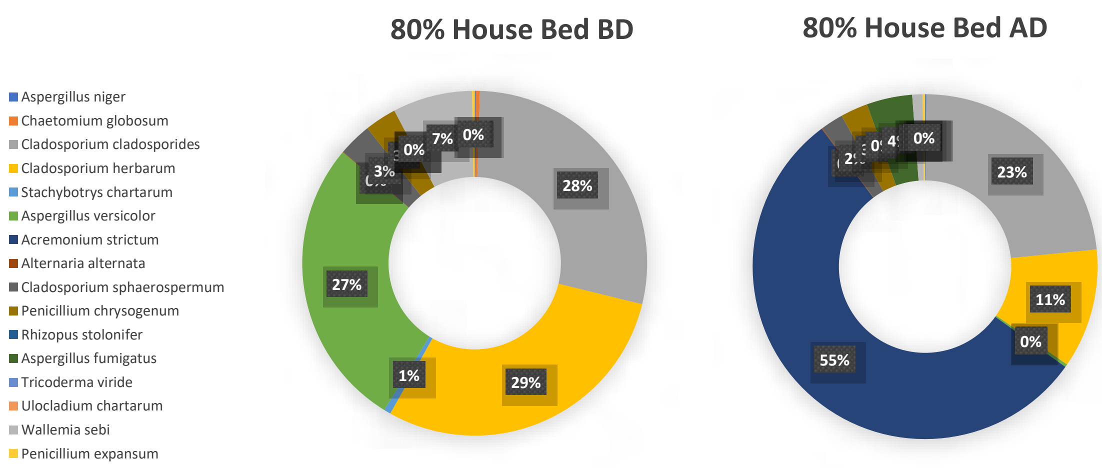


Figure 1: Percentage-wise distribution of the 16 fungal groups targeted in the rooms tested at the property located at Shaftesbury Park Terrace



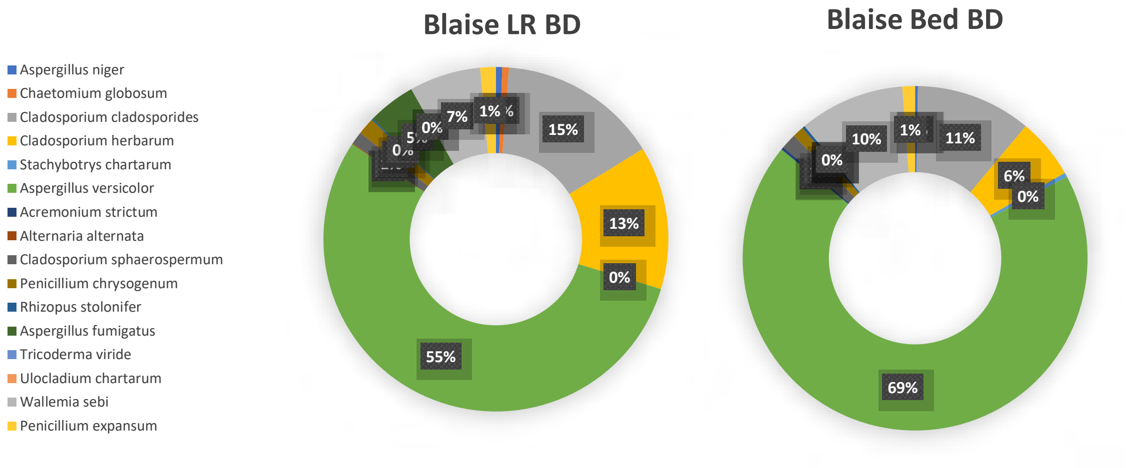


Figure 3: Percentage-wise distribution of the 16 fungal groups targeted in the rooms tested at the property located at Blaise Castle

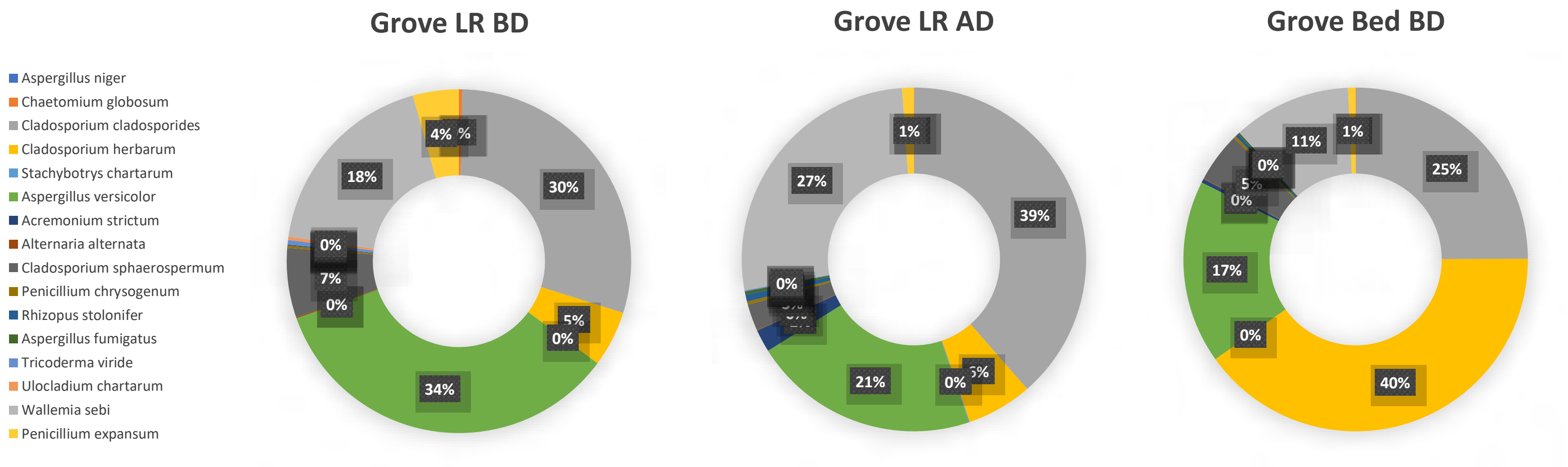


Figure 4: Percentage-wise distribution of the 16 fungal groups targeted in the rooms tested at the property located at Grove Cottage

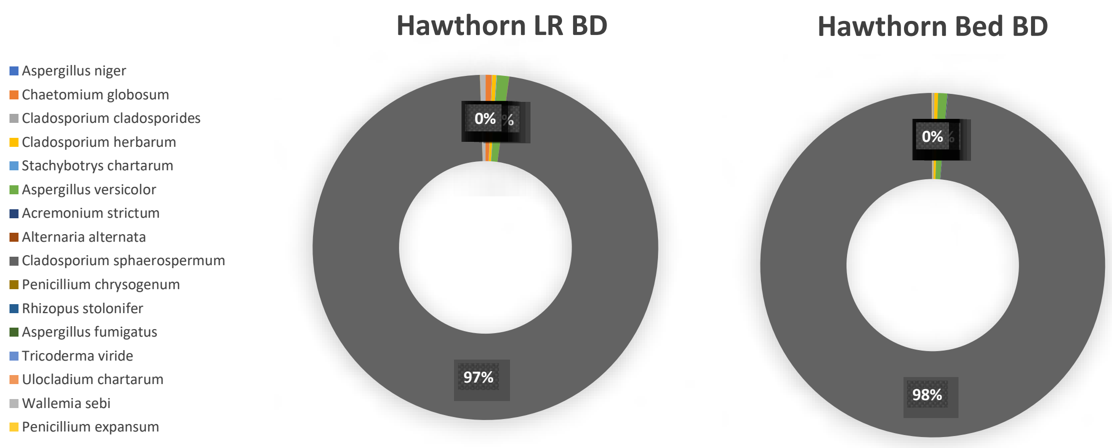


Figure 4: Percentage-wise distribution of the 16 fungal groups targeted in the rooms tested at the property located at Hawthorn Road

Appendix B – Basic Statistical Features of IAQ Measurements

Table 1: Summary of descriptive statistical features for spot indoor air quality measurements

Culford Bed BD	PM0.3 [Particle count]	PM0.5 [Particle count]	PM1.0 [Particle count]	PM2.5 [Particle count]	PM5.0 [Particle count]	PM10.0 [Particle count]	PMS1.0 (µg/m3)	PM2.5 (µg/m3)	PM 10.0 (µg/m3)	Temperature	RH
Average	287.5161	86.64516	30.96774	7.419355	2.16129	0.903226	0.258065	1.935484	4	21.56806	55.00129
St dev	88.6705	27.62915	10.26153	5.655524	2.050964	1.193171	0.444803	0.997847	2.75681	0.012225	0.272039
Min	150	49	18	0	0	0	0	0	1	21.55	54.6
Max	447	135	51	18	6	3	1	4	8	21.59	55.4

Culford Bed AD	PM0.3 [Particle count]	PM0.5 [Particle count]	PM1.0 [Particle count]	PM2.5 [Particle count]	PM5.0 [Particle count]	PM10.0 [Particle count]	PMS1.0 (µg/m3)	PM2.5 (µg/m3)	PM 10.0 (µg/m3)	Temperature	RH
Average	191.8065	54.54839	15.09677	2.032258	0.354839	0.354839	0.064516	0.774194	1.129032	20.71613	59.24581
St dev	50.86415	15.20929	5.055392	1.580799	0.550659	0.550659	0.249731	0.668814	1.117794	0.029629	0.317414
Min	123	32	5	0	0	0	0	0	0	20.66	58.73
Max	300	90	23	5	2	2	1	2	4	20.77	59.73

Grove Bed BD	PM0.3 [Particle count]	PM0.5 [Particle count]	PM1.0 [Particle count]	PM2.5 [Particle count]	PM5.0 [Particle count]	PM10.0 [Particle count]	PMS1.0 (µg/m3)	PM2.5 (µg/m3)	PM 10.0 (µg/m3)	Temperature	RH
Average	286.3548	86.74194	21.93548	4.709677	1.258065	0.806452	0.225806	1.225806	2.354839	26.05194	48.84065
St dev	76.35511	23.14299	4.567534	2.084763	1.124507	0.833441	0.425024	0.844972	1.050346	0.011081	0.060824
Min	138	42	14	1	0	0	0	0	1	26.03	48.78
Max	438	131	29	7	3	2	1	2	4	26.07	49.04

Grove LR BD	PM0.3 [Particle count]	PM0.5 [Particle count]	PM1.0 [Particle count]	PM2.5 [Particle count]	PM5.0 [Particle count]	PM10.0 [Particle count]	PMS1.0 (µg/m3)	PM2.5 (µg/m3)	PM 10.0 (µg/m3)	Temperature	RH
Average	475.7419	135.5484	48.83871	13.32258	2.935484	1.516129	1.483871	4.580645	8	20.37935	56.90032
St dev	163.3165	40.44077	13.49098	4.142359	0.813858	0.889605	0.676805	1.478156	2.03306	0.072247	0.283508
Min	207	69	18	7	1	0	0	2	4	20.27	56.6
Max	723	192	69	22	5	3	3	7	11	20.53	57.65

Grove LR AD	PM0.3 [Particle count]	PM0.5 [Particle count]	PM1.0 [Particle count]	PM2.5 [Particle count]	PM5.0 [Particle count]	PM10.0 [Particle count]	PMS1.0 (µg/m3)	PM2.5 (µg/m3)	PM 10.0 (µg/m3)	Temperature	RH
Average	378.3871	114.129	38.32258	7.645161	3	2.258065	0.677419	2.935484	5.419355	22.67516	47.80258
St dev	67.96944	20.5876	7.336607	2.665188	1.807392	1.264061	0.747757	0.928636	1.455431	0.028621	0.256216
Min	204	66	26	3	0	0	0	1	3	22.63	47.3
Max	495	151	50	12	6	5	2	5	8	22.74	48.2

Shaftesbury LR BD	PM0.3 [Particle count]	PM0.5 [Particle count]	PM1.0 [Particle count]	PM2.5 [Particle count]	PM5.0 [Particle count]	PM10.0 [Particle count]	PMS1.0 (µg/m3)	PM2.5 (µg/m3)	PM 10.0 (µg/m3)	Temperature	RH
Average	1324.935	386.4516	79.35484	7.483871	0.483871	0.290323	7.096774	10.83871	11.87097	20.53484	60.04065
St dev	200.8978	43.09821	9.548293	4.373183	0.769024	0.461414	0.870051	1.067607	1.784039	0.015027	0.246562
Min	906	291	61	3	0	0	6	8	8	20.51	59.73
Max	1518	441	97	18	2	1	9	12	16	20.57	60.44

Shaftesbury Bed BD	PM0.3 [Particle count]	PM0.5 [Particle count]	PM1.0 [Particle count]	PM2.5 [Particle count]	PM5.0 [Particle count]	PM10.0 [Particle count]	PMS1.0 (µg/m3)	PM2.5 (µg/m3)	PM 10.0 (µg/m3)	Temperature	RH
Average	976.2581	286.9032	59.35484	9.354839	2.774194	2.032258	4.516129	7.967742	10.19355	23.39194	55.48677
St dev	54.73266	17.96173	5.089521	4.38595	1.927169	1.622424	0.769024	0.836017	1.81511	0.029824	0.233843
Min	840	242	46	1	0	0	3	6	7	23.33	55.24
Max	1068	320	67	16	6	5	6	10	13	23.43	55.95

Shaftesbury Bed AD	PM0.3 [Particle count]	PM0.5 [Particle count]	PM1.0 [Particle count]	PM2.5 [Particle count]	PM5.0 [Particle count]	PM10.0 [Particle count]	PMS1.0 (µg/m3)	PM2.5 (µg/m3)	PM 10.0 (µg/m3)	Temperature	RH
Average	868.5484	251.6452	60.90323	7.354839	2.290323	1.225806	3.935484	7	8.967742	21.35935	57.68484
St dev	97.46344	28.6828	12.60781	2.388143	1.531743	1.283476	0.573613	0.57735	1.19677	0.050592	0.569449
Min	708	202	43	4	0	0	3	6	7	21.27	56.78
Max	1059	306	86	13	6	4	5	8	11	21.45	58.53

Hawthorn Bed BD	PM0.3 [Particle count]	PM0.5 [Particle count]	PM1.0 [Particle count]	PM2.5 [Particle count]	PM5.0 [Particle count]	PM10.0 [Particle count]	PMS1.0 (µg/m3)	PM2.5 (µg/m3)	PM 10.0 (µg/m3)	Temperature	RH
Average	842.129	254.5161	102.4839	30.67742	11.54839	9.290323	3.612903	11	20.96774	18.82323	49.17581
St dev	106.1938	33.93412	12.40664	5.850283	4.201894	3.407771	0.615219	1.65328	3.754853	0.05275	0.089023
Min	690	207	82	19	2	1	3	9	12	18.74	48.97
Max	1059	328	126	46	21	16	5	15	29	18.93	49.29

Hawthorn LR BD	PM0.3 [Particle count]	PM0.5 [Particle count]	PM1.0 [Particle count]	PM2.5 [Particle count]	PM5.0 [Particle count]	PM10.0 [Particle count]	PMS1.0 (µg/m3)	PM2.5 (µg/m3)	PM 10.0 (µg/m3)	Temperature	RH
Average	769.2581	225.4839	67.93548	21.64516	8.548387	4.967742	2.580645	7.16129	13.77419	24.2771	39.94484
St dev	88.25568	24.38014	12.10492	5.498778	4.418436	2.689286	0.62044	1.485413	13.77419	0.043604	1.471378
Min	528	163	53	7	1	1	1	4	13.77419	24.18	37.14
Max	921	265	93	29	15	10	4	10	13.77419	24.34	41.8

Blaise Bed BD	PM0.3 [Particle count]	PM0.5 [Particle count]	PM1.0 [Particle count]	PM2.5 [Particle count]	PM5.0 [Particle count]	PM10.0 [Particle count]	PMS1.0 (µg/m3)	PM2.5 (µg/m3)	PM 10.0 (µg/m3)	Temperature	RH
Average	340.8387	102.129	23.51613	2.129032	1.225806	0.774194	0.580645	1.290323	2.387097	21.58806	46.97516
St dev	51.91345	15.65406	6.850163	1.431594	1.585553	1.334408	0.50161	0.588419	1.358367	0.04505	0.301915
Min	237	68	16	0	0	0	0	0	1	21.51	46.56
Max	426	127	39	5	4	3	1	2	5	21.66	47.49

Blaise LR BD	PM0.3 [Particle count]	PM0.5 [Particle count]	PM1.0 [Particle count]	PM2.5 [Particle count]	PM5.0 [Particle count]	PM10.0 [Particle count]	PMS1.0 (µg/m3)	PM2.5 (µg/m3)	PM 10.0 (µg/m3)	Temperature	RH
Average	338.3793	103.6552	22.55172	1.62069	0.793103	0.724138	0.724138	1.517241	2.068966	23.46655	43.25655
St dev	97.17599	28.81006	6.185156	1.082781	0.412251	0.454859	0.797162	1.021927	0.997534	0.015184	0.272885
Min	189	63	15	0	0	0	0	0	0	23.43	42.97
Max	510	156	34	4	1	1	2	3	4	23.49	43.89

Abbreviations: Bed – Bedroom, LR – Living room, BD – Before depressurisation, AD – After depressurisation

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