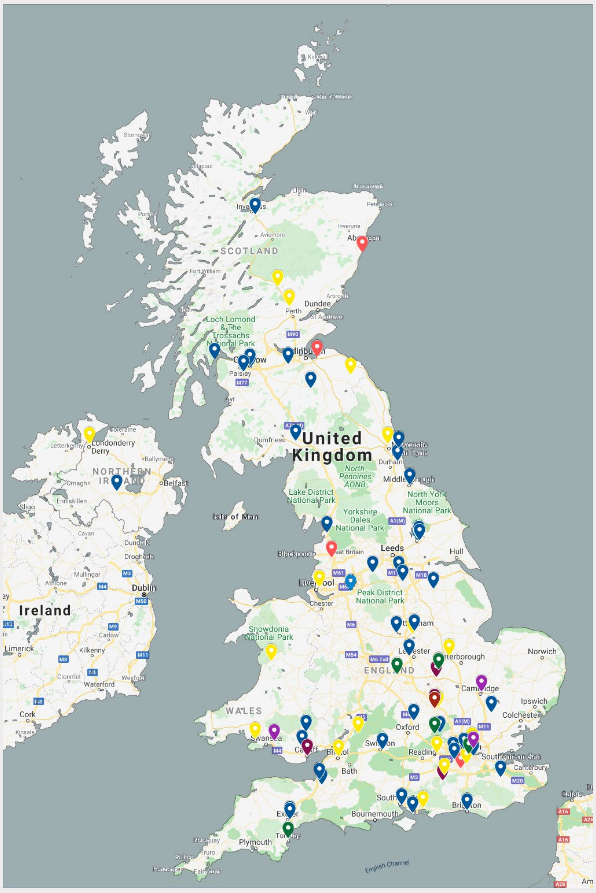
Building Performance Network

State of the nation review

Performance evaluation of new homes



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May 2020

Good Homes Alliance

This report should be referenced as:

Rajat Gupta and Matt Gregg (2020). State of the Nation review: Performance evaluation of new homes, Building Performance Network and Oxford Brookes University, UK

ISBN: 978-1-9161328-4-9

Published by: Building Performance Network and Oxford Brookes University

Funded by: Building Performance Network

Cover images: Photo: Crest Nicholson; map: Building Performance Network

The housing performance evaluation studies referenced in this report were performed by many universities and organisations funded by various agencies throughout the UK.

May 2020

Acknowledgements

The Building Performance Network thanks the following organisations for funding and supporting this research work:

Our gratitude also goes our delivery partners, the Good Homes Alliance, and, for their hard work and expertise, Oxford Brookes University.

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Foreword

The imperatives for testing the performance of our homes are clear, both for individual occupants and for our planet as a whole. By 2050, the UK must be net zero carbon. Accounting for approximately 25% of UK CO_2 emissions, homes are a critical part of our net zero carbon journey. However, recent evidence has shown that there is a disappointing performance gap between design intention and the actual energy performance and hence CO_2 emissions from homes once they are lived in. If we are going to have the homes we need, we must understand properly their actual energy and environmental performance. We must measure in order to properly understand and manage the operation of dwellings. Further, we must use this learning to improve the design and delivery of new homes and the upgrading of existing ones.

Across the country, homes have been measured and tested using a variety of building performance evaluation (BPE) methods. This study has successfully brought together and analysed these varied building performance results and produced a very useful resource, making the conclusions drawn and information gleaned more accessible.

- For researchers, further detail is available in both the online map of projects and the Data Navigator.
- Designers and developers, I urge you to incorporate building performance evaluation into your projects and use the findings to inform future developments.
- Policymakers, finance providers, procurers and those commissioning building performance evaluation, there is an overview of the types of studies that can be undertaken and the knowledge they bring: I hope you will consider this when exercising your influence to improve housing performance and drive down the performance gap to meet our net zero commitment.

With technology ever changing, this report also looks ahead at how the study of our homes may develop in the near future, suggesting that not only will it be possible to have a more detailed picture of energy demand, but that the health and well-being of residents may be better understood as well.

Our homes play such an important part in both the environmental impact of our lives and our comfort, health and well-being. Understanding how in reality good homes are built, used and perform is vital to ensure our national carbon targets are met. I heartily welcome this timely, accessible report.

Dr Kerry J Mashford OBE

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Executive summary

There has been an increase in studies undertaken over the last 10 years to understand the actual performance of homes addressing issues such as energy consumption and outcomes for residents and building owners. However, many of these studies are not widely publicised and are limited to a small audience.

Funded by the Building Performance Network (BPN), the inaugural State of the Nation study has produced this comprehensive report that provides an accessible review of key studies on new-build housing performance and building performance evaluation methods adopted, analysis of meta-data, as well as a look at the future of housing performance studies.

The study has also created for the first time, an online and interactive spatial map of housing performance studies undertaken in the UK. The housing performance map spatially locates 91 housing performance studies along with their meta-data such as number of dwellings studied, location tenure, study duration, study type and data availability.

The report is structured into five chapters as described below:

- CHAPTER 1: Introduction to housing performance: why, what, when?
  This chapter introduces the fundamentals of why, what and when housing performance studies are undertaken. Key metrics of housing performance are introduced and how they can be assessed.

- CHAPTER 2: Tools and methods to assess housing performance
  This chapter reviews major tools and methods that have been used in research for assessing the as-built and in-use performance of new-build housing.

- CHAPTER 3: Past studies on housing performance
  This chapter provides an accessible review of the objectives, scope and main findings of past studies and meta-studies on housing performance.

- CHAPTER 4: Meta-analysis of housing performance data
  This chapter conducts meta-analysis of large amounts of housing performance data (covering building fabric thermal performance, in-use energy, indoor environment and resident perception) to provide insights into housing performance studies at scale.

- CHAPTER 5: Key findings, recommendations and the future of housing performance evaluation
  This chapter describes what the diffusion of low-cost sensors, smart meters and wearables means in terms of assessing housing performance at scale in the future.

The report is aimed at the following audience:

- Individuals who may be new to building performance studies
- Constructors and developers with an interest in building performance
- Policymakers in local and national government with an interest in housing performance
- Local authorities
- Individuals who may be commissioning building performance studies.

Chapter 1: Introduction to housing performance: Why, What, When?

1.1 Introduction

The UK has committed to a net zero emissions target by 2050 and to five-year carbon budgets in the interim set by the Committee on Climate Change (HM Government, 2011). Over the years, various policies aimed at encouraging energy efficiency measures in domestic buildings such as Code for Sustainable Homes (CSH) and the Green Deal, have come and gone. According to the UK government's Department for Business, Energy and Industrial Strategy's (BEIS) Clean Growth Strategy (2018), the UK has outperformed the target emissions reductions; however, the housing sector, will need to do more to meet its share of reductions.

A potential pathway to success in 2032 (fifth carbon budget) would require a 20% reduction in emissions from homes. These carbon budgets have driven the need for new dwellings to be built with high standards of insulation with mechanical ventilation, high efficiency heating systems, and renewables. Given that housing projects are increasingly expected to meet higher and potentially more complex levels of performance, it is reasonable that actual performance of new housing is evaluated against expected performance or specific standards (e.g. Code for Sustainable Homes (CSH), Passivhaus). Such evaluations have shown that that low/zero energy dwellings often underperform as compared to the design specifications, due to discrepancy in building fabric thermal performance, performance of heating and ventilation systems, and resident behaviour.

Past studies (Monahan and Gemmell, 2011; Thompson and Bootland, 2011) have demonstrated that in-use energy use can be up to three-five times more than design predictions. This energy performance gap (EPG) between the predicted energy performance of a building and its measured performance has been highlighted by several studies (Bordass and Leaman, 2005; Gaze, 2014a, 2014b; Gill et al., 2010; Gupta and Kapsali, 2014; Lowe et al., 2007; Stevenson and Leaman, 2010; Williamson, Soebarto, & Radford, 2010; Wingfield et al., 2011). Clearly national policy targets for carbon reduction cannot be met without understanding, quantifying and minimising this performance gap.

Corresponding with the findings of Zero Carbon Hub (2014), studies that evaluated the in-use energy performance of new dwellings (Baborska-Narożny and Stevenson, 2019; Gaze, 2014a; Gupta, Gregg, & Cherian, 2013; Wingfield et al., 2011; Wingfield et al., 2008) indicated that the reasons for the performance gap can generally be attributed to discrepancies that arise across the building process, from the design and modelling tools used to design the building, through build-ability, materials and build quality (as-designed and as-built), systems integration and commissioning but also handover and operation, as well as the understanding, comfort and behaviour of the residents. For these reasons, systematic investigation of the performance gap through real-world building performance evaluation (BPE) studies is seen as a high priority by the Government, industry and academia. Unfortunately, BPE currently has a limited presence in education and practice (Stevenson, 2019a).

Building performance evaluation of homes (effectively *housing performance evaluation (HPE)*) is a process of systematically comparing the actual performance of buildings, places and systems to explicitly documented criteria for their expected performance. It is based on the post-occupancy evaluation (POE) process model developed by (Preiser, Rabinowitz, & White, 1988)" (Preiser and Vischer, 2006). There have been several studies undertaken over last 10 years to understand the performance of new-build homes addressing issues such as energy consumption and outcomes for residents and building owners. However, many of these studies are not widely publicised and are limited to a small audience. Also, most of the studies have been case-study based, and findings are largely fragmented and difficult to compare.

The purpose of this report is to provide an accessible review of key studies on housing performance, analysis of meta-data and main findings. The report also includes a review of BPE methods as well as a look at the future of housing performance studies. To address these objectives, the report covers the following aspects:

- Rationale and objectives of housing performance studies
- Review of key findings of studies and meta studies of building performance
- Key data, benchmarks and how they impact residents
- The future of building performance studies to guide methodologies for future studies.

The study has also created for the first time, an online and interactive spatial map of housing performance studies undertaken in the UK.

The report is aimed at the following audiences:

Individuals who may be new to building performance studies,

Constructors and stockholders with an interest in building performance, e.g.,

- Housing Associations:
  - Assessing the occurrence of summertime overheating in occupied and unoccupied low energy homes (Gupta, Gregg, & Bruce-Konuah, 2017) (Joseph Rowntree Housing Trust)
- Private developers:
  - Building Research Establishment exhibition site: Sigma Home study (Stevenson and Rijal, 2008)
  - Lessons from AIMC4 for cost-effective, fabric-first, low-energy housing Part 1: Introduction to AIMC4 (Cartwright and Gaze, 2013) (partially funded by consortium members: Stewart Milne Group, Crest Nicholson plc and Barratt Developments plc; also TSB, BRE H+H UK Ltd, (supplier))
- Supply chain such as Velux, Rockwool, St Gobain etc:
  - Whole house heat loss test methods (Alzetto et al., 2018)
  - Lessons from AIMC4 for cost-effective, fabric-first, low-energy housing Part 1: Introduction to AIMC4 (Cartwright and Gaze, 2013)

Policy makers in local and national government with an interest in housing issues, e.g.,

- Government departments, e.g. Innovate UK, Department for Business, Energy & Industrial Strategy (BEIS), Ministry of Housing, Communities & Local Government (MHCLG)
  - Building Performance Evaluation Programme (Palmer et al., 2016)
  - Retrofit for the Future (TSB, 2014)
  - Core cities Green Deal monitoring project (Gorse et al., 2017)
  - Heat pump field trials (EST, 2010)
  - Cavity party walls: measuring U-values (Palmer et al., 2019)

Individuals / groups who may be commissioning building performance studies, e.g.,

- Research funders, e.g. Engineering and Physical Sciences Research Council (EPSRC)
  - Evaluating the impacts, effectiveness and success of low carbon communities on localised energy behaviours (EVALOC) (Gupta et al., 2015)
  - Measuring and Evaluating Time- and Energy-use Relationships (METER) (Satre-Meloy, Diakonova, & Grünewald, 2019)
  - Consumer Appealing Low Energy Technologies for Building Retrofit (CALEBRE) (Spataru, Gillott, & Hall, 2010)
- Charitable organisations, e.g. the Joseph Rowntree Foundation
  - Temple Avenue Project: Energy efficient refurbished homes for the 21st Century (RPA & LMU, 2012)

1.2 Why are housing performance studies undertaken?

The objectives for performing housing performance studies often follow the objectives of the design intention. That is, if a dwelling is designed to meet a specific design target, the purpose of the study is to establish whether the target has been met. Following are the key reasons for assessing housing performance:

- Verify if design standards (e.g. CSH, Passivhaus) have been realised in practice:
  - Measure the performance of a home built to a design standard (Ridley et al., 2013).
- Test the performance of building fabric, services and systems against expected performance:
  - Test and verify fabric and/or system performance requirements (e.g. air permeability, ventilation) to meet a specific standard.
  - Test and verify the performance of new or different high performance materials (innovative solutions in housing performance) in the UK climate (Carfrae et al., 2009; Gupta, Gregg, & Cherian, 2013).
  - Evaluation of innovative methodologies for performance evaluation (Ozturk, Arayici, & Coates, 2012).
  - Evaluation and benchmarking of system or total energy performance gap; to understand the cause of the performance gap[1].

[1] The gap between design intent and actual outcome tends to occur due to assumptions made in modelling, build process and quality, systems integration and commissioning, handover and operation, and crucially the understanding, comfort and motivation of occupants.

- Process improvement:
    - Investigate suspected underperformance (e.g. performance gap).
    - Gather feedback for design and construction team to inform future building design, specification and performance (Gupta and Dantsiou, 2013).
    - To explore design and construction processes of a new building type or method.
- Resident perception and behaviours:
    - To evaluate the impact of resident experience and behaviours on in-use performance (Gupta and Chandiwala, 2010).

Going forward, the UK Government's *Clean Growth Strategy* (BEIS, 2018) has recommended that energy use of new buildings be reduced by 50% by 2030 through the use of new methods and technologies (Godefroy and Etude, 2019). This will be an important reason to carry out housing performance evaluations to verify if such targets are being met in reality.

1.3 What are the key metrics for measuring housing performance?

A range of key metrics can be used to assess the as-built (no residents) and in-use performance (with residents) of new homes. These are summarised in Table 1 below.

Table 1. Key performance metrics used in housing performance studies

Study element	Performance metrics	Performance indicator	Unit	Related standards
As-built performance				
Building fabric thermal performance	**Airtightness**	Air change rate (volumetric)	ac/h	-
		Air permeability	$m^3/(h.m^2)$@50 Pa	SAP/BRUKL required KPI
		Air permeability	ACH50	Passivhaus (PHPP) required KPI
	Heat loss	Heat loss coefficient (HLC)	W/K	-
		Fabric / thermal bridge heat loss	W/K: Χ (chi) value point thermal bridge heat loss coefficient W/mK: ψ (psi) value the heat loss per unit length of thermal bridge	-
		Heat loss parameter	W/m^2K	Code for Sustainable Homes (CSH) (no longer used) required KPI
	Thermal transmittance of measured unit	U-value	$W/(m^2 K)$	BRUKL KPI
	Moisture content in measured material	Fabric / material moisture content	% MC	-

Study element	Performance metrics	Performance indicator	Unit	Related standards
Services and systems performance	**Heating systems**	System (e.g. boiler) efficiency, COP (e.g. heat pump)	% / COP	-
	Ventilation systems	Ventilation rate	m^3/hr^{-1}; l/s; l/s per m^2; l/s per person	CIBSE (2015)
		Fan power	W/(l/s)	-
In-use performance				
Energy performance	**Energy consumption / generation and GHG implications**	Regulated and unregulated energy use / Total energy[2] [3]	kWh/a; **EUI:** $kWh/m^2/a$	-
		Space heating energy demand	$kWh/m^2/a$	Passivhaus required KPI
		Renewable primary energy demand	$kWh/m^2/a$	Passivhaus required KPI
		CO_2e emissions / DER	$kgCO_2/m^2$	SAP/BRUKL/CSH required KPI
		Heat energy	Wh	-
Energy end uses	**Water consuming appliances**	Water consumption per person	L/person	-
	Heating and hot water	Space heating / Domestic hot water energy use	kWh/a	-
	Cooling	Space cooling energy consumption	kWh/a	-
	Ventilation systems	Ventilation system energy consumption	kWh/a	-
	Electricity consuming appliances	Regulated and unregulated electrical loads (lights, pumps, fans and controls)	W/m^2	-
Indoor environment	**Thermal environment**	Temperature (e.g. dry bulb, air, mean radiant)	°C	CIBSE
		Relative humidity (RH)	%	CIBSE

[2] According to the Green Construction Board (2019), energy modellers often inaccurately utilize UK Building Regulations Part L calculation models for compliance as an ‘actual’ energy estimation/prediction. There is an incorrect assumption that a model, fit to comply with Part L, can accurately predict ‘regulated’ energy uses. “There are many reasons why Part L assessments do not predict energy use accurately (even regulated energy use), and this alone can result in the initial design stage calculation underestimating actual energy use by a factor of 20% to 600%.” (p.7). The suggested solution is that total energy consumption needs to be modelled without limitation.

[3] The Green Construction Board (2019) recommend ‘kWh at the meter’ as the universal metric to facilitate year-on-year comparisons of evaluation results and progress.

Study element	Performance metrics	Performance indicator	Unit	Related standards
		Overheating	% hours	CIBSE
	Indoor air quality (IAQ)	CO_2 concentration	ppm	CIBSE
		Total volatile organic compounds (TVOC)	ppb	-
		Particulate matter (PM 10)	µg/m^3	-
		Particulate matter (PM 2.5)	µg/m3	-
		Noise	dB	-
		Light	Lux	-
Resident experience / perception	**Long-range resident perception**	Resident satisfaction evaluation	Building Use Studies (BUS) benchmark	-
	Time of evaluation resident perception and environmental relationship	Thermal comfort threshold / overheating	% of total hours / % of occupied hours	Passivhaus required KPI

1.4 When are housing performance studies undertaken?

Historically evaluations have begun during construction, upon completion, or any time after initial occupation of the dwelling. Evaluation may be set to begin at a construction stage (e.g. to test the airtight layer before it is covered), or much later in response to a performance concern raised by the resident / owner. The past studies can be broadly categorised into the following two groups:

1. **Post-construction and early-occupation studies** capture the 'as-built' performance of the building fabric and installed equipment, and how residents react to it including the effectiveness of the handover process.
2. **In-use studies** capture the 'in-use' performance of the building over an extended period, once its fabric and systems have stabilised and the residents have become familiar with the dwelling.

Post-construction[4] performance is a process of comparing the constructed product with the designed expectation, and includes:

- Review of design intent
- Building fabric performance testing
- System performance testing / commissioning review of systems

[4] Note that post-construction, as-built, as-constructed, and post-completion have been used interchangeably to refer to the evaluation of the construction after it is completed. Pre-occupancy may be used sometimes to refer to the same but is strictly done before the building is occupied; whereas, the former can sometimes refer to the evaluation of construction quality even after the building is occupied.

Handover is a link between construction completion and in-use. It can facilitate communication of design intent to the user. The handover stage is typically the bridge between the studies as shown in the

Figure 1 below.

In-use performance (e.g. post-occupancy evaluation) is a process of comparing in-use with designed expectation (where available), and includes:

- Energy use monitoring
- System performance monitoring in-use (e.g. heating, ventilation)
- Indoor / outdoor environment monitoring
- Resident experience / behaviours

Figure 1 graphically shows the flow of these stages along the project delivery process and where the percentage of past housing performance studies reviewed have focussed.

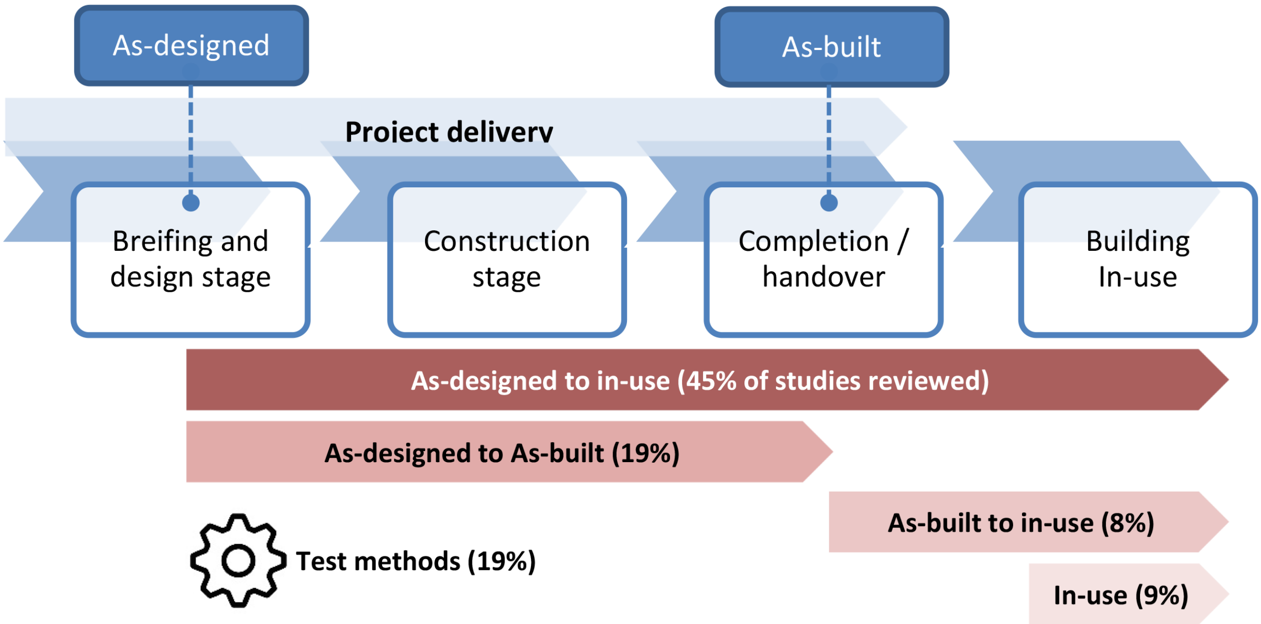

Figure 1. Stages of housing performance evaluation studies from design to in-use

Note: read as-built interchangeably as post-construction (see footnote).

As-built performance evaluation can take place during any point in the life of the building; however, some fabric or system evaluations are easier to perform before the dwelling is occupied. This is typically for reasons of access and disruption, but also to remove resident impact as a variable. As the title implies, in-use performance evaluation is limited to dwellings that have been in occupation (for at least six months) with residents.

The following chapter provides an in-depth review of various methods and tools that have been used in performance evaluation of homes. Following from there, Chapter 3 presents a review of housing performance studies that have implemented these methods and tools.

Chapter 2: Tools and methods to assess housing performance

This chapter describes and evaluates various methods and techniques that are used for assessing the *as-built* and *in-use* performance of new homes. The methods are evaluated in terms of Building Regulations requirement, stakeholder involvement, and complexity of implementation, time duration and cost. A housing performance evaluation framework is proposed to provide a 'how-to' guide for conducting housing performance evaluation studies.

2.1 As-built performance

Many housing performance evaluations begin as-built evaluation following the completion of construction as it is a good place to begin to assess as-designed against the as-built condition before the building is occupied. This is helpful as it allows for invasive tests to be done without disturbing residents and resident influence is not a factor in assessing a possible performance gap. Evaluation at this stage is also helpful in catching issues that can be fixed before occupation. Phase 1 of the Technology Strategy Board (TSB) (now Innovate UK) Building Performance Evaluation (BPE) Programme began at this stage, providing many examples and findings (Palmer et al., 2016; Seguro, 2015; TSB, 2012). The primary objectives of this as-built performance evaluation are:

- Review of design intent against as-built
- Technical building survey: fabric assessment
- Technical building survey: system integration and commissioning

2.1.1 Review of design intent against as-built

Design review helps to establish the design intent of the dwelling(s) and provides the reference against which the actual performance can be compared. Table 2 shows the methods that have been used with respect to design intent review. The following text describes each method.

Review of drawings and technical specification

The review of design intent is often done through an initial desktop review of drawings, construction documents, energy models and technical specifications. This review should be undertaken by someone who is aware of the design and construction process and able to undertake relevant design standard calculations, e.g. Standard Assessment Procedure (SAP) or Passive Housing Planning Package (PHPP) calculations. The Innovate UK BPE programme project execution report (2010) outlines what approach should be taken:

- Study the design drawings and specifications, examine the dwelling(s) for construction quality, identifying areas where the 'as-built' seems to differ from the 'as designed'. These apparent differences should be investigated with those responsible for delivering the buildings in order to establish the reasons for any deviations.
- Review the SAP/PHPP calculations to ensure these accurately reflect the design of the dwelling and to identify any aspects of the design that one would expect to affect performance but are not captured adequately in the SAP/PHPP calculations. This should confirm the 'as designed' performance of the dwelling.
- Prepare a general description of the realisation process from inception to initial occupation. This should touch on all aspects including the nature of the design process, interface with supply chain and how performance information provided by the supply chain is used.

Semi-structured interviews with designers, developers, client

Interviews with members of the design and construction team can clarify the process to this point and why there may be a difference between as-designed and as-built. Interviews with the design team can involve either one-on-one interviews with individual members of the design team or group interviews/discussion with the whole design team at once. The questions can be tailored to enable focused responses, depending on the requirements of the study. The interviews should be recorded and transcribed to be most effective for reference.

Table 2. Methods to review design intent against as-built performance

Techniques	Stage	Test type	What is assessed	Reveals / provides	Required for Building Regulations	Test output	Stakeholder involvement[5]	Complexity of implementation[6]	Est. Test duration (per dwelling)[7]	Cost[8]
Review of drawings and technical specification	Pre-construction through in-use	Qualitative; one-off; reflective	Changes in design & spec; availability of information	Connection between construction changes and tests results	Yes	Findings report/ checklist complete	Low	Medium	Medium	Low
Semi-structured interviews with designers, developers, client	Pre-construction through in-use	Qualitative; one-off; reflective	Changes in design & spec; what & why	Connection between construction changes and tests results	No	Transcript/ summary	High	Medium	1 day	Low
Site visits and walkthroughs	During construction / Post-completion / In-use	Qualitative; one-off; diagnostic	Visual irregularities, abnormalities in the fabric, known changes from design to implementation	Visual documentation to describe and cross-relate with fabric tests, system assessment, resident behaviour with findings	Yes	Findings report/ checklist complete	Medium	Medium	Low:	Low
Photographic surveys	During construction / Post-completion / In-use	Qualitative; one-off; diagnostic	Changes in design & spec; what & why	Visual documentation to describe and cross-relate with fabric tests, system assessment, resident behaviour with findings	No	Findings report with images	Low	Low	1-2 hours	Low

Methods are evaluated against the following criteria (using a scale of High, Medium and Low), using authors' experiences and a review of relevant BPE studies. The following notes are applicable to all following methods tables:

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[5] Stakeholder involvement: The scale of involvement, disruption and or approval required by various stakeholders, to implement a certain technique, can dictate whether or how often these techniques take place: e.g. Design review meetings with clients, developer and management require coordination, time and input from a range of stakeholders.

[6] Ease of implementation: Complexity of each method depending on the level of competency and specialist experience needed for its implementation, the quantity and size of the equipment and the duration of the investigation: e.g. monitoring the performance of renewable technologies requires qualified electricians for installation.

[7] Duration: dependent on complexity of development and availability of information. The time taken to implement any measure or technique (both installation and analysis).

[8] Cost: Cost of the equipment (purchase and installation) and human resources needed: e.g. Co-heating tests require specialist equipment; an unoccupied but heated building for an extended period and therefore incurs a high cost. Low: <£1000; Medium: ~£1000 – 2000; High: >£2000

Site visits and walkthroughs

Site visits and walkthroughs (with members of the design/construction team) can help uncover ‘forgotten’ issues as well as help the assessor gain a better understanding of the dwelling. An open-ended, repetitive script to provide prompts regarding relevant issues and points of interest in relation to different aspects of the construction and design is useful. Time should be given to the design/construction team members to bring up their own issues. It is recommended that notes are taken throughout the walkthrough, as well as pictures, and audio-recordings for future transcription.

Inspection of build quality / Photographic survey

At this level, design stage guidance can be used to evaluate whether the building is satisfying recommendations / requirements. As an example, whether designed in consideration of this design stage guidance or not, the building can be evaluated based on the Good Home Alliance’s (2019) Tool and guidance for identifying early stage overheating risks in new homes. A photographic survey integrated with walkthroughs enables the evaluator to document and investigate a variety of areas relating to the physical and technical characteristics of a dwelling. It is recommended that design/construction team member(s) are present to provide additional information relating to the area in question and highlight issues that may not be apparent to the researcher.

Some limitations of these methods are:

- Quality and accuracy of findings dependent on availability of drawings, models and performance data; availability of interviewees and information.
- Requires assessor to have expertise; knowledge of construction and design.
- Data collection can be time-intensive; preparation including pilot interviews essential.
- Due to nature of 'spot-checks' issues that crop up between visits may be missed/not reported.

2.1.2 Building fabric thermal performance

In a typical new build home, thermal bridging can account for 20-30% of the total heat loss (Whale, 2016) while the respective share of air leakage may be up to 50% (EST, 2009). With the insulation standards and requirements for new build dwellings becoming tighter over time, the identification of such issues becomes even weightier for the thermal performance of the building shell. Measuring the performance of the building fabric ‘as-built’ is vital in quantifying and finding reasons for the performance gap. A portfolio of diagnostic techniques is available for fabric testing which measure air tightness, insulation performance, etc.

The literature addressing the fabric performance of new build dwellings in the UK is largely dominated by Building Performance Evaluation (BPE) studies (Palmer et al., 2016), where the building fabric was investigated predominantly by means of air permeability tests (pressurisation and depressurisation), co-heating tests and in-situ measurements of U-value, all revealing that discrepancies between the design intent and reality are rather regular. Generally, all building fabric performance tests and measurements should be taken post-construction but prior to handover in order to provide ‘as-built’ results and allow time for remedial works to be undertaken before dwellings are occupied. In order to understand the degradation rates of the building fabric, it may be advised that the tests are repeated at regular intervals over a significant period of time. Table 3 shows the as-built evaluation methods that have been used with respect to fabric assessment. The following text describes each technique.

Air permeability testing

Achieving a good level of air tightness is important for the energy efficiency of a building; poor air tightness can be responsible for up to 40% of heat loss from buildings (NHBC Foundation, 2016). Air leakage testing using the pressurisation technique as outlined in the Air Tightness Testing and Measurement Association’s (ATTMA) document, ‘Measuring air permeability of building envelopes (dwellings)’ is required by Building Regulations. Whilst Building Regulations Part L1A (Conservation of Fuel and Power) set a maximum allowable air permeability measure for all new dwellings, the specific performance required is dependent on the SAP or PHPP calculations.

If the development/dwelling fails to meet the relevant performance requirements, the regulations require the contractor to carry out remedial work (to the tested dwelling as well as the un-tested dwellings), and the development to be re-tested. As such, it is recommended that airtightness tests are combined with means to identify where the air leakage sources are such as tracer gas testing, smoke tests and/or thermal imaging.

Table 3. Table of fabric assessment techniques

Techniques	Stage	Test type	What is assessed	Reveals / provides	Required for Building Regulations	Resulting measure	Stakeholder involvement	Complexity of implementation	Est. Test duration (per dwelling)	Cost
Air permeability testing (e.g. Fan pressurisation test)	Post-construction (preferably pre-handover) through life of building	Quantitative; one-off; measurement	Air leakage (air flow rates)	Provides air-permeability rating	Yes	Air changes per hour @50Pa	Medium	Medium	Low: 1 day	Low
Tracer gas test	Post-construction (pre-handover)	Quantitative; one-off; measurement	Air leakage / building ventilation rates	Whole building ventilation rates / air leakage	No	Air changes per hour (ACH)	Medium	High	Low: 1 day	Low
Co-heating test	Post-construction (pre-handover)	Quantitative; one-off; measurement	Heat loss coefficient (HLC)	Heat loss from both fabric and uncontrolled ventilation	No	W/K	High	High	High: 1-3 weeks	High
In situ heat flux measurement	Post-construction (pre-handover)	Quantitative; one-off; measurement	U-value (whole & individual elements)	Actual value of insulation improvements	No	W/m2K	Medium	High	High: 2 weeks	Medium
Infra-red thermography	Post-construction through life of building	Qualitative; one-off; diagnostic	Heat loss, thermal bridging, gaps in insulation, changes in insulation, areas of in/ exfiltration, etc. Identify areas in need of improvement or repair	Qualitative visualization of surface temperatures	No	-	Low	Medium	Low: 1-2 hours	Medium
Air leakage identification e.g. smoke tests	Post-construction (pre-handover)	Qualitative; one-off; diagnostic	Location of defects in building fabric /air leakage paths	Paths of infiltration and identify specific weak points in the building envelope.	No	-	Medium	Medium	Low: 1-2 hours	Low
Borescope investigation (thermal bridging)	Post-construction through life of building	Qualitative; one-off; diagnostic	Location of defects in building fabric	Location of defects in building fabric	No	-	Medium	High	Low: 1-2 hours	Low

Tracer gas method

A tracer gas is normally used to measure whole building ventilation rates but can also be used to measure air leakage. The technique involves introducing an inert gas into the building and then observing how the gas behaves as air leaks both into and out of the building. The air leakage rate can then be determined by either measuring the concentration of the gas inside the building over time or measuring the rate at which the tracer gas needs to be introduced into the building to maintain a specific concentration.

Whole house heat loss tests: Co-heating test

A co-heating test is a method of measuring the heat loss (both fabric and background ventilation) in W/K attributable to an unoccupied dwelling. It was developed by Leeds Beckett University (Wingfield et al, 2010). It involves heating the inside of a dwelling electrically, using electric resistance point heaters, to an elevated mean internal temperature (typically 25 °C) over a specified period of time, typically between 1 to 3 weeks. By measuring the amount of electrical energy that is required to maintain the elevated mean internal temperature each day, the daily heat input (in Watts) to the dwelling can be determined. The heat loss coefficient for the dwelling can then be calculated by plotting the daily heat input against the daily difference in temperature between the inside and outside of the dwelling (ΔT). The resulting slope of the plot gives the Heat Loss Coefficient (HLC) in W/K. The test potentially allows deviations from the design performance to be identified by comparing the HLC, derived using the co-heating procedure, with the HLC determined through the Standard Assessment Procedure (SAP) using the building design parameter values. In order to obtain a sufficient value of ΔT (generally 10 K or more), the co-heating test should be carried out in the winter months, usually between October/November and March/April.

Heat flux measurements / in-situ U-value testing

Heat flux sensors installed in-situ (Figure 2) provide a direct measure of flux from a surface into and through a construction element. They can be used to determine the u-value of individual construction materials (which is usually not necessary as manufacturers have been required to undertake such testing and provide data on the material u-values in order to market their product) or, more usefully in building performance evaluations, the U-value of surfaces of whole elements of the building envelope comprising several layers, e.g. block-work, insulation, render, or a sandwich SIP panel. Its value lies in providing data that enables investigative examination of a range of heat loss mechanisms. Although such measures can be valuable on their own, particularly when used in occupied dwellings, they can be particularly enlightening if undertaken in conjunction with whole house heat loss measurement.

Figure 2. Heat flux sensors on walls (co-heating test instrumentation also shown)

Whilst tests like co-heating provide useful performance measurements which can be compared to expected performance, they do not necessarily provide insight into where the performance is being compromised. The following methods can be described as inspection methods and can provide detailed diagnostics to enable appropriate remedial measures to be undertaken. In current building projects these can be used during the construction period and pre-handover to ensure the as-built dwelling meets design performance expectations as close as possible. Some of these tests are, however, flexible and non-invasive enough to be used during the in-use stage of the building.

Thermal imaging surveys

Thermal imaging or infra-red thermography is often used as a diagnostic tool. It provides an infra-red image which gives an indication of surface temperatures and can enable thermal anomalies in construction to be identified. Such anomalies may be the result of gaps in insulation layers, different insulation characteristics, air movement within the structure or, more usually, a combination of all three. The technique is therefore particularly effective in combination with other techniques, for example during an air permeability test, by directing the use of smoke test to specific areas of the building, focusing attention on construction details that may be performing poorly, ensuring that u-value measurements are conducted at locations that adequately represent the area to which they relate

There are two survey approaches to thermal imaging; internal (Figure 3) and external (Figure 4). Whilst an external survey involves less disruption of the residents and can locate potential areas of heat loss, it is more difficult to get accurate results due to the reliance of thermal imaging on specific climatic conditions (no sun, dry, still, cold and cloudy). Internal surveys allow more accurate interpretation of issues related to heat loss, air leakage and the presence of moisture due to the more stable environmental conditions.

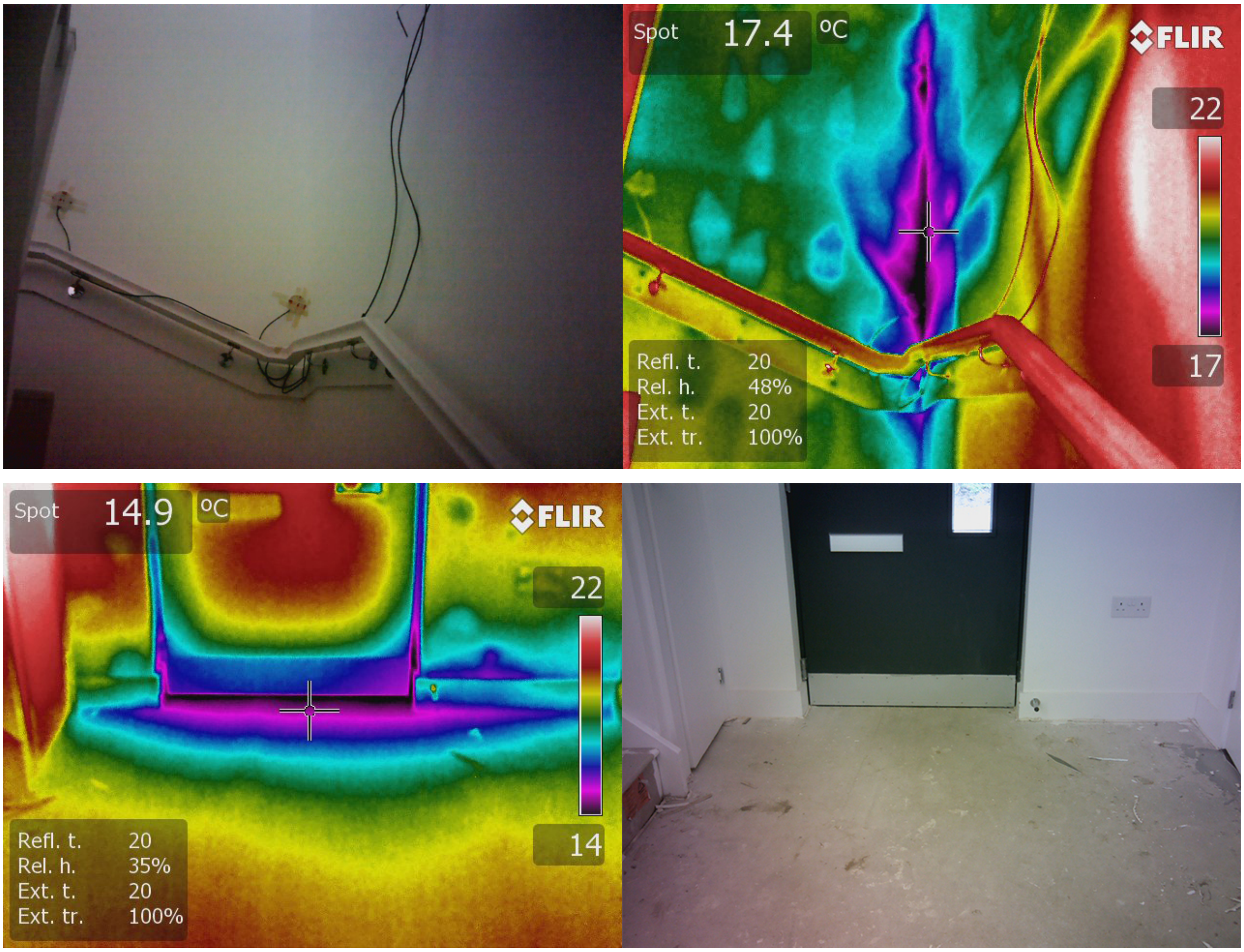


Figure 3. Internal thermal images

Figure 4. External thermal image

Smoke test

Smoke testing is a diagnostic tool that allows air leakage paths to be identified. There are a variety of ways to carrying out smoke tests, and all of them require the building to be pressurised (e.g. during an airtightness test):

- Smoke pencils can be used to identify local air leakage paths. This is a useful technique, particularly for smaller buildings, but can be time consuming.
- Whole house smoke test: smoke generators can be distributed around the whole building and left switched on for a period of up to an hour. The building should then be pressurised to around 30 Pa and the smoke egress from the building observed and preferably recorded on video. Such tests take less than three hours, even for quite large buildings, and give building contractors a good idea of the location of problem areas.

Some of the limitations of the above methods are:

- Often require specialist expertise to perform method, use equipment and analyse results.
- Some methods like air permeability testing can require disruption to internal space.
- Sensitive to external conditions thereby restricting timing such as whole house heat loss method.

Borescope inspections

Borescope inspections are carried out to confirm the quality of insulation in the cavity of a building element, typically the wall. Inspection holes are drilled in the wall and the cavity is examined using a Borescope in order to determine whether insulation is missing or of unusually low compactness. A thermal imaging camera can assist in identifying and deciding where exactly to drill for the Borescope inspection as drilling into the wall can be an invasive process. The following is the recommended method for performing an inspection on a single-storey dwelling (Ross, 2014):

Three Borescope readings per elevation should be recorded:

- One at least 300mm above the DPC
- One within 300mm of the wall plate below the roof (for gable walls this should be along or just above the dividing line between the ground floor accommodation and the loft)
- One below a windowsill (for gable walls where there are no windows, this can be halfway up the wall between the ground and roof space line)

2.1.3 Review of system commissioning and performance

Generally, all services and systems tests and measurements should be taken post-construction but prior to handover in order to provide 'as-built' results and allow time for remedial works to be undertaken before the dwellings are occupied. Research indicates that one area which can affect the long-term performance of services and systems is their regular maintenance (or lack thereof). Therefore, depending on the information required, it may be advisable that one-off systems tests are repeated at regular intervals over a significant period of time. Table 4 shows the as-built evaluation methods that have been used with respect to assessment of system integration and commissioning.

Installation and commissioning review

England and Wales Building Regulations Part F (HM Government, 2010) outline the requirements for installation and commissioning. In addition, the BPE programme's project execution report outlined the best practice approach:

- Ensure that all services and equipment have been correctly installed and commissioned
- For any and all micro-generation and renewable energy technologies, ensure that installation and commissioning has been undertaken in accordance with the Microgeneration Certification Scheme guidelines.
- For any and all MVHR technologies, ensure that installation and commissioning has been undertaken in accordance with the compliance guide for Part F 2010.
- Review operational strategy for lighting, heating/cooling, ventilation, domestic hot water and compare with equipment installed, referring to appropriate design guidance calculations if appropriate.

Mechanical ventilation testing

When Mechanical Ventilation (either continuous mechanical extract (MEV) or continuous mechanical supply and extract with heat recovery (MVHR)) is installed, two key aspects of MV systems with or without heat recovery need to be measured as part of a performance evaluation study: airflows and the electrical energy consumed to generate those airflows. In MVHR the efficiency of heat recovery can also be important. Post-construction spot-measurement of the electrical energy consumption of MV systems is not a regulatory requirement but is best practice.

Usability of controls: controls interface survey

Control interfaces are the meeting point between the users and the building technology. The six-point criteria developed by Buildings Controls Industry Association (BCIA) (2007) are used to visually rate the performance and usability of control interfaces of cooling, heating, ventilation and lighting systems, as well as touchpoints of the building fabric (window controls). Evaluators can assess the usability of controls themselves by surveying the controls installed and assessing the controls based on several criteria including:

- Clarity of purpose
- Intuitive switching
- Labelling and annotation
- Ease of use
- Indication of system response
- Degree of fine control

Whilst this can provide a relatively objective review of the usability of the controls, it does not necessarily reflect the ability and understanding of different residents in relation to the controls. It must also be noted that the assessors are likely to have some level of expertise and as such their assessment of the controls are likely to be influenced by this. See (Baborska-Narożny and Stevenson, 2019) for recent implementation in case studies.

Table 4. Techniques to assess system installation and performance

Techniques	Stage	Test type	What is assessed	Reveals / provides	Required for Building Regulations	Resulting measure	Stakeholder involvement	Complexity of implementation	Est. Test duration (per dwelling)	Cost
Installation and commissioning review	Post-construction (in-use if necessary)	Quantitative; one-off; measurement & diagnostic	Mechanical & electrical services (e.g. lighting, heating, cooling, ventilation) operation, settings, energy flows	Assurance of correct installation and commissioning or reasons for imbalance, inefficiency or failure of systems	Yes	Various: dependent on system/s tested	Low	High	Medium: 1-2 days	Medium
Mechanical ventilation testing (energy consumption)	Post-construction (in-use if necessary)	Quantitative; one-off; measurement	Heat recovery efficiency; air flows; internal & external temps	Energy consumption of ventilation system	No	W	Low	Medium - high	Medium: 1 day	Low
Mechanical ventilation testing (air flow)	Post-construction (in-use if necessary)	Quantitative; one-off; measurement	Volumetric air flow	Correct balancing of ventilation flow rates	Yes	l/s	Low	Medium - high	Medium: 1 day	Medium
Survey of controls and interfaces	Post-construction / in-use	Quantitative; one-off; diagnostic	Usability of heating, cooling, ventilation, lighting controls (and other controls/interfaces as required)	Appropriateness of design & implementation of controls. Can be compared with resident opinion.	No	-	Low	Low	Low: 1-2 hours	Low

MV tests are recommended to be undertaken post-construction but pre-handover to allow any remedial measures to be undertaken prior to occupancy. Tests can be taken at ‘in-use’ stage to assess maintenance issues and long-term performance.

Some limitations of the above techniques are:

- Requires assessor to have knowledge of construction and design and expertise in undertaking such testing and analysis.
- Reliant on information on system configuration/manufacturer's manuals being available/accessible.
- Testing required varies and can be very complex; may require specialist equipment.
- Reliability and accuracy of results reliant on expertise and objectivity of assessor.
- Does not provide insight into how controls are used by residents.
- Potentially time-consuming as it requires on-site survey.

2.2 Handover: communication of design intent to residents

The handover process can have an impact on the overall energy performance gap. Therefore, it is important to monitor and evaluate the handover process. Much like the evaluation of the design and construction process, there is no quantitative method of evaluating handover; however, there are two techniques that provide qualitative insights and its potential impact upon the future resident's knowledge and understanding of the dwelling, its installed services and maintenance. Both techniques require an evaluator who has experience within the building industry. Cultural sensitivities should also be taken into consideration when working with occupants (Stevenson and Baborska-Narozny, 2018). Table 5 shows the handover evaluation techniques that have been used. The following text describes each technique.

Assessment of handover guidance and building information materials

A variety of material, including user guides, Operation & Maintenance (O&M) manuals and building logbook, is given to occupants of new builds. In the residential sector this is often simply a home user guide. The effectiveness of the material is critical to the use, management and maintenance of the systems, services and controls. Where possible, these should be evaluated in terms of its clarity, comprehensiveness and usability.

Several aspects relating to these should be assessed including the format, quality of illustrations, use of simple and understandable language, as well as an adequate explanation of how to use, maintain and even future adaptation of all the key features. In addition to this assessment, it is important to understand the resident's perspectives and attitudes towards the guidance material. This can be done in the form of a self-completion questionnaire, or through an open-ended question in a semi-structured interview.

Whilst there is not a standard checklist within the building industry, the Code for Sustainable Homes Technical Guide (DCLG, 2008) provided a best practice schedule of evidence required as well as checklists for home user guides.

Observation of user induction and guidance process

Ideally after the review and revisions of handover materials, the observation of user induction and guidance process should take place. The BPE programme's project execution report (TSB, 2010) outlines what approach should be taken;

> *The developer's user handover process should be directly observed, with a member of the evaluation team shadowing a typical user introduction to the equipment and functioning of the home by customer services and providing feedback and recommendations to the developer. The evaluator should have a copy of the home user guide and any written induction procedures with them in order to follow the handover process and should make a note of any errors or omissions in the process as they occur. The handover process should be evaluated in terms of clarity, communication and user engagement. It is useful to take photos of the procedure, but this must always be with the written consent of the parties involved. Typically, a handover visit will last about half an hour to an hour.*

Furthermore, asking that the resident follow along in a home user guide will help provide a familiar reference in the home user guide for later use.

2.3 In-use performance

Most housing performance evaluation studies cover only the operational aspects of dwellings (Forster, Randall, & Churcher, 2014). The primary study elements of the in-use stage are generally:

- Energy assessment
- Indoor environment
- Resident satisfaction and perception

2.3.1 Energy assessment

Measuring the energy use of a dwelling is a key metric for housing performance. In new build housing, ideally the data is gathered for two years to cover two heating seasons. Both ***regulated*** (energy used heating, hot water, ventilation and lighting) and ***unregulated*** (energy consumed by appliances) energy uses should be measured. Table 5 shows the in-use energy assessment methods. The following text describes each technique.

Table 5. Techniques for assessing handover and in-use performance

Techniques	Stage	Test type	What is assessed	Reveals / provides	Required for Building Regulations	Test output/ resulting measure	Stakeholder involvement	Complexity of implementation	Est. Test duration (per dwelling)*	Cost*
Handover stage										
Assessment of handover guidance & information material	Handover	Qualitative; one-off; diagnostic	Handover process & availability & type of info	Communication effectiveness of guidance and information documents / opportunity to revise and improve handover guidance and documents	No	Findings report/ checklist complete	Medium	Low	Low: 1 day	Low
Observation of user induction and guidance process	Handover	Qualitative; one-off; reflective	Handover process	Effectiveness of handover process / opportunity to improve future process	No	Findings report/ checklist complete	High	Low	Low: 1 day	Low
In-use energy performance										
Meter readings (annual, monthly)	In-use	Quantitative; continuous; measurement	Total energy consumption (gas; electricity)	Annual energy data	No	Gas: m3/ft3 Elec: kWh	Low	Low	Low: 5mins (per week/ month/ year)	Low
Smart metering	In-use	Quantitative; continuous; measurement	Total energy consumption (gas; electricity; water; oil)	High frequency energy data	No	Gas: m3 Elec: kWh Water: Litres	Low	Medium - high	High (long-term) As required	Medium
Sub-metering	In-use	Quantitative; continuous; measurement	Electricity breakdown (reg/unreg; indiv elements)	Sub-metered (disaggregated) energy use: isolation of performance and problem solving	No	Gas: m3 Elec: kWh Water: Litres	Low	High	High (long-term) As required	Medium
Appliance level monitoring	In-use	Quantitative; continuous; measurement	Unregulated energy use	Disaggregated (unregulated) energy use: isolation of performance and problem solving		kWh	Low – medium	Medium	Low: 1 day	Medium

Techniques	Stage	Test type	What is assessed	Reveals / provides	Required for Building Regulations	Test output/ resulting measure	Stakeholder involvement	Complexity of implementation	Est. Test duration (per dwelling)*	Cost*
DomEARM	In-use	Quantitative; one-off; diagnostic	Energy use breakdown (e.g. heating, hot water, type of appliances & electrical items, lighting)	Isolation of performance and problem solving	No	kWh	Low	Medium	Medium: 1-2 hours (survey)	Medium
Monitoring of low carbon technologies (eg. heat pumps, solar PV, solar thermal)	In-use	Quantitative; continuous; measurement	Power & heat generation, energy used by LCTs (e.g. heat pumps; solar thermal; PV); environmental factors (e.g. solar irradiation, wind speeds, ground/air temps)	Sub-metered (disaggregated) energy use / generation: isolation of performance and problem solving	No	kWh; W/m2; W; m/s; degC; CoP	Low – medium	High	1 day (input/ analysis)	Medium

**Costs and time also depend on whether suitable meters/sub-metering have been installed as part of development or need to be retrofitted.*

Meter / bill readings

The Green Construction Board (GCB) (2019) recommends 'kWh at the meter' as the universal metric to facilitate year-on-year comparisons of evaluation results and progress. The benefit of this metric is it can easily be measured and understood by all stakeholders, most importantly the people running and occupying the building. The simplest way to obtain energy data is through fuel bills / invoices that provide periodic reporting on energy consumption. Periodic meter readings can also be taken when convenient to the researcher and resident. Depending on the source, meter readings can be gathered on a weekly, monthly or annual basis. Whilst annual energy use does not give insights into specific patterns, it can give an overview of the energy use within a household. Monthly and weekly meter readings can provide more detailed profiles of energy consumption, particularly in terms of seasonal variations.

Meter readings can be accessed in several ways, including resident records (e.g. energy bills) or from the energy supplier. Retrospective anonymised annual gas and electricity consumption data for individual households can be accessed from governmental records; if written permission from the householder is provided and the unique Meter Point Administration Number (MPAN) for electricity supply and Meter Point Reference Number (MPRN) for gas supply to the dwelling are known.

Smart metering and sub-metering of energy consumption and low carbon technologies

More detailed long-term and 'real-time' data on the energy consumption and other utilities such as water can be gathered through the access of installed smart meters and/or sub-metering equipment. The data can be gathered over an indefinite period, at any interval (e.g. from 5 minutes, used in research studies such as the BPE programme, to hourly, a common reporting interval for supplier installed smart meters). Smart meters enable secure remote access (via internet) to the energy consumption. This, in theory, allows for frequent and accurate readings of energy use. It also ideally, if connected to a suitable web-based platform, can provide real-time visual display of the data to provide early detection and correction of any issues with the data collection. Common metering provide data on the energy used for: Heating, Domestic Hot Water (DHW), Lighting, Cooking, Ventilation (particularly MVHR), and Appliances.

Sub-metering can also be done for low carbon technologies (LCTs) over the long-term such as: photovoltaic systems, solar thermal systems, Air/ground source heat pumps. Many newly installed PV systems have inverters with smart metering capabilities. By monitoring the following variables over an extended period of time, it is possible to calculate the CoP (Co-efficient of Performance) and establish how the heat pump (for example) is performing in relation to its modelled/estimated performance.

Equipment required includes:

- Electricity meters (to monitor power used by pump; PV generation and export)
- Heat flux meters and temperature sensors (to monitor heat output/performance of heat pumps)
- Pyranometers (to monitor solar irradiation)

Remote monitoring of heat pumps can provide frequent and accurate data on:

- The system heat output (using a heat flux meter)
- Electricity (power) used by the pump
- Ground/air temperature

Recommendations:

- Designers should design in monitoring or anticipation of post-occupancy monitoring. Monitoring decisions should be made early to integrate kit design into that of the building space and the M&E systems;
- Kit specifications (e.g. accuracy, frequency) should be selected to meet the nature of monitoring and flexibility to meet and changes in monitoring requirements when the monitoring is underway;
- Calibration and recalibration requirements and frequency should be clear from the start to ensure continuing good performance of the kit;
- Ensure that the kit installation and commissioning is by a qualified person and it is done as specified and designed;
- Verify data early to ensure that sensors are capturing valid data and transmitters and archive/backups and transmitting and storing accurate data;
- Consider the impact on the residents to ensure it is not obtrusive or located in inconveniencing locations. If possible, ensure that access by the monitoring team for checks and recalibration is easy and of minimal disruption to residents;
- Choose locations of sensors to best represent the space being monitored, and minimise risk of resident interference with the kit;
- Facilitate alerts to be sent should data sensing or logging fail;

- Minimise the risk of data loss through signal failure by providing adequate time lag through local data storage so that this can be transmitted when signal reconnects;
- Good rapport and communication with residents are essential so that access is easy when needed.

Energy and appliance audit / energy breakdown and reporting

Another method of assessing the unregulated energy use within a dwelling is the use of power-meters. These can be installed at specific sockets within the dwelling and record the energy usage of individual appliances. They can be installed over a short time period (e.g. 1-2weeks) or over the long-term (e.g. 1-2 years).

An energy and appliance audit, undertaken by a trained individual, can help breakdown the electricity consumption of a household and identify areas of over-consumption, when the dwelling is occupied. DomEARM is a 'best practice' energy assessment and reporting methodology used in both industry and academia. It was developed by Arup with Oxford Brookes Institute for Sustainable Development: Low Carbon Building Group (OISD:LCBG). It is based on both total and individual fuel and power data and provides a much more detailed understanding of how and where energy is used in the home.

Limitations:

- Meter / bill readings does not provide detailed energy use breakdown.
- Reliability dependent on who has supplied data (e.g. based on estimates or read direct from meter).
- Monitoring and sub-metering requires specialist skills for installation, processing, management and analysis of data.
- Risks/issues found in previous studies: Poor quality of meters; lack of reliable and accurate communication between sub-meters and BMS; incorrect labelling of sub-meters; wireless signal drop-out and other issues leading to a lack of reliable and full dataset; can be time-consuming and expensive as well as invasive to householders if additional sub-metering/visits are required to overcome data shortcomings

2.3.2 Indoor environment: comfort and air quality

Gathering actual temperature and other indoor environmental conditions (e.g. relative humidity (RH) and CO_2 concentration levels) is important in terms of understanding resident's thermal and environmental comfort, and its relation to energy consumption. Table 7 shows the in-use environment assessment methods. The following text will describe each technique. Environmental data can be collected in two ways:

1. Short-term (one-off) spot measurements and
2. long-term monitoring.

Spot measurements

Common spot measurements are typically one-off measurements of:

- Temperature (°C),
- Relative Humidity (%RH),
- CO_2 (ppm),
- Light (lux) ('nice to have' and may be only necessary in specific studies, e.g. to establish the effectiveness of design to provide claimed level of daylight for a space to meet specific standards), and
- Noise (dB) ('nice to have' and may be only necessary in specific studies, e.g. to validate claims of noise complaints or the impact of a busy road nearby).

In addition, Air speed (m/s), Clo, and Met are used for Predicted mean vote (PMV) analysis.

Beyond IAQ and thermal comfort, spot measurements of volatile organic compounds (VOCs), particulate matter (e.g. PM 10, PM2.5) and other indoor pollutants can be measured to assess indoor environmental quality (IEQ) for certain standards (Table 6). Spot measurements are relatively simple to undertake, with a small amount of training in how to use the equipment and how to record and analyse the data correctly and accurately. They are useful if the installation of remote monitoring and/or long-term data loggers is not possible. It is recommended that measurements are taken over a period of at least 5 minutes, with an average then taken.

Table 6. Maximum concentration levels and testing methods for IEQ (USGBC, 2016)

Contaminant	Maximum concentration	ASTM and U.S. EPA methods	ISO method
Formaldehyde	27 ppb	ASTM D5197; EPA TO-11 or EPA Compendium Method IP-6	ISO 16000-3
Particulates (PM10 for all buildings; PM2.5 for buildings in EPA nonattainment areas)	PM10: 50 micrograms per cubic meter	EPA Compendium Method IP-10	ISO 7708
Ozone (for buildings in EPA nonattainment areas)	PM2.5: 15 micrograms per cubic meter	ASTM D5149 - 02	ISO 13964
Total volatile organic compounds (TVOCs)	0.075 ppm	EPA TO-1, TO-15, TO-17, or EPA Compendium Method IP-1	ISO 16000-6
Target chemicals listed in CDPH Standard Method v1.1, Table 4-1, except formaldehyde	500 micrograms per cubic meter	ASTM D5197; EPA TO-1, TO-15, TO-17, or EPA Compendium Method	ISO 16000-3, 16000-6
Carbon monoxide (CO)	CDPH Standard Method v1.1–2010, Allowable Concentrations, Table 4-1	EPA Compendium Method IP-3	ISO 4224

* ppb = parts per billion; ppm = parts per million; μg/cm = micrograms per cubic meter

Long-term monitoring

Long-term environmental monitoring is a relatively simple and accessible method of providing temperature, relative humidity and even CO_2 data on a continuous and regular basis (30-minute to one-hour intervals recommended). The data loggers can log at a variety of rates; from one minute to daily and weekly. The rate of logging is dependent on the level of detail required as well as the length of the assessment period. Although some data loggers require regular checks and replacement due to their storage capacity, some data loggers enable remote connectivity via Wi-Fi, which reduces the need for the evaluators to visit sites in order to download the data. Whilst the actual data collection units are not always vastly expensive, the remote monitoring hub increases costs substantially. In addition, some sensors require an electrical socket, and this should be considered when installing the systems for a long period of time.

Typical data to be collected are internal and external temperature and RH and internal CO_2 concentrations. The data collection, storage and processing systems can also be particularly time intensive, so the data variables collected need to be carefully considered in relation to the requirements of the evaluation.

Other environmental monitoring data can include:

- Occupancy monitoring (motion detection (I/0) commonly measured using passive infrared sensor (PIR) which is an electronic sensor that measures infrared (IR) light radiating from objects in its field of view),
- window and door sensors (I/0) to observe natural ventilation habits and occupancy, and
- Solar radiation (W/m2) - informative for PV installations.

Key limitations of the methods include:

- Reliant on experience of practitioner; cost of sensors; no agreed location for installing the sensors.

2.3.3 Resident satisfaction and perception

Residents can have a significant impact on housing performance (Stevenson, 2019b). There are several ways in which resident behaviour can be assessed which are described in the following sub-sections. However, due to the many and varied factors involved in the energy consumption of households, quantifying the impact of the residents on the overall energy consumption of the dwelling is extremely difficult.

As the methods described in the following sub-sections are related to residents, they can be undertaken when the dwelling is in-use. These methods can provide insights on several resident-related aspects such as number of residents, pattern of use, occupation hours, perception of thermal comfort, understanding and operation of controls for heating and ventilation. Table 7 shows the methods for gathering resident feedback.

Resident satisfaction surveys - assessing perceived comfort and satisfaction with indoor environment

Resident's perception of thermal comfort and satisfaction can be assessed and evaluated through semi-structured interviews, self-completion questionnaires such as the Building Use Survey (BUS), self-completion diaries and focus groups (for multi-residential buildings). Conducting surveys amongst residents requires skill and sensitivity, ensuring their personal data and views are held in confidence and creating the right relationship between developer and resident. It is advised that the consent of individuals taking part in the survey is obtained.

1. **Self-completion questionnaires:** The BUS questionnaire is a standardised questionnaire that has been used within BPE and POE projects. It requires a license from Arup, and although the data collection and distribution are the responsibility of the evaluator, analysis and benchmarking is undertaken by Arup. It can be used to assess the opinions of residents at early-stage occupancy as well as further into the occupancy period, once the residents have settled into their home and become familiar with the home.

   Resident's understanding of controls can be assessed and evaluated through walkthroughs and interviews (described previously), photographic surveys (described previously), and self-completion questionnaires. A self-completion questionnaire is a useful, yet relatively simple tool to gather quantitative data on both the resident's use and understanding of the controls within their home. It can be produced in either paper or online form. Both formats have positives and limitations; an online survey has the added benefit of the answers being stored automatically (saving the evaluator time in processing and managing the data) but do not often allow for additional (but relevant) comments to be made by the participant. Paper questionnaires afford the evaluator the potential to meet face-to-face with the participants and can be very useful discussion tools.

2. **Semi-structured interview** with residents helps to identify any first-hand experiential issues with building performance.

3. **Diaries:** Self-completion diaries (for example over a period of 1-2 weeks during different seasons) enable a more long-term understanding of resident's thermal comfort to be gathered and evaluated. The results of a diary (if correctly dated) can be compared against actual temperature and other environmental data for that period, which can give a more comprehensive insight into the resident's thermal comfort. Thermal comfort / activity logging sheets can pick up information relating to resident behaviours over a period of time and allow changes in behaviours to be recorded. These can be useful as seasonal comfort assessments where clothing (clo), activity level (met) at a particular time of day can be assessed with temperature, RH and air speed (where measured) to compare actual mean vote (AMV) to predicted mean vote (PMV) (Gallardo et al., 2016; Yao, Li, & Liu, 2009).

   The number of residents, and occupancy patterns which impact upon the energy consumption of the household can be assessed using such methods as occupancy sensors and activity log sheets. Normalisation and/or logging sheets, which are completed by the residents and capture how the residents use the home can provide an insight into typical behaviours, occupancy patterns and numbers. Ideally, this would be undertaken during both the winter and summer to pick up any seasonal differences in behaviours and occupancy patterns.

4. **Resident focus group** can promote interaction ad consensus amongst residents and provide collective feedback about the performance of the building. Specifically, for multi-residential buildings or development-scale neighbourhoods constructed concurrently.

Table 7. IEQ and resident assessment techniques

Techniques	Stage	Test type	What is assessed	Reveals / provides	Required for Building Regulations	Test output/ resulting measure	Stakeholder involvement	Complexity of implementation	Est. Test duration (per dwelling)	Cost
Environmental monitoring										
Spot measurements of indoor and outdoor environmental conditions	Post-construction / in-use	Quantitative; one-off; measurement	Temperature; relative humidity; indoor air quality (CO_2); noise levels; light levels; wind speed, etc.	Pre/ post-retrofit comparisons, comparisons with resident perception, and isolation of irregularities with implications on energy use	No	Degrees C, RH%, CO_2 ppm, etc.	Low	Low	Low: 1-2 hours	Medium - high
Monitoring of indoor and outdoor environmental conditions	Post-construction / in-use	Quantitative; continuous; measurement	Temperature; relative humidity; indoor air quality (CO_2), etc.	Pre/ post-retrofit comparisons, comparisons with resident perception, and isolation of irregularities with implications on energy use	No	Degrees C, RH%, CO_2 ppm, etc.	Low	Medium	High: (long-term) As required	Medium - high
Resident assessment										
Occupancy sensors	In-use	Quantitative; continuous; measurement	No. of residents; occupancy patterns	Occupation patterns and habits – to be analysed against energy use, IAQ, opinion, etc.	No	1 / 0	Low	Low	High: (long-term) As required	Low - medium
Text diaries and activity logging sheets	In-use	Qualitative; continuous; diagnostic	Resident behaviours & activities; thermal comfort; no. of residents; occupancy patterns	Resident habits, opinion, and interaction / Pinpoint issues, problem resolution	No	Qualitative occupancy pattern data	High	Low	High: 5-10mins per day/week	Low
Photographic surveys	In-use	Qualitative; one-off; diagnostic	Resident behaviours & activities	Resident habits, opinion, and interaction / Pinpoint issues, problem resolution	No	Photo-documentation	Low	Low	Low: 1-2 hours	Low

Techniques	Stage	Test type	What is assessed	Reveals / provides	Required for Building Regulations	Test output/ resulting measure	Stakeholder involvement	Complexity of implementation	Est. Test duration (per dwelling)	Cost
Video diaries	In-use	Qualitative; one-off; reflective	Resident use of controls	Resident habits, opinion, and interaction / Pinpoint issues, problem resolution	No	Photo-documentation	High	Low	High: varies	Low
Semi-structured interview with residents	In-use	Qualitative; one-off; reflective	Resident behaviours & activities; thermal comfort; no. of residents; occupancy patterns	Opinion on aesthetic, comfort, noise, air quality, perception of health and control, etc. Pinpoint issues, problem resolution	No	Wide-range of qualitative occupancy data	Medium	Low - medium	Low: 1-2 hours per visit	Low
Walkthroughs with residents	In-use	Qualitative; one-off; reflective	Resident behaviours & activities; thermal comfort; no. of residents; occupancy patterns	Opinion on aesthetic, comfort, noise, air quality, perception of health and control, etc. Pinpoint issues, problem resolution	No	Qualitative occupancy data	Low	Low	High: (long-term) As required	Low - medium
Self-completion questionnaire (BUS)	In-use	Quantitative; one-off; measurement	Resident behaviours & attitudes/views; thermal comfort; no. of residents; occupancy patterns	Opinion on aesthetic, comfort, noise, air quality, perception of health and control, etc. Pinpoint issues, problem resolution	No	Comfort / satisfaction	High	Low	High: 5-10mins per day/week	Low

Limitations of some of the methods include:

- Reliant on residents to complete
- Relatively expensive to undertake (BUS - under license)
- Concern within BPE studies that BUS is ineffective in providing useful findings
- Text diaries and activity logging sheets: Time consuming; Accuracy and reliability dependent on co-operation & skills of those recording observations (e.g. residents).
- Photographic surveys: Quality of assessment dependent on assessors having in-depth knowledge of building design & construction; Due to nature of 'spot-checks' issues that crop up between visits may be missed/not reported.
- Video diaries: Time consuming; Accuracy and reliability dependent on co-operation & skills of those recording the video diaries (e.g. residents).
- Semi-structured interviews with residents: Reliability and quality of findings dependent on expertise of evaluators; availability of interviewees and information; Data collection can be time-intensive; preparation including pilot interviews essential.
- Walkthroughs with residents: Quality of assessment dependent on assessors having in-depth knowledge of building design & construction; Time intensive (including travel and data collection); Due to nature of 'spot-checks' issues that crop up between visits may be missed/not reported.

2.4 New tools to support performance evaluation

Building energy performance improvement toolkit (BEPIT)

BEPIT[9] provided by Bioregional, combines detailed but easily understood learning materials with in-depth facilitation by an expert through each stage of a housebuilding project – design, procurement and construction. The methodology stems from the realization that the performance gap consists of multiple, minor, and frequently occurring issues spread throughout most elements of a building.

- Smoother build – save time and money on snagging
- Improved design details – fewer buildability clashes on site
- Keep clients and owners happy – by building quality homes.

The BEPIT approach helps:

- Tackle root causes - Through research Bioregional developed a set of seven clusters of performance-critical issues to focus on.
- Pre-empt problems - help mitigate against these issues proactively at each stage of the project: design, procurement and construction.
- Get buy-in - Get up-front buy-in from developer and project teams - making sure the message comes from the top is key to creating culture change.
- Build collaboration among teams - BEPIT enables teams to collaborate and communicate with each other to solve minor problems before they escalate. Through a combination of focused meetings using our toolkit to educate and help communicate about issues and solutions, Bioregional work together with the lead contractor and subcontractors to beat the performance gap on the project.

Assured Performance Process (APP)[10] (NEF)

Independent and expert input to the development process to minimise energy, overheating, and indoor air quality performance gap.

APP maps to the RIBA Plan of Work and has five stages of expert, impartial review and assessment (Figure 5). APP assessors are accredited by The National Energy Foundation (NEF) for their expertise and they offer two services:

- APP implementation across all five key stages – supporting the client throughout the development process. This is a bespoke service.
- One off reviews tailored to the stage of the development

[9] https://www.bioregional.com/projects-and-services/creating-sustainable-homes-communities/building-energy-performance-improvement-toolkit-bepit
[10] http://www.assuredperformanceprocess.org.uk/what-is-app/

Figure 5. APP implementation process

Online energy performance monitoring and evaluation tool (ObepME)

Online energy performance monitoring and evaluation tool (ObepME) (Jradi et al., 2018) is a tool developed to continuously monitor and evaluate building energy performance. ObepME, serves as a basis for fault detection and diagnostics and forming a backbone for continuous commissioning. The platform requires simulations from the calibrated dynamic energy performance model and the actual measured energy consumption data as two key pillars. The ObepME tool aims to ensure that the building is performing and operated in the most efficient manner and to reduce the dynamic energy performance gap through automatic comparison between the simulations from the dynamic energy performance model and the measured data from the different meter streams in the building. The tool requires that a calibrated detailed energy model be automatically run on a daily basis to simulate the building transient performance for the previous day taking into account measured weather conditions, occupancy counts at different building entrances, and inputs from the building management system in terms of energy systems' operational parameters and set-points. While the building energy performance for the previous day is automatically simulated and reported on a daily basis, the simulation results are used as a baseline and compared to the measured energy consumption data from the building to evaluate the energy performance gap.

Insurance-backed warranty for whole life housing energy performance (I-LIFE)

The I-LIFE project[11] funded by Innovate UK developed and tested a new commercial insurance product designed to underpin a whole-life warranty for the energy performance of new housing. The project developed an integrated approach to building performance assurance, supported by specification and long-term building testing, socio-technical monitoring protocols and a building information modelling execution plan to underpin the warranty. The I-Life insurance framework is set out in three phases: (1) Sell the insurance to developers or house purchasers; (2) Construction phase: I-Life construction checklists are developed and used to evaluate process; and (3) Insured phase.

The insurance backed warranty is based on the principle that if there are deficiencies in the building fabric or energy systems (building factors) of an insured dwelling which causes excessive energy consumption, the insurance would cover these deficiencies. Conversely, I-life would not insure excess energy consumption resulting from climatic or occupancy factors. The need to parse out the difference between these factors necessitates BPE. To be able to accurately identify the cause (building, climatic or occupancy factors) of excessive energy use, a socio-technical building performance evaluation based claims process is developed and tested for four new-build flats located in a housing development in Southeast England (Gupta, Gregg, & Salvati, 2020). Results of the trial in new-build low energy flats indicated that occupant behaviour does not significantly affect actual space heating demand (which is mainly determined by building related factors), as much as hot water and use of electrical appliances, indicating that in low energy gas heated dwellings, excessive gas use is more likely to be eligible for an insurance claim than high electricity use.

[11] https://ilifebuildings.wordpress.com/

2.5 Developing a housing performance evaluation framework

To bring consistency and flexibility in evaluating housing performance, a framework is developed as shown in Table 8 that lays out what methods can be used in which s building life-cycle stage covering inception and briefing, design and construction, handover, post-construction and in-use stages.

The framework is designed to have three levels starting at the ‘basic’ level and developing incrementally to ‘core’, and ‘advanced’ levels. The expertise required to conduct and interpret evaluation activities vary and are shown to increase along the three levels as shown in the table.

Table 8. Housing performance evaluation framework. Adapted from Gupta, Gregg, & Cherian (2019) and Gupta et al. (2019).

			Time, cost, expertise required / depth of study →		
No.	**Phase**	**Study elements**	**Level 1 – Basic**	**Level 2 – Core**	**Level 3 - Advanced**
1	**Inception / briefing**	Planning	-	-	Initial induction with design, build teams and client. Specifications, roles, evaluation plan (e.g. logging equipment integration), performance targets finalized. BPE team integrated with design and construction team from start.
2	**Design and construction**	Progress review	-	Site assessment: Photographs, Assess sub-metering arrangements, location of sensors	Walkthrough and interviews with design and construction teams. Photographs, review sub-metering plan, review commissioning plan, review logging equipment installation plan
3	**Handover**		-	Evaluation of handover information	Observation of handover and user induction process
4	**Post-construction / In-use**	Review of design intent	Collection and desktop review of available design data (e.g. construction drawings, model, PHPP), metering strategy, details of building and its use)	Desktop review of building services and energy systems (e.g. assessment of M&E drawings, commissioning documents, etc.)	Completion walkthrough and Interviews with key stakeholders (e.g. designer, owner, developer) What changed? What would be done differently?
5		Technical building survey (fabric and systems)	Inspection of build quality and services using photographic / video documentation Assessment of building fabric: air permeability test, infra-red thermography	Assessment of building fabric: air permeability test, infra-red thermography Controls interface survey	Review of installation and commissioning of services Assessment of building fabric: air permeability test, infra-red thermography, heat flux measurements
6	**In-use**	Energy assessment (consumption and generation)	Meter readings / energy bills for at least one year	Monitoring of utility meters (smart or installed logging equipment): analysis of energy demand / generation profiles	Sub-metering of energy (e.g. energy generation, cooling/ heating, hot water, ventilation, lighting, equipment) Electricity plug load monitoring of individual appliances
7		Environmental monitoring	Temperature and RH spot readings (internal and external) (coincide with resident survey)	Temperature and RH loggers/ monitoring (internal and external (including weather station data)) Additional parameters spot read/ logged, e.g. CO2, lux, noise, wind speed.	Additional parameters spot read/ logged, e.g. carbon monoxide (CO), PM(x) (particulate matter), bioaerosols, volatile organic compounds (VOCs) (depending on objectives, e.g. IAQ studies) In addition, clo and met (contributes to predicted / actual mean vote analysis)
8		Resident satisfaction and perception	Resident satisfaction survey (perception of indoor environment and control) e.g. BUS	Semi-structured interview (individual residents)	Thermal comfort diary (thermal sensation and thermal preference of residents) Focus group (relevant for multi-resident buildings)

Chapter 3: Past studies on housing performance

This chapter provides an overview of major studies that have been undertaken on housing performance in the UK. A Data Navigator is developed to review the studies; their objectives, scope and key findings.

Using a combination of desk research and online survey with experts, the following resources on housing performance are identified:

1. **Research programmes** (6) on housing performance
2. **Repositories** (5) and **Meta-studies** (8) that store and compile data from the individual housing performance evaluation (HPE) studies.
3. **HPE studies** (91) are individual studies of housing performance which are location based.

A Data Navigator framework was developed to characterise the meta-data associated with the above.

3.1 Online survey

An online questionnaire was developed to survey professionals with any connection to housing performance evaluation. The questionnaire sought to discover new HPE study data that might exist. The questionnaire was open from March 2019. Since then, the questionnaire received 11 responses. Five of these respondents had some information on HPE studies but only three had information specific enough to be categorised in the Data Navigator (total number of HPE studies added = 7).

Among the respondents, energy/sustainability consultant was the most represented followed by architecture, construction and engineering professionals, as well as academics and housing associations. The aspects of housing performance that respondents were most interested in was thermal performance of dwellings, given that space heating is the largest end use of energy (Figure 6). The least interesting or engaged method given was feedback from residents.

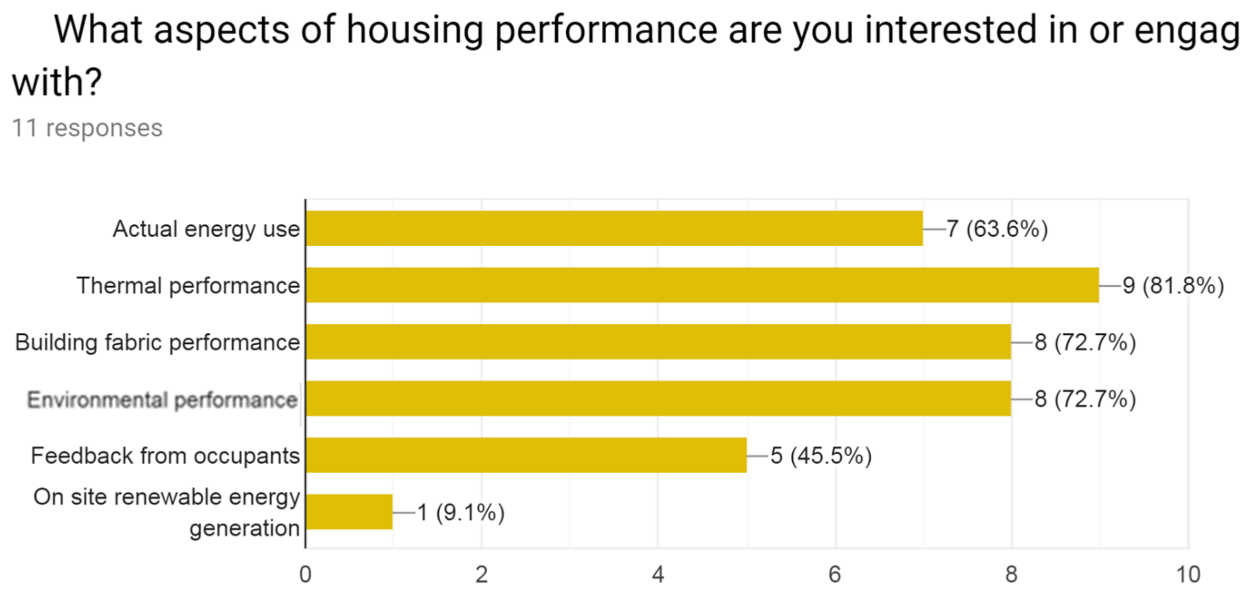


Figure 6. Aspects of housing performance in which respondents were most interested.

3.2 Data Navigator

To review the different types of housing performance resources, a Data Navigator framework was developed having two levels of operation covering:

- Research programmes, repositories and meta-studies
- Individual housing performance evaluation studies

Table 9 shows the meta-data criteria included in the Data Navigator for characterising different research programmes, repositories and meta-studies, identified from the desk research and online survey.

Table 9. Data Navigator for characterising housing performance research programmes, repositories and meta-studies

Meta-data	Purpose / example
Housing performance resource	research programme / repository / meta-study title
Description	e.g. objectives, methods, findings
Number of dwellings studied	Relevant numbers regarding dwellings evaluated
Location	Regional location represented
Tenure	e.g. social housing, private
Duration	Longitudinal / cross-sectional
Study Type / source type	e.g. HPE study, dataset, raw data
Ownership / Controller	Association: e.g. Innovate UK
Location of Data	Online link(s)
Data Formats	e.g. report, dataset
Data Quality	See Table 10
Availability / Access	e.g. public access, free, private dataset
Meta-study or other cross-availability	Cross representation between research programme / repository / meta-study

To assess data quality associated with the research programmes, repositories and meta-studies, data quality standards are incorporated following the method defined by (Forster, Randall, & Churcher, 2014) (Table 10).

Table 10. Scoring matrix for assessing dataset quality

Assessment	Data capture standard	Data capture consistency	Transparency of processing	Type of publication	Type of peer review
Level 3	Following an independent standard (e.g. ISO, BS, chartered institute)	Method defined pre-study and applied consistently throughout	Method of analysis or processing was published and peer reviewed	Results published and available (e.g. report, papers)	Suitable for an academic journal
Level 2	In-house standard but defined and published or available	Method evolved during early part of study, or standard not applied consistently	Method of analysis or processing was published but not peer reviewed, or only parts were published/ reviewed	Results were written up but retained in-house or restricted circulation, or only partially written up	Informal peer review (e.g. web forum)
Level 1	No known standard for capture, or standard not published	Method evolved during early & late stages of study	Method of analysis or processing has not been published	Results were not written up	No peer review
Unknown	It is not known whether a standard was applied or not	It is not known whether data was captured consistently or not	It is not known whether the processing or analysis method has been published or not	It is not known whether the results were written up or not	It is not known whether the results were peer reviewed or not

In the Data Navigator, the levels are listed in order following each assessment. That is if:

- Data capture standard were at level 3,
- Data capture consistency were at level 3,
- Transparency of processing were at level 1,
- Type of publication were at level 2, and
- Type of peer review were at level 3

The data quality results would be presented as 3, 3, 1, 2, 3

The Data Navigator framework is also used to characterise HPE studies. Meta-data criteria associated with this are shown in Table 11.

Table 11. Data Navigator for characterising individual studies of housing performance

Meta-data	Purpose
Case Study Title	Published title of HPE study
Programme / funding	Association with programme
Location	Location of HPE study (city / town)
Period of study	Years of evaluation
Purpose / performance evaluation phases covered	Description of intent; Evaluation phase: post construction, in-use, both
Typology / tenure	e.g. private, social
Total dwellings in development	Number of dwellings in development
Number of evaluated dwellings	Number of dwellings evaluated
Design Standard	Design standard sought by HPE study dwellings
Number of Passivhaus dwellings	Number of Passivhaus dwellings
SAP range / SAP mean	Range of SAP and mean for evaluated dwellings
Ventilation type	e.g. MVHR, MV
Low carbon technologies / unique construction feature	e.g. PV, heat pump, SIPs
Citation / source	Reference of related study, links to online presence
External reference number	e.g. BPE programme reference number
Fabric data: Air-permeability, HLC, U-value	Number of dwellings with available data
Systems: MVHR flow data, PV, solar thermal	Number of dwellings with available data
In use: Energy use data, designed (SAP) vs. as-built energy use, space heating energy use, environmental data, overheating data, BUS (responses)	Number of dwellings with available data

3.3 Research programmes, repositories and meta-studies

The following research programmes, repositories, and meta-studies on housing performance have been identified covering Government funded programmes, field trials and a range of published meta-studies.

RESEARCH PROGRAMMES:

1. Innovate UK (formerly TSB) BPE Programme
2. AIMC4
3. Partners in Innovation Project
4. Good Homes Alliance Monitoring Programme
5. EST Heat Pump domestic field trials
6. PV domestic field trials

REPOSITORIES:

7. Digital Catapult | Building Data Exchange
8. Low energy buildings database
9. EMBED: Building Performance Platform
10. EPC Register
11. UKERC energy research centre

META-STUDIES:

12. Insights from Social Housing Projects - Building Performance Evaluation Meta-Analysis (NEF)
13. Innovate UK Building Performance Evaluation Programme: Findings from domestic projects: Making reality match design
14. Innovate UK MVHR meta-study
15. EST Heat Pump domestic field trials Phase 1: Getting warmer: a field trial of heat pumps
16. EST Heat Pump domestic field trials Phase 2: The heat is on
17. PV domestic field trials evaluation
18. Insurance-backed warranty for whole life housing energy performance (I-Life) - Performance gap analysis of Innovate UK's BPE programme data
19. Evaluation of the UK Government's Renewable Heat Premium Payment (RHPP) scheme

These programmes and meta-studies have been characterised using the Data Navigator as shown in **Appendix 1** available online so that the table can be dynamically searched, sorted, or filtered. A snapshot of the table is shown here (Figure 7).

Housing performance resource	Description	No. of dwellings studied	Location	Tenure	Duration	Ownership	Data / report(s) location (Repository cross-reference)	Data formats	Data quality	Availability / access	Publications
RESEARCH PROGRAMMES											
Innovate UK (formerly TSB) BPE Programme	£8m TSB funding for 4yr programme looking at domestic new build (and non-domestic). It aimed to gain real world performance data from recently completed buildings; to enable the industry to learn more about the factors and variables that influence performance; to embed a culture of building performance evaluation in the construction industry; and to generate a knowledge base of building performance case studies. All buildings studied were designed to high sustainability standards. 54 studies were undertaken; 10 of which were based on the same site; creating 44 unique studies. Organisations: Innovate UK; Academic and industry partners; developers and housing associations Methodology/Approach: Phase 1: Post-completion & Early occupation including design, commissioning, construction reviews; Phase 2: In Use & Post Occupancy Evaluation including energy and environmental monitoring, performance testing (fabric & services), surveys and questionnaires. Weblink: https://connect.innovateuk.org/web/building-performance-evaluation/overview https://buildingdataexchange.org.uk/	350 dwellings over 44 studies	Great Britain	Mix (social / private)	2010 - 2014	Innovate UK	Digitial Catapult | Building Data Exchange	Datasets: reports, publications including guidance & templates	3,3,2,3,3 (quantitative and qualitative available)	Public free (reports only; datasets private)	Insights from Social Housing Projects Building Performance Evaluation Meta-Analysis (NEF) (Seguro, 2015) Building Performance Evaluation Programme: Findings from domestic projects Making reality match design (Innovate UK) Palmer *et al.*, 2016) MVHR meta-study Insurance-backed warranty for whole life housing energy performance (I-Life)
AIMC4	AIMC4 is a unique partnership of companies, created to research, develop and pioneer the volume production of the low carbon homes for the future. The AIMC4 consortium will develop and apply innovative materials, products and process to meet the Governments Code for Sustainable Homes, Level 4 energy performance, through innovative fabric and building services solutions only thus embedding reduced carbon emissions within the performance of the dwelling. It is co-funded by TSB as part of the Low Impact Building Programme. Organisations: Technology Strategy Board (TSB, now Innovate UK), Stewart Milne Group, Barratt Developments PLC and Crest Nicholson PLC, the Building Research Establishment (BRE), H+H UK Ltd, BRE Scotland. Methodology/Approach: SAP, CLIP & CALIBre tools, As Built testing and measurement, Post-occupancy monitoring incl. Social surveys and physical monitoring. ***Findings / provides:*** • Early engagement between project partners is essential • A U-value of around 0.15 appears optimal for masonry and SIP solutions when weighing up cost and buildability. • For site installation, triple-glazed windows and double-glazed French doors should be the new standard.	17 (14 studied)	England & Scotland (5 locations)	Mix (social / private)	2009 - 2013	AIMC4 Consortium	AIMC4 information papers 1-4	Reports	3,3,2,3,3 (quantitative and qualitative available)	Public free (reports only; datasets private)	
Partners in Innovation Project	**Organisations:** DCLG, National Trust, Redrow Homes, Bryant Homes, NHBC, Concrete Block Association, Vent-Axia, Leeds Beckett University (formerly Leeds Met University), UCL; JRF, JRHT, Housing Corporation, DETR, Wates Construction Ltd, York Housing Association. **Methodology/Approach:** The projects were conducted using an action research (AR) approach, in which the research teams simultaneously participated in (largely in a consultative capacity) and observed the various aspects of the development process. Qualitative and quantitative measuring and monitoring tools were used in some cases but due to project delays in others it was not completed.	>700	England	Mix (social / private)	1999 - 2010	DCLG, *et al.*	No main source: see individual case studies	Reports, publications	3,3,3,3,3 (quantitative and qualitative available)	Public free (reports only; datasets private)	

Figure 7. Screenshot of programme and meta-study data navigator (level 1)

3.4 Studies on housing performance

About 91 studies on housing performance have been identified, ranging from studies conducted for a single dwelling to multiple dwellings on a single location.

The housing performance studies have been characterised using the Data Navigator as shown in **Appendix 2** available online so that the table can be dynamically searched, sorted, or filtered. A snapshot of the table is shown here (Figure 8).

No.	Case Study Title	Programme / funding	Location	Developer / organization	Period of study	Purpose / performance evaluation phases covered
1	**Stamford Brook development**	Partners in Innovation Programme	Altrincham, England		2004-2010	Performance evaluation of a planned 25-35% efficiency over 2002 UK Building Regulations
2	**St. Nicholas Court**		York, England		1999-2003	To explore the implications of an enhanced energy performance standard for new housing for the design, construction and performance of timber framed dwellings.
3	**AIMC4_1**		Meridian Park, Corby, Northants	Barratt Developments	2009-2013	Purpose: to develop robust technical and commercial solutions to meet the energy requirements of Level 4 of the Code for Sustainable Homes using fabric-first solutions. Stage 1: preconstruction stage involving development of the supply chain and the design/technical specification, which were interactive and iterative processes that involved not only the supply chain but also the developers' construction teams. Stage 2: delivery, ie the construction phase. Stage 3: as-built performance evaluation followed by a 12-month postoccupancy study.
		AIMC4 (BRE Trust funded)				

Figure 8. Screenshot of case study data navigator (level 2)

In total there are about 826 dwellings for which performance evaluation studies in the UK were identified. The studies are categorized by the programme or funding source as shown below:

- Innovate UK BPE Programme (43)
- Domestic PV field trials (18)
- AIMC4 (5)
- Private (5)
- Building for 2050 (3)
- Good Homes Alliance Monitoring Programme (3)
- MK Energy Park studies (3)
- Partners in Innovation Programme (2)
- Zero Plus (2)
- Various / other (7)

Figure 9 shows the timeline of housing performance studies. The two programmes with the largest concentration of studies in time are indicated. Figure 10 shows the count of study type for HPE studies where data were available. Figure 11 shows the dwelling typology percentages across dwellings in the HPE studies where data were available.

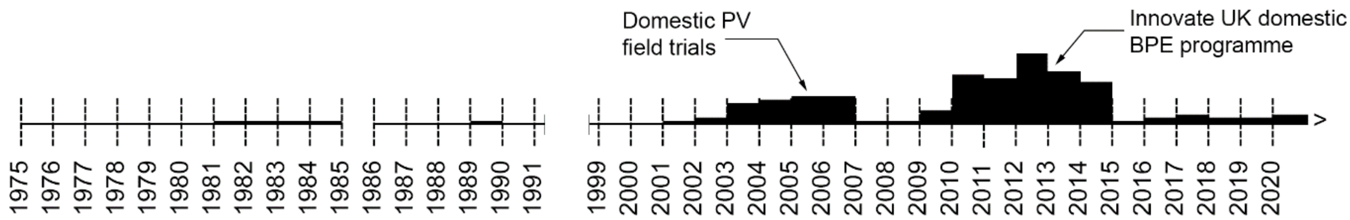


Figure 9. Housing performance study timeline

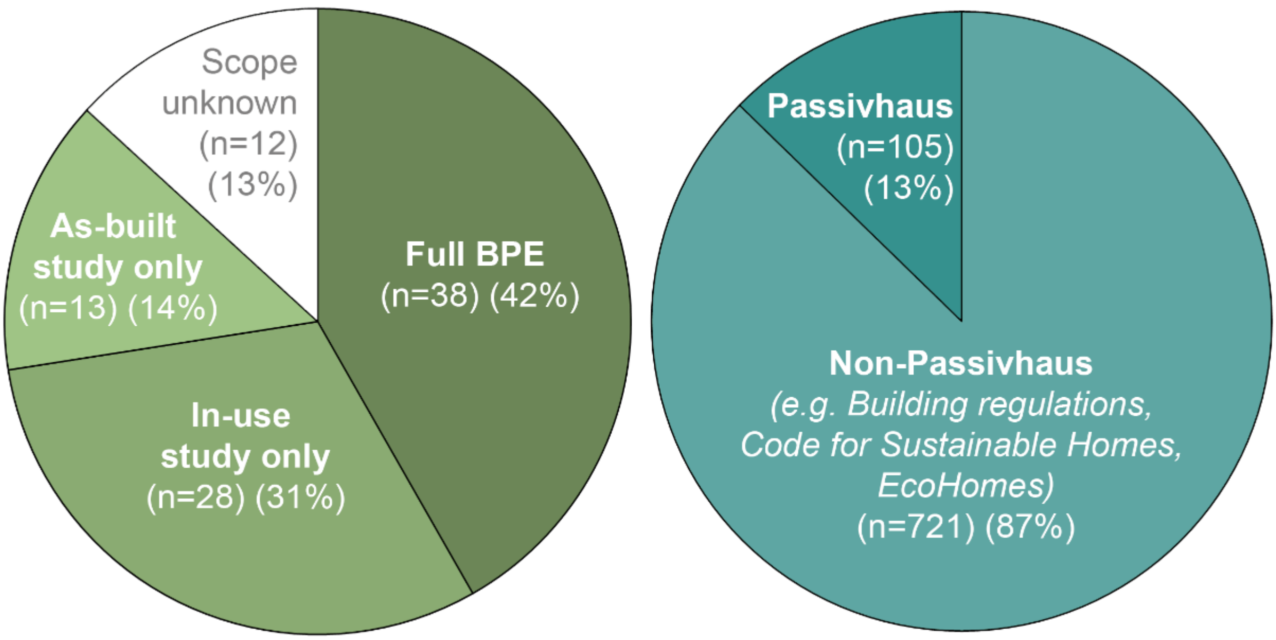


Figure 10. Housing performance study type (extent of evaluation)

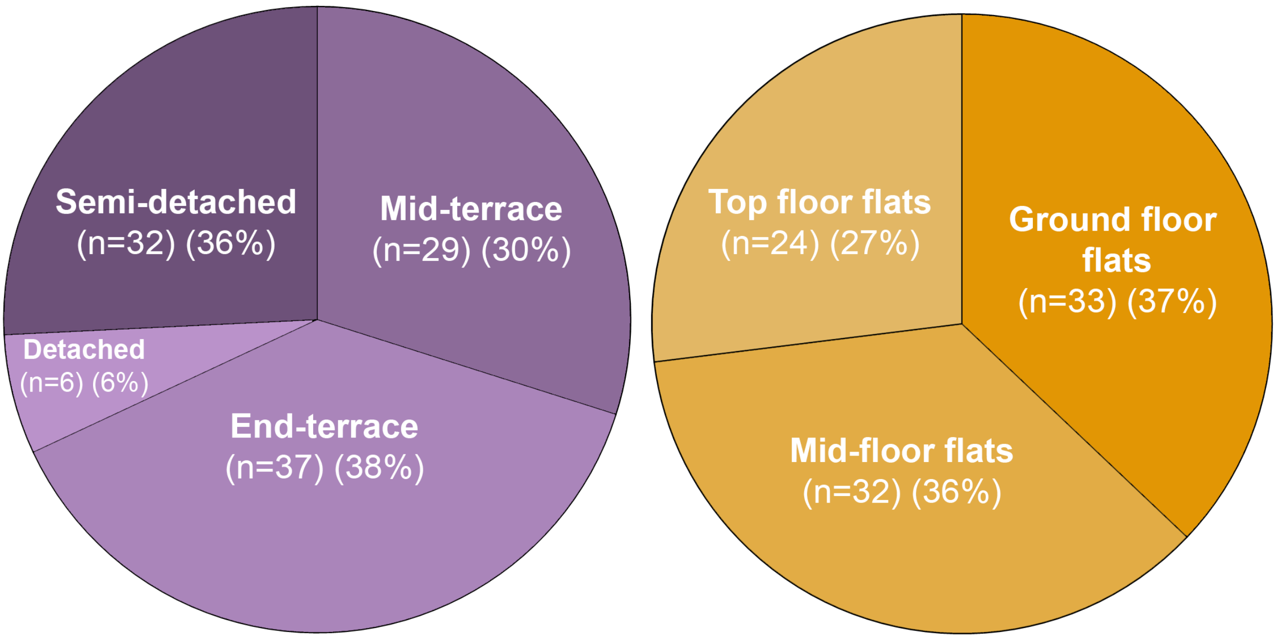


Figure 11. Housing performance study typologies (house types n=94 total; flats = 89 total)

Table 12 shows the housing performance evaluation techniques used for a few select programmes and HPE studies. As the table shows, generally a mix of cross-sectional surveys and testing as well as long-term monitoring is used at different stages during the building process.

Table 12. Techniques used in different housing performance programmes / HPE studies

BPE stage	Design review	Construction evaluation	Pre-occupancy	In-use evaluation		Total duration
Technique	**Survey / reviews**	**Survey / reviews**	**Surveys & testing**	**Surveys & testing**	**Long-term monitoring in-use (minimum)**	
Innovate UK BPE (Phase 1) (Palmer et al., 2016)	Y (retro)	Y (retro)	Y	Y	N	1 year
Innovate UK BPE (Phase 2) (Palmer et al., 2016)	Y (retro)	Y (retro)	Y	Y	2 heating seasons	2 years
AIMC4 (SMG, 2019)	Y	Y	Y	N	1 year	> 18 months
Stamford Brook (Partners in Innovation) (Sutton et al.,	Y	Y	Y	Y	1 year	6 years

2016)						
St Nicholas Court (Partners in Innovation) (Lowe, Bell, & Roberts, 2003)	Y	-	-	-	-	3 years
Elm Tree Mews (JRF) (Wingfield et al., 2011)	Y	Y	Y	Y	1 year	4 years
Temple Avenue Project (JRF) (Miles-Shenton et al., 2011)	Y (retro)	Y (retro)	Y	Y	N	~ 18 months
Model Home 202 (Velux) (Sian, 2013)	Y	Y	Y	Y	1 year	3 years
Good Homes Alliance (Phase 1 and 2) (GHA, 2019)	Y (retro)	Y (retro)	Y	Y	6 months	3 years
Pennyland Project (Chapman, Lowe, & Everett, 1985)	Y	Y	Y	Y	18 months	8 years
Linford Field Trial (Everett, Horton, & Doggart, 1985)	Y	Y	Y	Y	18 months	8 years

The key aspects of housing performance considered in the studies were assessment of building fabric thermal performance and energy use. Fabric assessment was overwhelmingly represented by air permeability testing and analysis. This could be partly due to the UK building regulations requirement to perform an air permeability test. Least studied areas included overheating assessment, indoor environmental quality, including daylighting, noise levels, and measurement of indoor pollutants such as formaldehyde, particulates and volatile organic compounds.

A review of methods and tools included in the Innovate UK's domestic BPE programme indicated that there was some consensus in terms of the length of BPE study wherein long-term monitoring covering heating and non-heating seasons is seen as advantageous. This was due to the fact that it enables anomalies to be spotted either due to building fabric thermal defects, services/system degradation and/or occupancy patterns. Such anomalies are usually difficult to up during short-term trials lasting less than 3 months.

Overall, there was inconsistency in the way methods were applied across different HPE studies. Therefore, it is recommended that standardisation of performance evaluation of housing is necessary to provide regularisation of the approaches used to evaluate housing performance.

3.5 Spatial map of housing performance

For the first time, an online and interactive spatial map on housing performance in the UK has been created that spatially locates the 91 HPE studies along with their meta-data provided by the Data Navigator, such as number of dwellings studied, location tenure, study duration, study type and data availability.

Figure 12 shows a snapshot of the housing performance map. Clicking on the map will take the reader to the interactive online version which can be explored.

The housing performance map is a living document for industry, policymaking and research communities to remain aware of what type of housing performance studies have happened, where in the UK and what their scope is.

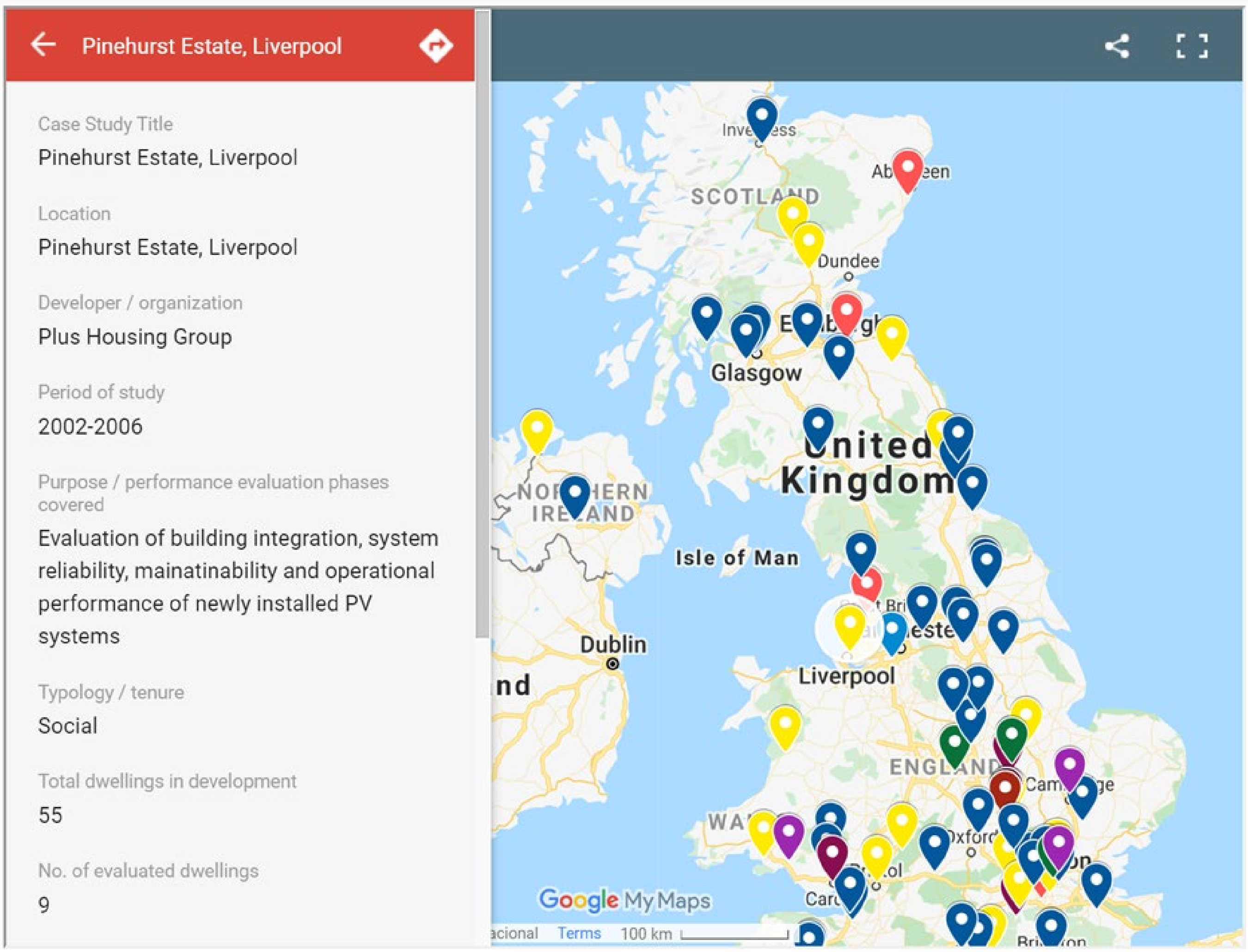


Figure 12. Screenshot of online housing performance case study map

Chapter 4: Meta-analysis of housing performance data

Meta-analyses of housing performance data are undertaken to provide insight into housing performance at scale and identify trends and issues in housing performance. The meta-analyses cover the following aspects of housing performance:

1. Building fabric thermal performance: air permeability, heat loss coefficient, U-value and thermal imaging
2. Energy: in-use energy consumption and space heating energy
3. Indoor environment: temperature, relative humidity, CO_2 levels, and assessment of overheating risk
4. Resident satisfaction and perception: indoor air quality, comfort and control

Table 13 shows the number of dwellings for which data were available for the different aspects of housing performance analysed. Each dwelling is represented by a unique ID for each section (e.g. DW1, DW2, DW3, etc.). Due to data availability, the respective sample sizes varied between 188 dwellings for air permeability and 12 dwellings for analysis of indoor environmental data.

Table 13. Sample size of housing performance data analysed (no. of dwellings)

A-built performance: Building fabric thermal performance analysis			
	Passivhaus	**Non-Passivhaus**	**Total**
Air permeability	50	138	188
External wall U-value	14	48	62
Roof U-value	5	15	20
Whole house heat loss	6	23	29
Thermal imaging	10	34	44
In-use performance: energy assessment			
	Passivhaus	**Non-Passivhaus**	**Total**
Annual energy consumption	30	62	92
Energy performance gap	19	49	68
Space heating energy use	12	56	68
In-use performance: indoor environment			
	Passivhaus	**Non-Passivhaus**	**Total**
Temperature & relative humidity	12	38	50
CO_2 concentrations	12	28	40
In-use performance: resident satisfaction and perception			
	Passivhaus	**Non-Passivhaus**	**Total**
BUS surveys	80	438	518

4.1 Building fabric performance analysis

The meta-analysis of the building fabric performance data includes:

- Airtightness
- Whole house heat loss (Co-heating tests)
- Heat flux measurements (U-values for external wall & roof)
- Infrared thermal imaging surveys

The first three were investigated at dwelling level whereas the data from the thermal imaging surveys were analysed at project site level. All the building fabric performance data are drawn from the Innovate UK BPE programme.

	Passivhaus	Non-Passivhaus	Total
Air permeability	50	138	188
External wall U-value	14	48	62
Roof U-value	5	15	20
Whole house heat loss	6	23	29
Thermal imaging	10	34	44

4.1.1 Air permeability

Designed and measured air permeability data were reviewed for 188 dwellings (Table 14) in 43 developments. The data comprised of 138 non-Passivhaus (NPH) and 50 Passivhaus (PH) dwellings, including 94 houses, 89 flats and 5 bungalows with floor areas from 37m^2 to 346m^2, designed to diverse standards from Passivhaus and Fabric First approach to Code of Sustainable Homes (CSH 2-6) and Building Regulations.

In the HPE study projects, the data were derived from air permeability tests conducted to the ATTMA standard (ATTMA, 2016), though the tests had been extended to include both pressurisation and depressurisation with the final air permeability result represented by the average of the two.

Table 14. Summary of airtightness-tested dwellings reviewed

	Passivhaus	Non-Passivhaus	Total
Bungalows	3	2	5
Flats	27	62	89
Houses	20	74	94
Total	50	138	188

The design and measured air permeability for the 188 dwellings ranged between:

- Designed: 0.4 - 10 m^3/h/m^2@50Pa and
- Measured: 0.3 - 9.3 m^3/h/m^2@50Pa

The average measured air permeability over the 188 dwellings (3.8 m^3/h/m^2@50Pa) is marginally lower than the respective design value (4.0 m^3/h/m^2@50Pa) indicating that overall, the sample of dwellings performs slightly better than the design intent. However, the median value of design and measured air permeability is 3 m^3/h/m^2@50Pa and 4 m^3/h/m^2@50Pa demonstrating a performance gap. Most dwellings (96 out of 188; 51%) failed to meet the designed air permeability levels. Figure 13 shows the entire dataset of designed and measured air permeability.

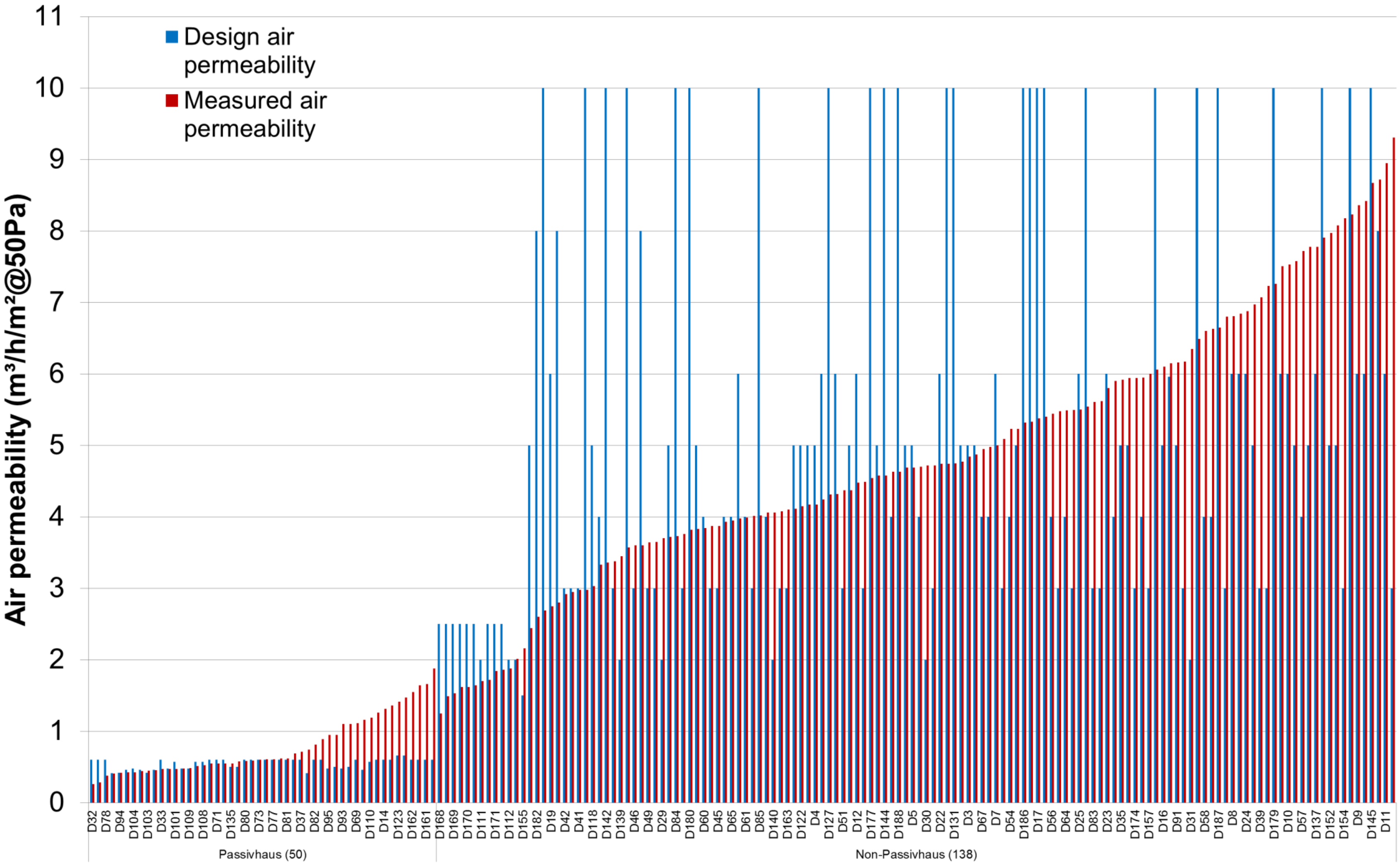


Figure 13. Design and measured air permeability for 50 PH and 138 NPH dwellings (n=188)

The mean difference for the 92 dwellings which performed as predicted or better was 1.9 m³/h/m²@50Pa, indicating that the "over-performance" of dwellings which met the design intent is on average higher than the "under-performance" of dwellings which failed to meet the design intent.

About 58% of PH dwellings did not meet their design target, on average 0.5 m³/h/m²@50Pa higher air permeability and deviations of up to 1.3 m³/h/m²@50Pa. In contrast, 49% of NPH dwellings had a much higher mean measured air permeability of 1.9 m³/h/m²@50Pa, higher than the design target with deviations of up to 6.3 m³/h/m²@50Pa.

Figure 14 demonstrates that the lower the air permeability is set at design stage the larger the gap is, thus highlighting the importance of workmanship in achieving high levels of airtightness. The scatter plot below focuses on the 138 NPH dwellings and shows that for every 1 m³/h/m²@50Pa decrease in design air permeability the gap between measured and design air permeability increases by 0.8 m³/h/m²@50Pa. A strong tendency of dwellings with design air permeability equal or lower to 5 m³/h/m²@50Pa to fail the design intent is apparent.

The measured air permeability was also investigated against the measured space heating energy, revealing a weak correlation between the two. When separating the dwellings between PH and NPH, the correlation is strong for PH dwellings and almost non-existent for NPH dwellings (Figure 15), demonstrating that good levels of airtightness do not necessarily result in low space heating energy. Importantly, this indicates the influence of other factors such as heating system, controls, occupancy and behaviour.

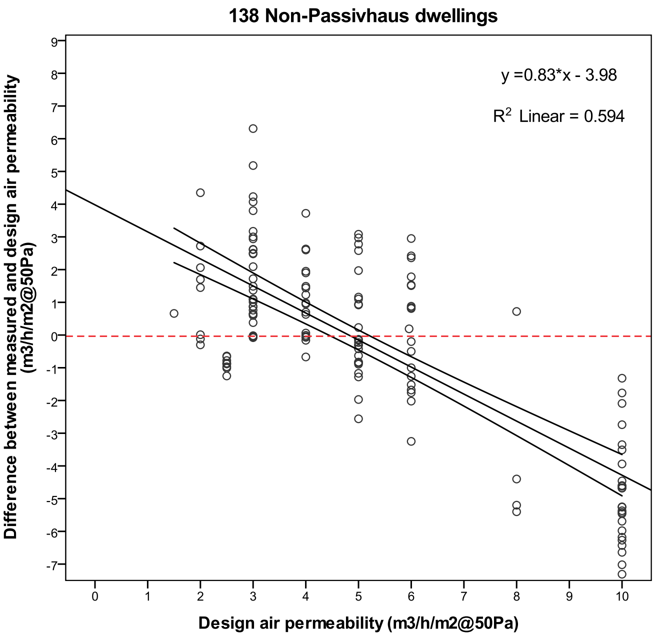


Figure 14. Increasing difference between measured and design air permeability

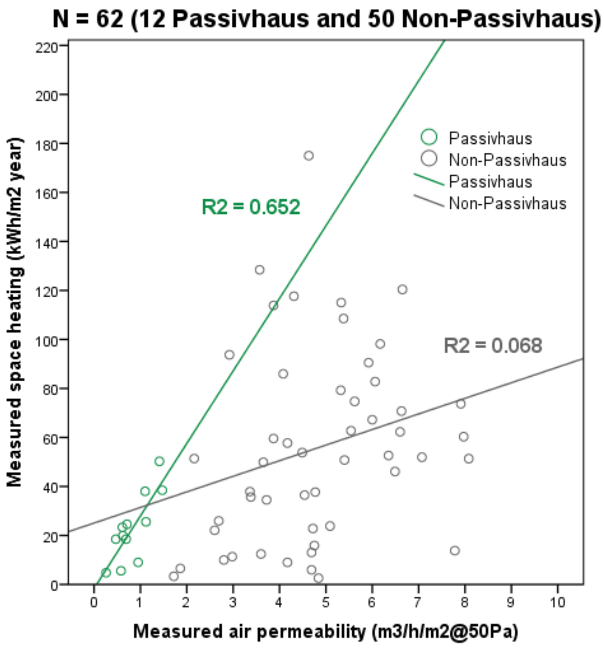


Figure 15. Relationship between air permeability and space heating energy in PH and NPH dwellings

4.1.2 Heat Loss Coefficient (HLC)

Co-heating test data were available in 21 unique projects totalling 29 dwellings out of which six were PH and 23 NPH dwellings (Table 15).

Table 15. Summary of dwellings reviewed for heat loss coefficient

	Passivhaus	Non-Passivhaus	Total
Bungalows	2	1	3
Flats	0	5	5
Houses	4	17	21
Total	6	23	29

The relationship between measured and predicted HLC is strong in the dataset (R = 0.75) and considerably stronger among PH (R = 0.94) than NPH (R = 0.83) dwellings. The mean predicted and measured HLC for the 29 dwellings is 92.6 W/K and 109.4 W/K respectively, demonstrating an average difference of 16.8 W/K (Table 16). This discrepancy is in the order of 18% which is above but close to the widely accepted close match of 10-15%.

Table 16. Descriptive statistics of predicted and measured heat loss coefficient for 29 dwellings

	Predicted HLC				Measured HLC			
	Mean	Min	Max	Std. Dev.	**Mean**	Min	Max	Std. Dev.
All dwellings (n=29)	**92.6**	36.6	337.8	58.5	**109.4**	38.1	245.0	57.1
PH (n=6)	**46.3**	36.6	63.6	11.5	**48.8**	38.1	60	7.9
NPH (n=23)	**104.6**	36.7	337.8	59.9	**125.2**	39.4	245	53.6

Only nine out of the 29 dwellings (i.e. 31%) performed as predicted or better, with the difference between predicted and measured HLC being in the range of 3.3-103.8 W/K while presenting a mean value of 18.4 W/K. On the other hand, in 20 out of 29 dwellings (69%) the co-heating test revealed a performance gap from as little as 0.4 W/K to 127 W/K, and on average 32.8 W/K wide (Figure 16 & Figure 17).

Differentiating between PH and NPH dwellings, the results showed that:

- The average difference between measured and predicted HLC is only 2.5 W/K wide for the PH dwellings (n=6) and considerably higher at 20.6 W/K among the NPH dwellings (n=23).
- 5 out of 6 PH dwellings did not perform as predicted, however, the average performance gap was only 4.5 W/K.
- 15 out of 23 NPH dwellings did not perform as predicted, with an average performance gap of 42.1 W/K.

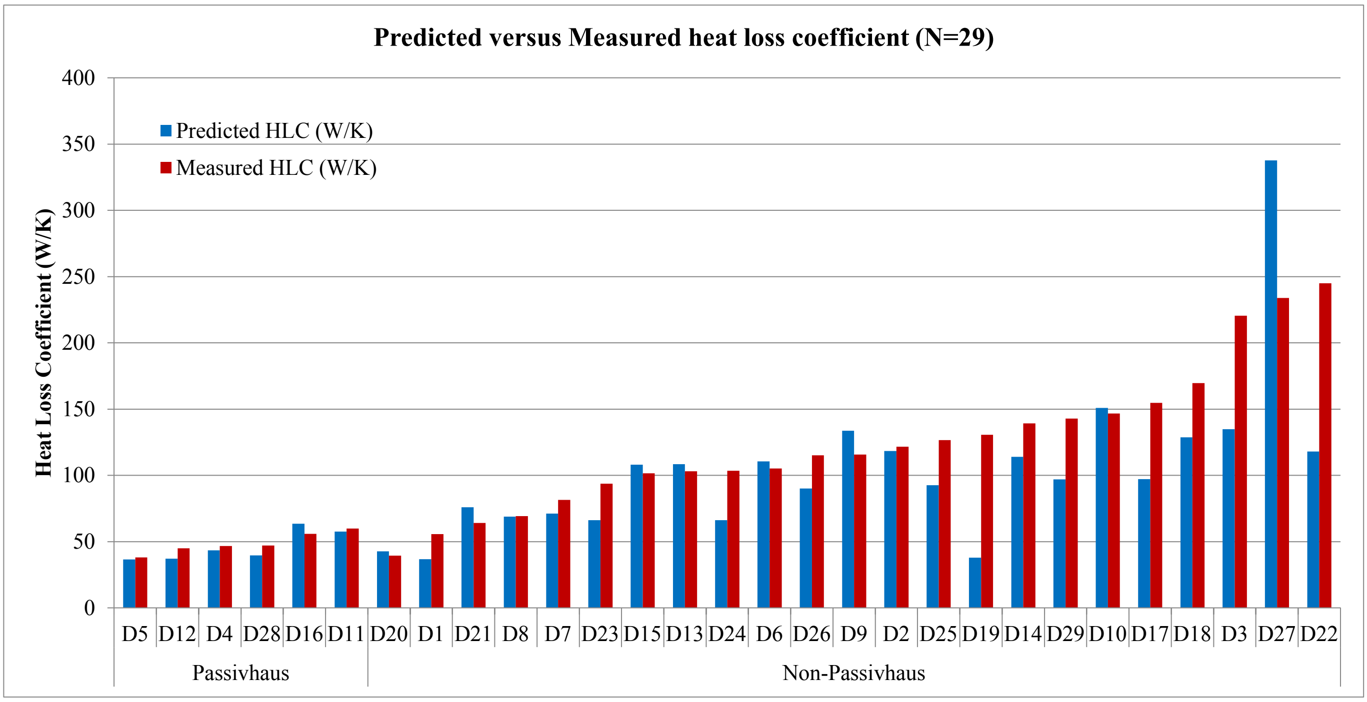


Figure 16. Predicted versus measured heat loss coefficient for the 29 dwellings reviewed.

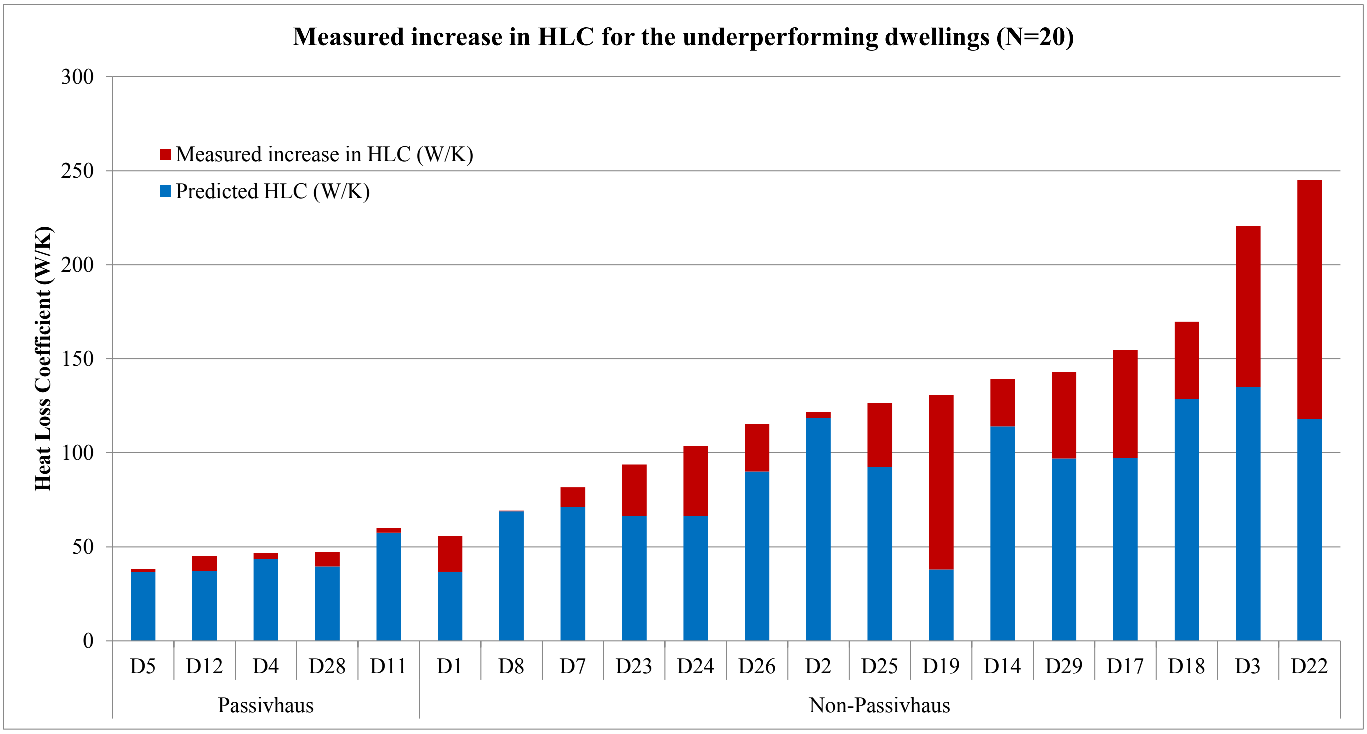


Figure 17. Measured increase in HLC in dwellings with co-heating test revealed performance gap.

The results from the whole house heat loss tests were investigated against the measured space heating energy. The sample size is small (n=9) but the results reveal a very strong correlation (Figure 18). Though the number of dwellings is much lower, the comparison of Figure 15 and Figure 18 shows that space heating energy is better explained by the heat loss coefficient than the airtightness, implying that a comprehensive building fabric test may be more reliable than just an air permeability test.

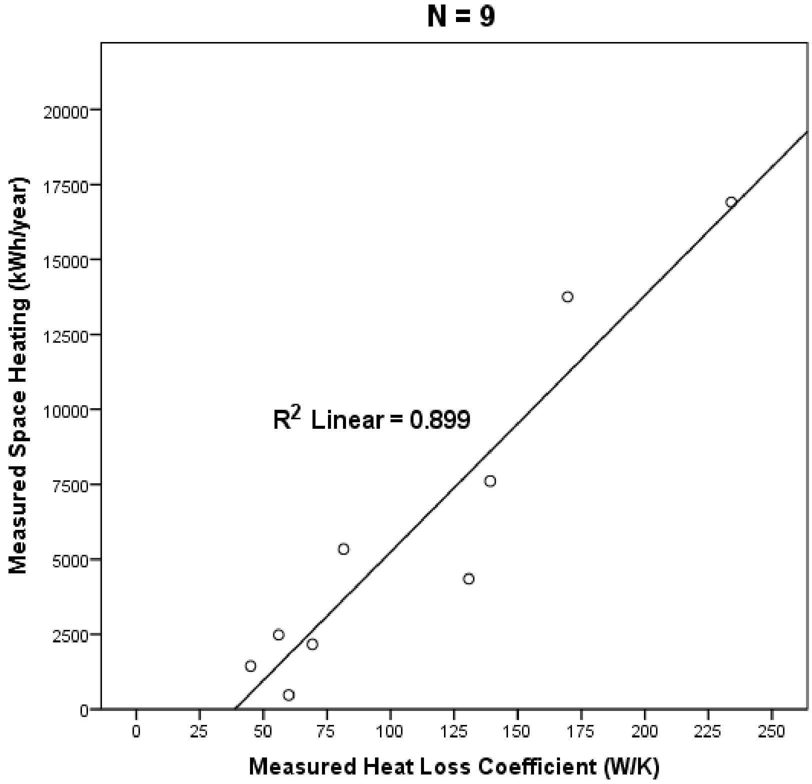


Figure 18. Relationship between measured heat loss coefficient and space heating energy

4.1.3 Heat flux measurements: U-value

Design and in-situ U-value data were collected for the external walls, roofs, (ground) floors, windows and doors. However, the number of dwellings with full comparative data (i.e. with both design and in-situ measurements) for (ground) floor, windows and doors was very small (Table 17). Therefore, this section focusses only on the data analyses for external walls and roofs.

Table 17. U-values database: no. of dwellings with both design and in-situ U-value data available

Area	No. of dwellings
External wall	62
Roof	20

Area	No. of dwellings
(Ground) floor	9
Windows	8
Doors	2

External wall U-value: Design and in-situ U-values for the external walls were available for 62 dwellings (14 PH and 48 NPH) representing 37 unique project sites (Table 18). Overall, the mean measured U-value was higher than the design value by 0.06 W/m^{2}K (i.e. 35% higher).

Table 18. Descriptive statistics for design and in-situ external wall U-values for 62 dwellings

	Design External Wall U-values (W/m^2K)				In-situ External Wall U-values (W/m^2K)			
	Mean	Min	Max	Std. Dev.	**Mean**	Min	Max	Std. Dev.
All dwellings (n=62)	**0.17**	0.09	0.27	0.04	**0.23**	0.09	1.27	0.17
PH (n=14)	**0.11**	0.09	0.15	0.02	**0.14**	0.10	0.20	0.03
NPH (n=48)	**0.18**	0.11	0.27	0.04	**0.25**	0.09	1.27	0.19

The respective difference is only 0.03 W/m^2K (27% higher) among PH dwellings and wider at 0.07 W/m^2K (39% higher) among NPH dwellings (Table 18, Figure 20). The maximum deviation from the design intent was 0.27 W/m^2K for PH dwellings and 1.27 W/m^2K for NPH dwellings.

Table 19 focuses on 37 out of 62 dwellings (60%) where the in-situ measurements revealed higher values than the design values and an average gap of 0.12 W/m^2K. The respective gap among PH dwellings is 0.05 W/m^2K whereas among NPH dwellings it is of the order of 0.14 W/m^2K. However, a t-test showed that there is no statistically significant difference (at $p<0.05$) in terms of the gap between PH and NPH dwellings.

Table 19. Descriptive statistics for design and in-situ external wall U-values for the 37 dwellings where design intent was not met

	Design External Wall U-values (W/m^2K)				In-situ External Wall U-values (W/m^2K)			
	Mean	Min	Max	Std. Dev.	**Mean**	Min	Max	Std. Dev.
All dwellings (N=37)	**0.17**	0.09	0.24	0.04	**0.29**	0.13	1.27	0.20
PH (N=8)	**0.11**	0.09	0.13	0.02	**0.16**	0.13	0.20	0.02
NPH (N=29)	**0.19**	0.13	0.24	0.02	**0.33**	0.15	1.27	0.21

Roof U-value: Design and in-situ U-values for roofs were available for 20 dwellings (5 PH and 15 NPH) studied over 17 projects in 14 unique project sites. Overall, the mean measured U-value was higher than the design value by 0.08 W/m^2K (i.e. 62% higher). The respective difference was 0.04 W/m2K (44% higher) among PH and higher at 0.10 W/m2K (71% higher) among NPH dwellings (Table 20, Figure 19).

Table 20. Descriptive statistics for design and in-situ roof U-value for the 20 dwellings reviewed

	Design Roof U-values (W/m^2K)				In-situ Roof U-values (W/m^2K)			
	Mean	Min	Max	Std. Dev.	**Mean**	Min	Max	Std. Dev.
All dwellings (n=20)	**0.13**	0.09	0.18	0.03	**0.21**	0.09	0.65	0.17
PH (n=5)	**0.09**	0.09	0.10	0.01	**0.13**	0.09	0.16	0.03
NPH (n=15)	**0.14**	0.10	0.18	0.02	**0.24**	0.11	0.65	0.18

The in-situ measurements showed that the roof element failed to perform to its design intention in 15 (4 PH and 11 NPH) out of the 20 dwellings with the average underperformance being 0.12 W/m²K. Again, the underperformance is found to be lower at 0.04 W/m²K for the PH dwellings (n=4) and higher at 0.15 W/m²K for the NPH (n=11) dwellings.

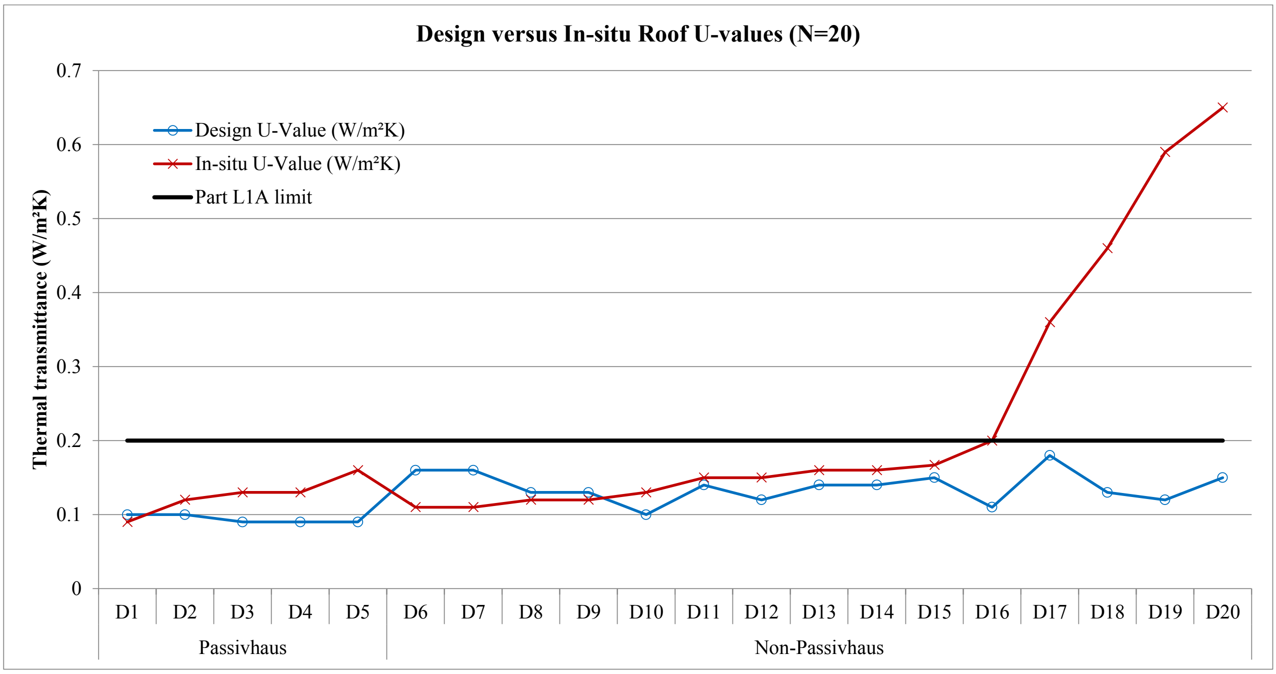


Figure 19. Design versus in-situ roof U-values for the 20 dwellings reviewed

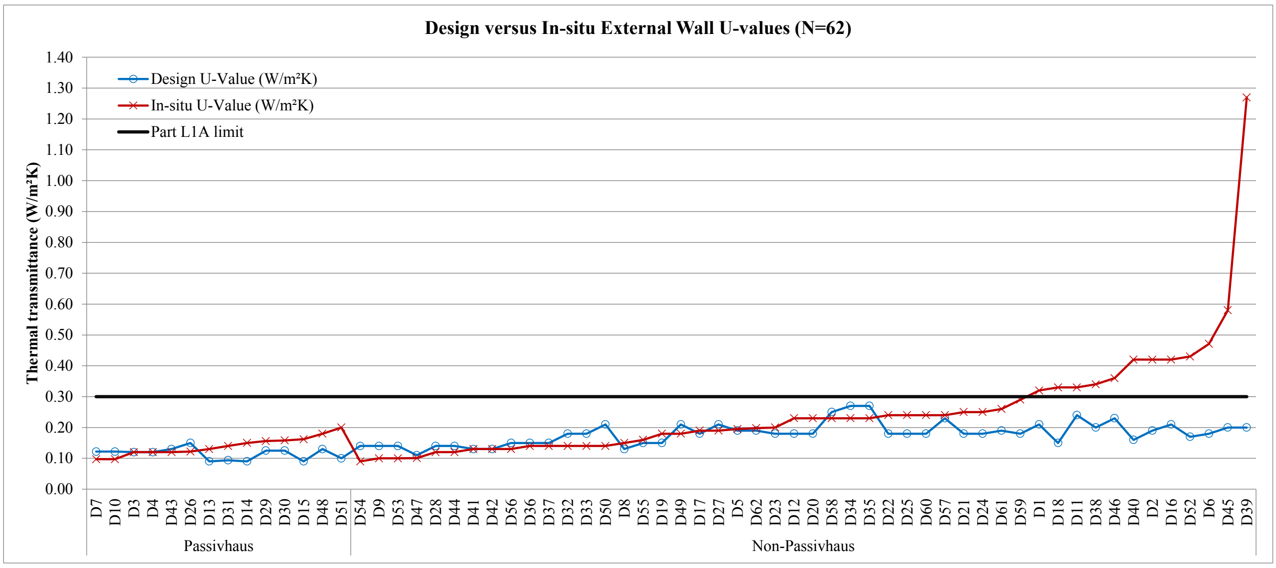


Figure 20. Design versus in-situ external wall U-values for the 62 dwellings reviewed

4.1.4 Thermal imaging

Thermal imaging surveys were conducted in 44 project sites (Innovate UK BPE programme). The data were analysed at project site level. The building areas where faults were identified were classified into the eight categories shown in Table 21.

Thermal weakness at openings seems to be endemic across the sector as issues with doors and/or windows were identified in 84% of the project sites, demonstrating a need to improve detailing, specification and workmanship. “Junctions and joints” and “roof, eaves and loft space” are also highlighted as areas requiring attention, as thermal bridging issues were pinpointed in nearly half the project sites.

Table 21. Faulty areas and frequency

	Project No.	Dwelling type	Construction system	Roof/Eaves & Loft space	Junctions & Joints	Walls only	Ceilings only	Windows & Doors	Fittings/Service penetrations	Slab/ground level	Other
Passivhaus	450014 & 450070	Bungalow	Timber					✓			
	450019 & 450066	House	Timber				✓	✓			
	450023 & 450049	House	Timber					✓			
	450038	House	Masonry	✓		✓		✓			
	450065	Flat	Masonry			✓		✓			✓
	450071 & 450080	House	Timber				✓	✓			
	450072	House	Timber			✓		✓	✓		
	450076	Flat	Masonry					✓			
	450095	House	Masonry	✓			✓	✓			
	450097	House	Timber					✓			✓
Non-Passivhaus	450009	Flat	Concrete		✓			✓			
	450011	House	SIPs	✓	✓			✓			
	450013 & 450040	Bungalow	Timber	✓	✓				✓		✓
	450015	House	Timber		✓			✓	✓		✓
	450016 & 450020	Flat	Concrete					✓			
	450017	Flat	Steel	✓				✓			
	450018 & 450050	House	Timber			✓		✓	✓		
	450021	House	Timber	✓			✓				
	450022 & 450025	House	Masonry	✓	✓	✓		✓	✓		
	450036	House	Timber				✓	✓		✓	
	450037 & 450039	Flat	Masonry		✓	✓		✓			
	450052	Flat	Concrete		✓	✓	✓	✓			✓
	450054	House	Timber		✓			✓	✓		
	450055	House	Masonry	✓				✓			✓
	450056	Flat	Timber					✓		✓	
	450067	House &	Concrete	✓	✓					✓	
	450069	House	Timber			✓		✓			
	450073	House	Timber		✓		✓	✓			
	450077	House	Masonry	✓	✓	✓					
	450078	House	Masonry	✓	✓	✓					
	450079	House	Masonry	✓		✓					
	450081	House	Timber		✓			✓			
	450082 & 450105	House	SIPs		✓			✓			
	450083	Flat	Masonry	✓	✓			✓			
	450093	House	Masonry	✓		✓		✓	✓		
	450094	House	Timber	✓	✓		✓	✓			✓
	450096	House	Timber	✓		✓	✓	✓			
	450098	House	SIPs	✓	✓	✓		✓	✓		
	450099	House	Timber	✓	✓			✓			✓
	450100	House	Steel			✓	✓	✓			✓
	450101	Flat	Masonry		✓			✓			✓
	450102	Flat	Concrete						✓		✓
	450103	House	Masonry	✓	✓			✓			
	450104	House	Timber	✓	✓		✓	✓	✓	✓	
				19/44 (43%)	**20/44 (45%)**	**14/44 (32%)**	**11/44 (25%)**	**37/44 (84%)**	**10/44 (23%)**	**4/44 (9%)**	**11/44 (25%)**

Separating per construction system, the results show that despite the expected advantages in workmanship associated with offsite timber construction, timber frame dwellings have thermal bridging issues (Table 22) with a frequency of occurrence comparable to that in masonry dwellings.

Table 22. Faulty areas and frequency per construction system

	Roof/Eaves & loft space	Junctions & Joints	Walls only	Ceilings only	Windows & Doors	Fittings/Service penetrations	Slab/ground level	Other
Timber (20)	**6/20 (30%)**	**8/20 (40%)**	**4/20 (20%)**	**8/20 (40%)**	**18/20 (90%)**	**6/20 (30%)**	**3/20 (15%)**	**5/20 (25%)**
Masonry (14)	**10/14 (71%)**	**7/14 (50%)**	**8/14 (57%)**	**1/14 (7%)**	**11/14 (79%)**	**2/14 (14%)**	**0/14 (0%)**	**3/14 (21%)**
Concrete (5)	1/5	3/5	1/5	1/5	3/5	1/5	1/5	2/5
SIPs (3)	2/3	3/3	1/3	0/3	3/3	1/3	0/3	0/3
Steel (2)	1/2	0/2	1/2	1/2	2/2	0/2	0/2	1/2

Moreover, separating between PH and NPH, the frequency of faults appears to be considerably higher in NPH developments. It is characteristic that issues associated with junctions and joints were identified in over 60% of the NPH project sites and in none of the PH developments (Table 23).

Table 23. Faulty areas and frequency separately for PH and NPH developments

	Roof/Eaves & loft space	Junctions & Joints	Walls only	Ceilings only	Windows & Doors	Fittings/Service penetrations	Slab/ground level	Other
Passivhaus (10 project sites)	**2/10 (20%)**	**0/10 (0%)**	**3/10 (30%)**	**3/10 (30%)**	**10/10 (100%)**	**1/10 (10%)**	**0/10 (0%)**	**2/10 (20%)**
Non-Passivhaus (34 project sites)	**18/34 (53%)**	**21/34 (62%)**	**12/34 (35%)**	**8/34 (24%)**	**27/34 (79%)**	**9/34 (26%)**	**4/34 (12%)**	**9/34 (26%)**

4.1.5 Key insights

From the assessment of as-designed and as-built conditions of the fabric, an important finding is that meeting the design air permeability is not commonplace. The average difference between design and measured air permeability among Passivhaus (PH) dwellings was 0.5 $m^3/h/m^2$@50Pa and considerably higher at 1.9 $m^3/h/m^2$@50Pa among non-Passivhaus (NPH) dwellings. However, no PH dwelling had an air permeability measurement above 2.0 $m^3/h/m^2$@50Pa. The strict, low-target, restriction on air tightness in PH dwellings likely led to more on-site intensity from designers and builders to ensure air-tightness methods were applied correctly. In contrast, though 3.0 $m^3/h/m^2$@50Pa was a common design target for NPH dwellings with MVHR, there was no penalty in place to inspire deep concern for meeting the target. As a result, 90% of these dwellings were above the design target and the average magnitude of the performance gap was an average of 2.15 $m^3/h/m^2$@50Pa (four times that of PH dwellings).

Dwellings with MVHR are associated with higher levels of airtightness, however the smaller samples of dwellings with MEV and NV were seen to perform better than the design expectations. A recommendation would be to require strict air tightness levels and installation checks.

However, considering the above, heat loss coefficient (HLC) (as opposed to air permeability) was found to be a better variable to explain the relationship between fabric and space heating energy consumption. This is expected as the co-heating test simulates the process of heating the home over a long period of time. Though the testing can be involved and time consuming it reveals a lot of information about potential performance without resident impact and provides a baseline on which to improve fabric before occupation. As a result, a comprehensive building fabric test would be suggested and more reliable than simply an air permeability test.

Overall, the performance gap in wall U-values was small; however, masonry dwellings were found to have the largest gap in terms of airtightness, external wall U-value and whole building heat loss. This finding shows the importance of assigning special attention and more time to ensuring the insulation and air tightness in building types which may be more prone to leakiness and poor construction practices. Air sealing in masonry dwellings are addressed in Jaggs and Scivyer (2009).

Thermal weakness at openings (doors/windows) appears to be endemic across the sector, demonstrating a need to improve detailing, specification and workmanship. Overall, the fabric performance gap was considerably higher in NPH dwellings.

4.2 In-use performance: Energy assessment

The meta-analysis of the in-use energy data includes:

- Annual energy consumption
- Energy performance gap
- Space heating energy use

The data are from the Innovate UK BPE programme. *Note the dwelling identifications are different than those used for previous assessments.*

Energy Analysis

	Passivhaus	Non-Passivhaus	Total
Annual energy consumption	30	62	92
Energy performance gap	19	49	68
Space heating energy use	12	56	68

4.2.1 Measured energy use

Data for measured (annual) energy use were available for 92 dwellings in 28 developments. Of the 92 dwellings, 30 are PH and 62 NPH dwellings with the built form breakdown given in Table 24.

Table 24. Number and build form of dwellings with measured energy use data

	Bungalows	Flats	Houses	Total
Passivhaus	6	7	17	30
Non-Passivhaus	0	28	34	62
Total	6	35	51	92

Overall, energy consumption across the 92 dwellings was within the range of 35 - 232 kWh/m^2. The average consumption was 103 kWh/m^2 (Table 25), which is half the UK national average in 2013 (Table 25).

Table 25. Annual energy use for 92 dwellings

	Measured Total Energy (kWh)				Measured Total Energy (kWh/m^2)			
	Mean	Min	Max	Std. Dev.	**Mean**	Min	Max	Std. Dev.
PH (n=30)	**5893**	2728	16581	3001	**73**	38	198	30
NPH (n=62)	**10350**	1776	37353	6544	**117**	35	232	50
All (n=92)	**8897**	1776	37353	5999	**103**	35	232	49

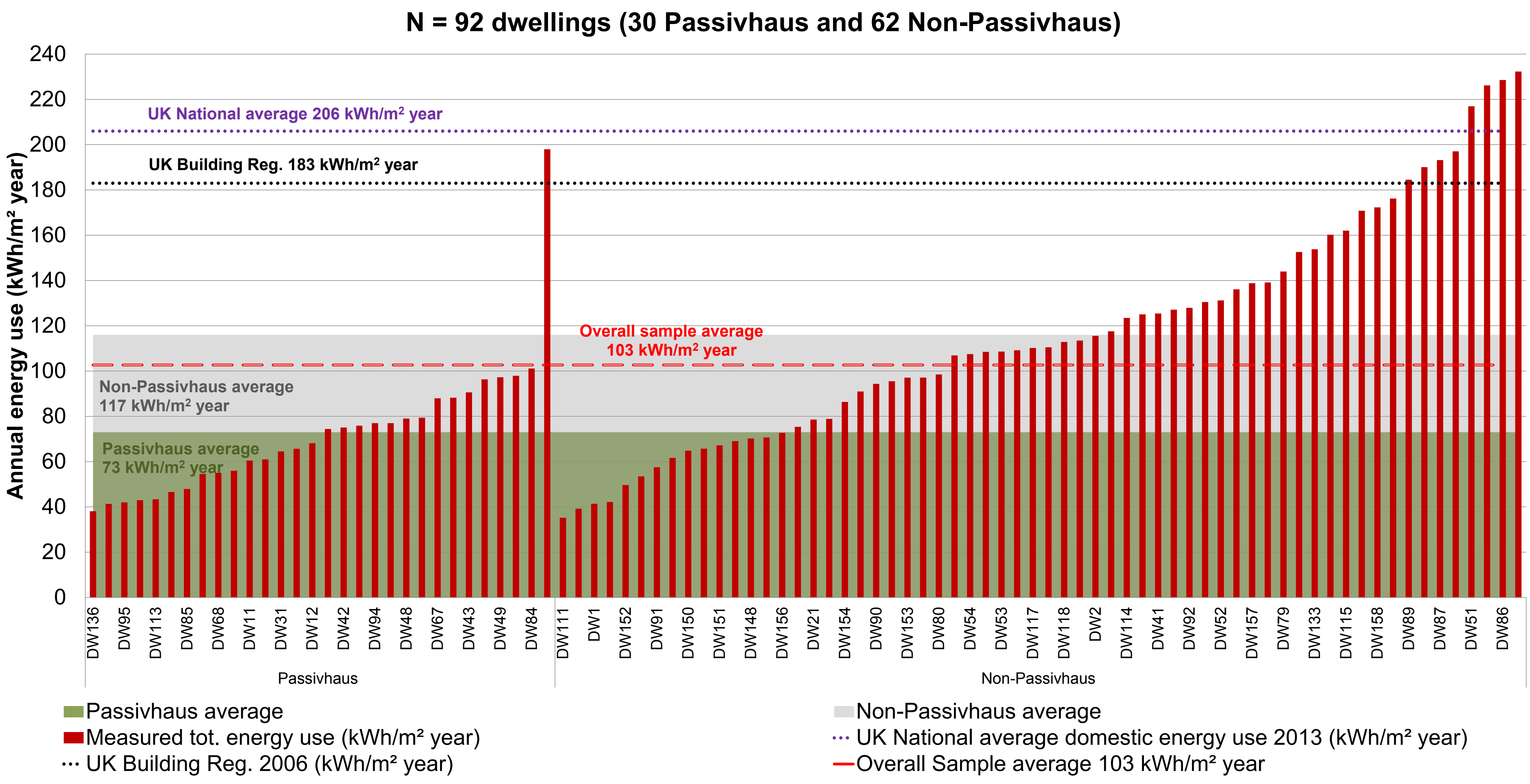


Figure 21. Annual energy use

Measured energy use by fuel type

Descriptive statistics for the breakdown of energy use by fuel type in the 92 dwellings is provided in Table 26. These figures show that on average:

- **Passivhaus** dwellings use more electrical energy per square metre of floor area than fossil fuel and biomass.
- **Non-Passivhaus** dwellings use considerably higher amount of fossil fuel compared to electricity and biomass.
- There is a small difference between PH and NPH dwellings in electrical energy use and a significant difference in fossil fuel and biomass. More specifically, the use of fossil fuel and biomass in non-Passivhaus is on average 2.4 and 3.3 times higher respectively, whilst that of electricity is only 1.2 times higher.

Table 26. Descriptive statistics for energy use breakdown by fuel

	Passivhaus (30)				Non-Passivhaus (62)				Mean difference
	Mean	Min	Max	Std. Dev.	**Mean**	Min	Max	Std. Dev.	
Fossil fuel* (kWh/m^2)	36.4	18.9	67	14.2	87.1	4.5	175	44.6	139%
Biomass (kWh/m^2)	14.4	2.8	25	8.7	47.6	20	97.2	27.8	231%
Electricity (kWh/m^2)	47.3	18.7	198	32.5	55.4	6.9	226.2	40.8	17%

* Fossil fuel includes gas and LPG fuel

4.2.2 Measured vs. predicted energy use

Predicted energy use data from SAP were available for 68 out of 92 dwellings. Therefore, full comparative data for measured vs. predicted energy use were available for 68 dwellings. Table 27 shows that both PH and NPH dwellings use on average 1.6 times more energy than predicted in SAP, with the mean difference between measured and SAP energy use being 29 kWh/m^2 and 46 kWh/m^2 respectively. Since SAP does not cover all end uses, some difference between measured and predicted energy use is expected.

Table 27. Descriptive statistics for SAP and measured energy use for 68 dwellings

	SAP (predicted) Energy use (kWh/m^2)				Measured Energy use (kWh/m^2)			
	Mean	Min	Max	Std. Dev.	**Mean**	Min	Max	Std. Dev.
PH (n=19)	**47**	32	88	16	**76**	38	198	36
NPH (n=49)	**77**	31	136	22	**123**	35	232	48
All (n=68)	**68**	31	136	24	**110**	35	232	50

Therefore, there is a weak relationship between SAP and measured energy use (Figure 22). More specifically, R is only 0.37 when considering all 68 dwellings and drops to 0.24 and 0.17 for PH and NPH dwellings respectively, demonstrating no relationship between SAP predicted and actual energy use.

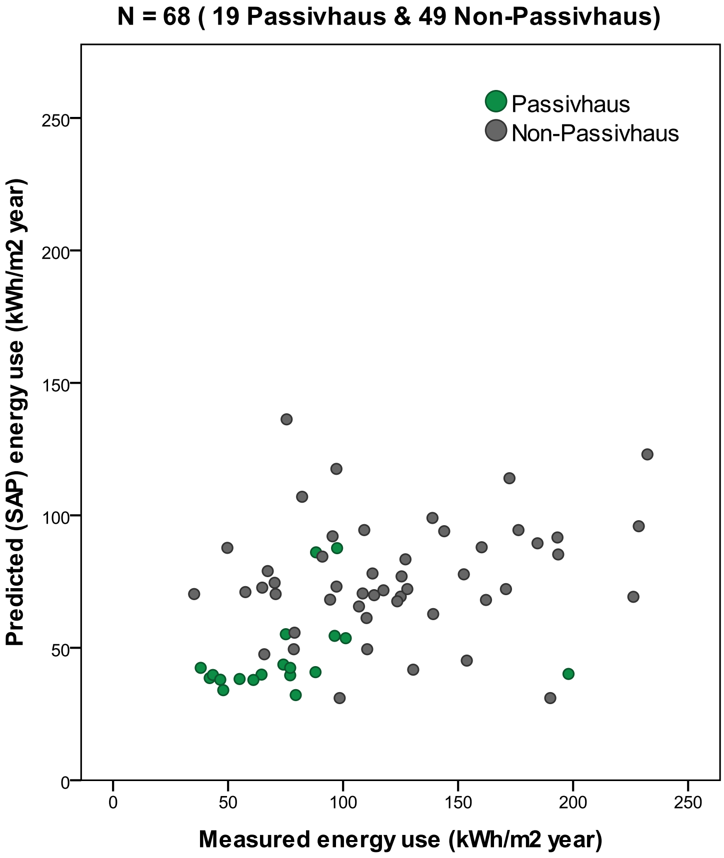


Figure 22. Relationship between SAP (predicted) and measured energy use.

The energy performance gap in NPH dwellings was found to be twice that of PH dwellings (Figure 23). Measured energy use is greater than predicted for proportionally more Passivhaus than non-Passivhaus dwellings; however, the average performance gap is 32 kWh/m^2 for Passivhaus and nearly two times higher at 62 kWh/m^2 for non-Passivhaus dwellings

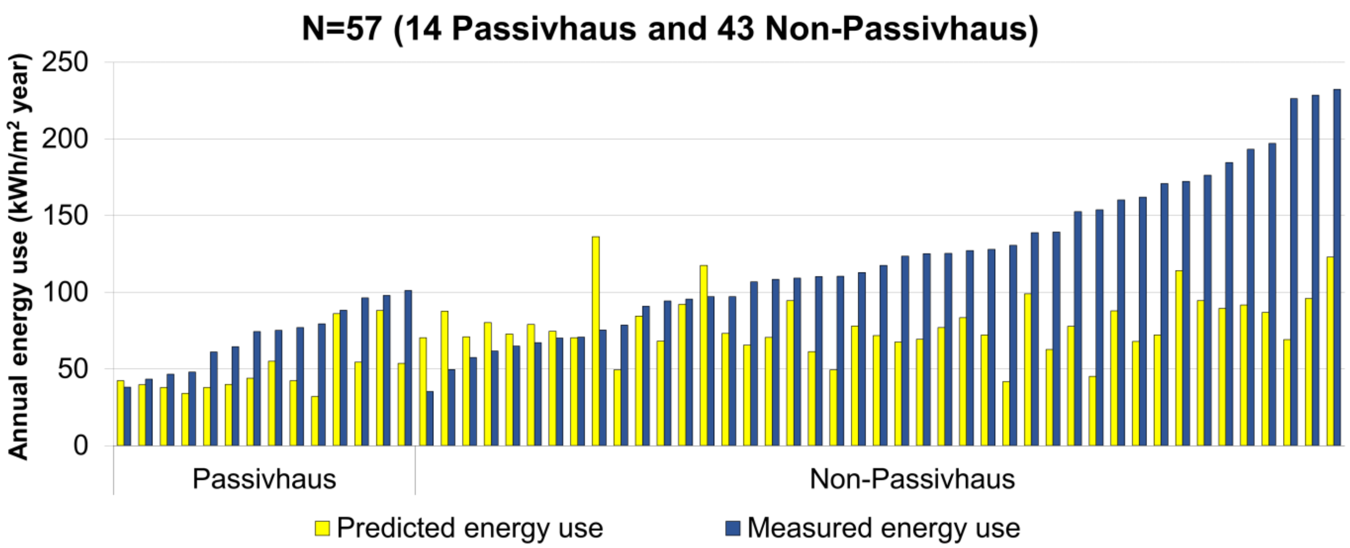


Figure 23. Predicted and measured energy use comparison for PH and NPH dwellings

4.2.3 Space heating energy use

Data for measured space heating energy were available for 68 dwellings including 12 PH and 56 NPH). SAP space heating data –SH_{gap} data – were available for 62 (12 PH and 50 NPH) out of the 68 dwellings.

Table 28 gives the descriptive statistics for measured space heating across the 68 dwellings. The average energy used for space heating in PH dwellings is 23 kWh/m^2 and 2.4 times higher at 55.3 kWh/m^2 in NPH dwellings.

Table 28. Descriptive statistics for measured space heating

	Measured Space Heating (kWh)				Measured Space Heating (kWh/m^2)			
	Mean	Min	Max	Std. Dev.	**Mean**	Min	Max	Std. Dev.
PH (n=12)	2255	475	6400	1814	23.0	4.8	50.3	13.8
NPH (n=56)*	5148	117	16912	4238	55.3	2.6	175.0	37.2
All (n=68)	4637	117	16912	4064	49.6	2.6	175	36.4
*The respective figures for NPH dwellings with the exclusion of the 6 dwellings with no SAP heating energy data change marginally and can be seen in the single row below:								
NPH (n=50)	5559	357	16912	4274	58.3	3.3	175.0	37.3

There is a moderate (overall) relationship between predicted (SAP) and measured space heating energy (R = 0.61). For NPH dwellings R = 0.54 while no relationship is identified for PH dwellings which is likely due to the small sample size.

Table 29 gives the descriptive statistics of SAP and measured space heating energy for PH and NPH dwellings. PH dwellings are seen to use on average 14.2 kWh/m^2 more heating energy than predicted in SAP whereas for NPH dwellings this difference is almost double at 27.8 kWh/m^2.

Table 29. Descriptive statistics for measured and SAP space heating energy

	SAP space heating (kWh/m^2)				Measured space heating (kWh/m^2)			
	Mean	Min	Max	Std. Dev.	**Mean**	Min	Max	Std. Dev.
PH (n=12)	8.8	5.3	18.4	3.6	23.0	4.8	50.3	13.8
NPH (n=50)	30.5	6.8	64.2	14.2	58.3	3.3	175.0	37.3

4.2.4 Key insights

- Overall, the annual energy consumption ranged from 35 – 232 kWh/m^2/year with a mean of 103 kWh/m^2/year (73 kWh/m^2/year for PH and 117 kWh/m^2/year for NPH). PH dwellings on average used 38% less energy than NPH dwellings.
- PH dwellings used much less fossil fuel and biomass per m^2 than electricity (non-heating) because of their high thermal standards. NPH dwellings used a considerably higher amount of fossil fuel compared to electricity and biomass.
- The average energy used for space heating in PH dwellings is 23 kWh/m^2 and 2.4 times higher at 55.3 kWh/m^2 in NPH dwellings. PH dwellings are seen to use on average 14.2 kWh/m^2 more heating energy than predicted in SAP whereas for NPH dwellings this difference is almost double at 27.8 kWh/m^2.
- As expected, most dwellings use higher amounts of energy than predicted in SAP. For both PH and NPH dwellings this is on average 1.6 times higher with the mean difference between measured and SAP energy use being 29 kWh/m^2 and 46 kWh/m^2 respectively.

4.3 In-use performance: Indoor environment

The meta-analysis of building environmental data includes:

- Temperature and relative humidity
- Indoor CO_2 concentrations

The temperature, RH and CO_2 data for the first two aspects are based on the Innovate UK BPE programme. The overheating data are from multiple smaller studies with some Innovate UK BPE data also included. Refer to the data navigator for more information. *Note the dwelling identifications are different than those used for previous assessments. Refer to the data navigator for HPE study connection.*

Environmental analysis

	Passivhaus	Non-Passivhaus	Total
Temperature and RH	12	38	50
CO_2 concentrations	12	28	40

Environmental data, including indoor dry bulb temperature, relative humidity (RH) and carbon dioxide (CO_2) levels, were sourced and reviewed from 50 dwellings across 21 developments. In dwellings with more than one bedroom, the study reviewed the data associated to the master bedroom. The analysis was conducted with monthly calculations (i.e. min, max and mean).

4.3.1 Indoor temperatures

Figure 24 shows the profile of monthly temperatures in bedrooms (BR) and living rooms (LR) separately for PH and NPH dwellings. Interestingly, PH and NPH dwellings appear to have very similar temperature profiles, and consequently, nearly identical mean temperatures over the heating and non-heating periods. More specifically, the average monthly temperature in PH dwellings was in the range of 20.4-24.6ºC presenting a mean of 21.8 ºC in BRs and 22.3 ºC in LRs and therefore an overall mean of 22.1 ºC.

In NPH dwellings, the average monthly temperature presented a similar range (20.1-24.5 ºC), a mean of 21.7 ºC and 22.2 ºC in BRs and LRs respectively and an overall mean of 22.0 ºC. Moreover, in the heating season, the average PH dwelling was heated to 21.2 ºC (21.5 ºC in LR and 20.9 ºC in BR) similarly to the average NPH dwelling which was heated to 21.0 ºC (21.3 ºC in LR and 20.7 ºC in BR).

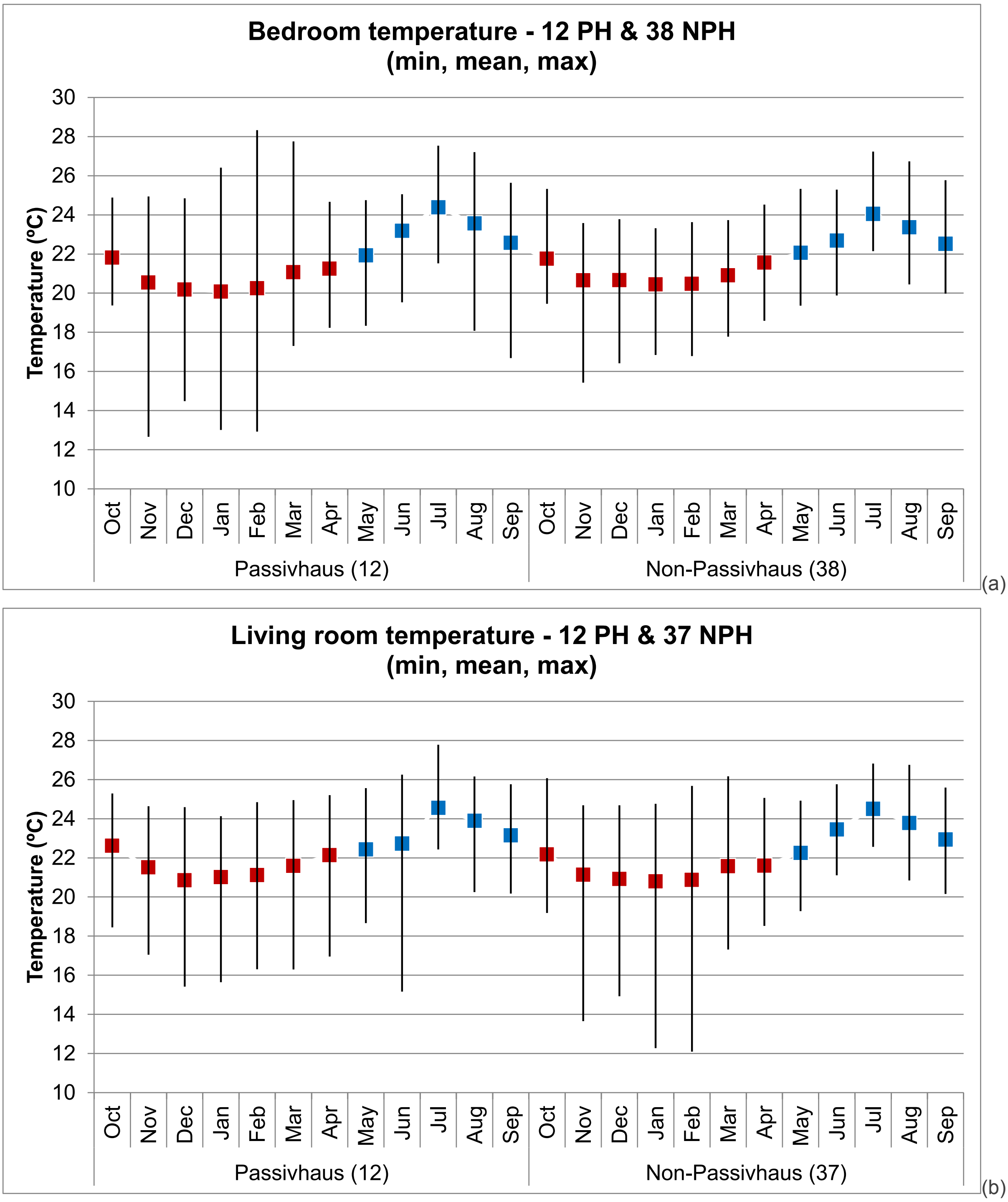


Figure 24. Min, mean and max monthly temperature in (a) bedroom and (b) living room for PH and NPH dwellings

4.3.2 Relative humidly

Again, PH and NPH dwellings appear to have very similar RH% profiles, and consequently, nearly identical mean RH% over the heating and non-heating periods (Figure 25).

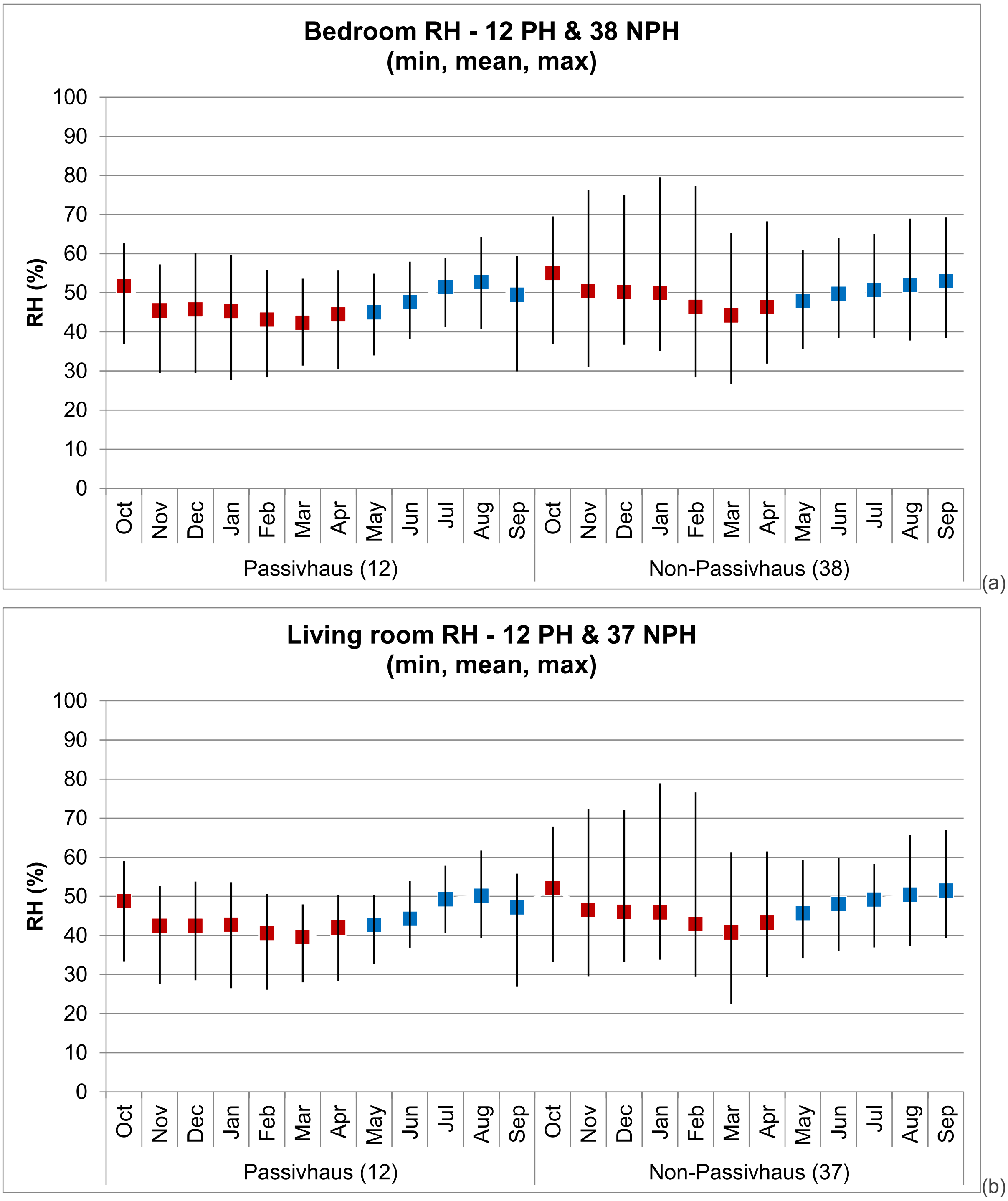
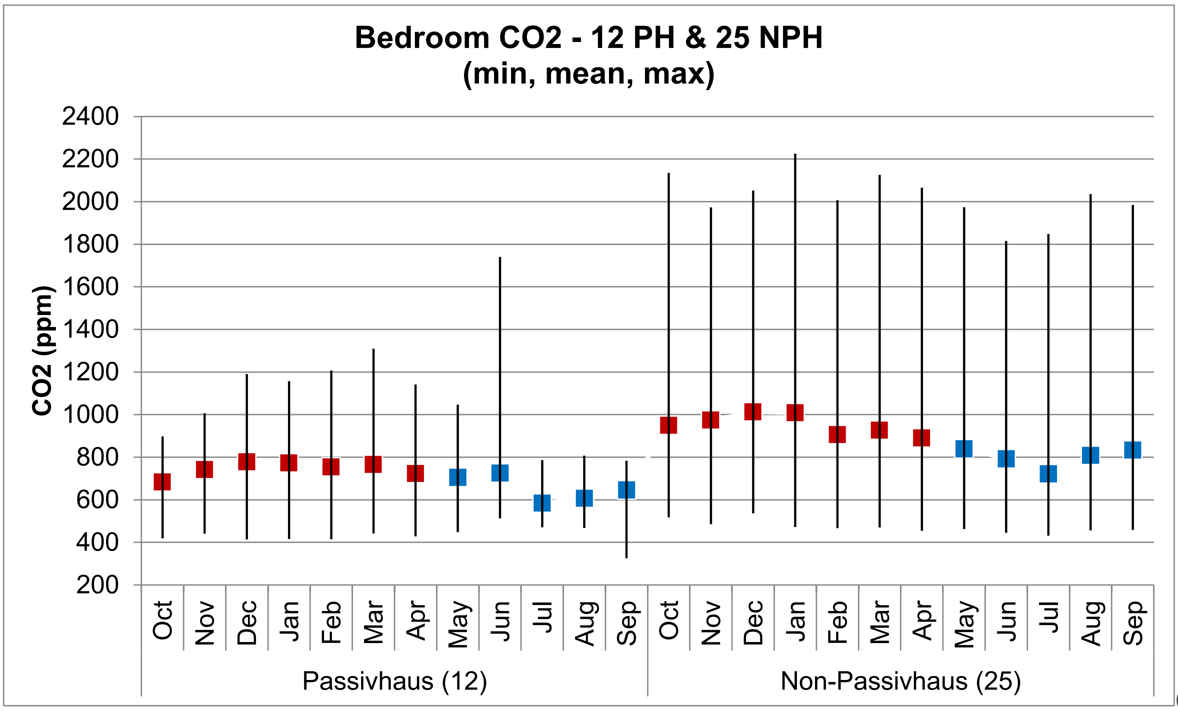


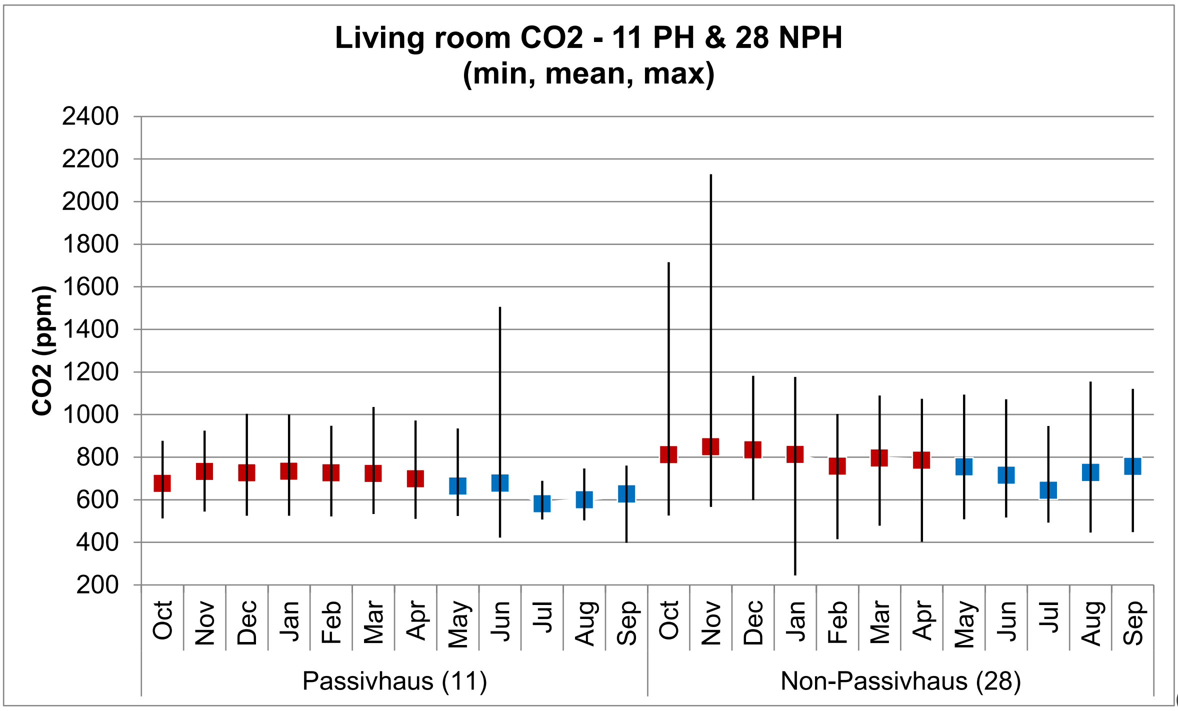
Figure 25. Min, mean and max. monthly RH% in (a) bedroom and (b) living room in PH and NPH dwellings

4.3.3 Indoor CO_2 levels

The data analysis revealed consistently higher mean monthly CO_2 concentrations in NPH dwellings than in PH dwellings, with the difference being more significant in bedrooms (Figure 26). The mean monthly difference was found to range from as little as 31ppm to 266ppm and was on average 89ppm in living rooms and 179 in bedrooms.



(a)



(b)

Figure 26. Min, mean and max. monthly CO_2 levels in (a) bedroom and (b) living room in PH and NPH dwellings

4.4 In-use performance: Resident satisfaction

The meta-analysis of the resident perception is comprised of data from the resident BUS questionnaires. The data are from the Innovate UK BPE programme. From the Innovate UK BPE programme there were a total of 518 BUS responses covering 38 developments (HPE studies). *Note the dwelling identifications are different than those used for previous assessments. Refer to the data navigator for HPE study connection.*

Resident perception analysis

	Passivhaus	Non-Passivhaus	Total
BUS	80	438	518

BUS questionnaire

The BUS methodology is an established way of benchmarking resident satisfaction levels within buildings against a large database of results from similar buildings. Developed and refined in the 1990's, the BUS methodology uses a structured questionnaire where respondents rate on a scale of 1-7 various aspects of the building's performance while also providing comments to allow for both quantitative and qualitative data to be collected. The BUS survey consists of over 45 variables covering a diversity of aspects from thermal comfort, ventilation, indoor air quality and lighting to personal control, noise, space, design, image and needs.

About the dataset

BUS data were extracted from individual questionnaires conducted in 38 developments between 2011 and 2015. The sample size across the developments ranged from as little as 1 to 51, totalling 518 residents. The average sample size was 13 residents (median value was 8 residents), with 73% being 30 years old or over and a 43:57 male-female ratio.

4.4.1 Resident satisfaction in Passivhaus and non-Passivhaus dwellings

Figure 27 shows the BUS results for winter. Though the different dwelling types are well grouped on winter assessment, PH dwellings are slightly less satisfied (than NPH) overall and regarding aspects of temperature and air quality. However, the results on average are satisfactory. Figure 28 shows summer BUS results. The results between the dwelling types are more spread out for summer assessment. Though overall satisfaction is the same for both, aspects of temperature and air quality such as too hot, humid, and stuffy are not as high-rated for PH dwellings. Again, overall, the results are satisfactory; however, summer temperature discomfort is on the edge of potentially unacceptable for PH dwellings.

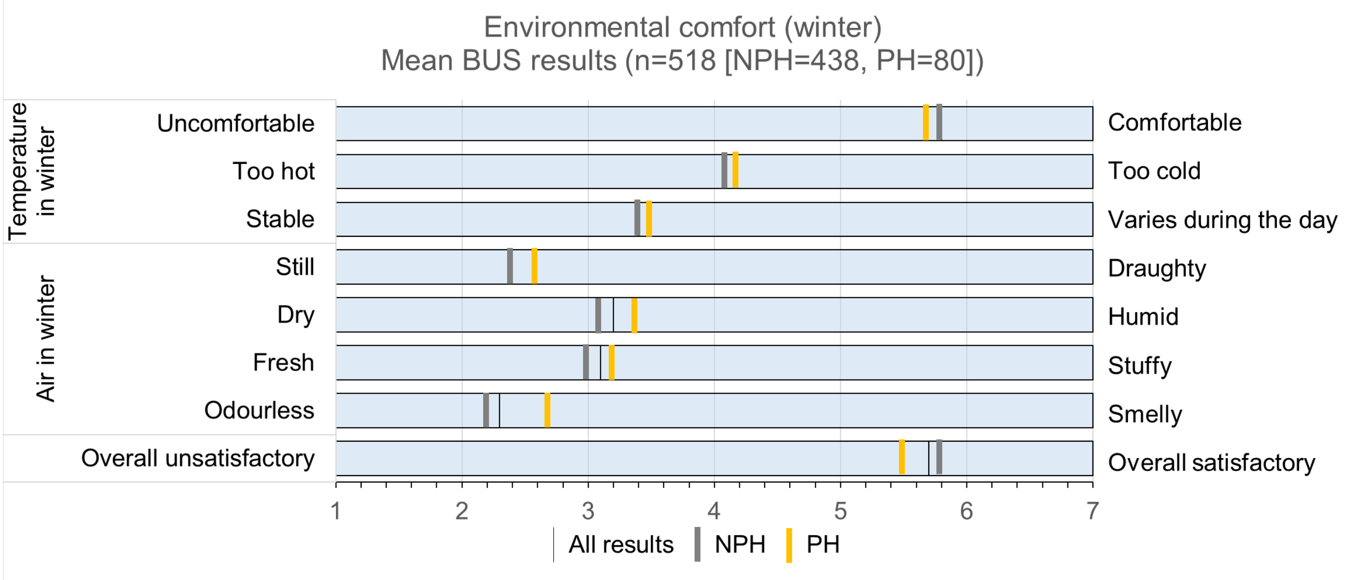


Figure 27. Winter comfort and satisfaction with air quality results (PH & NPH)

Note in the graphs, where there is overlap it is always 'NPH' overlapping 'all results'. PH overlaps NPH and all results if only PH is seen.

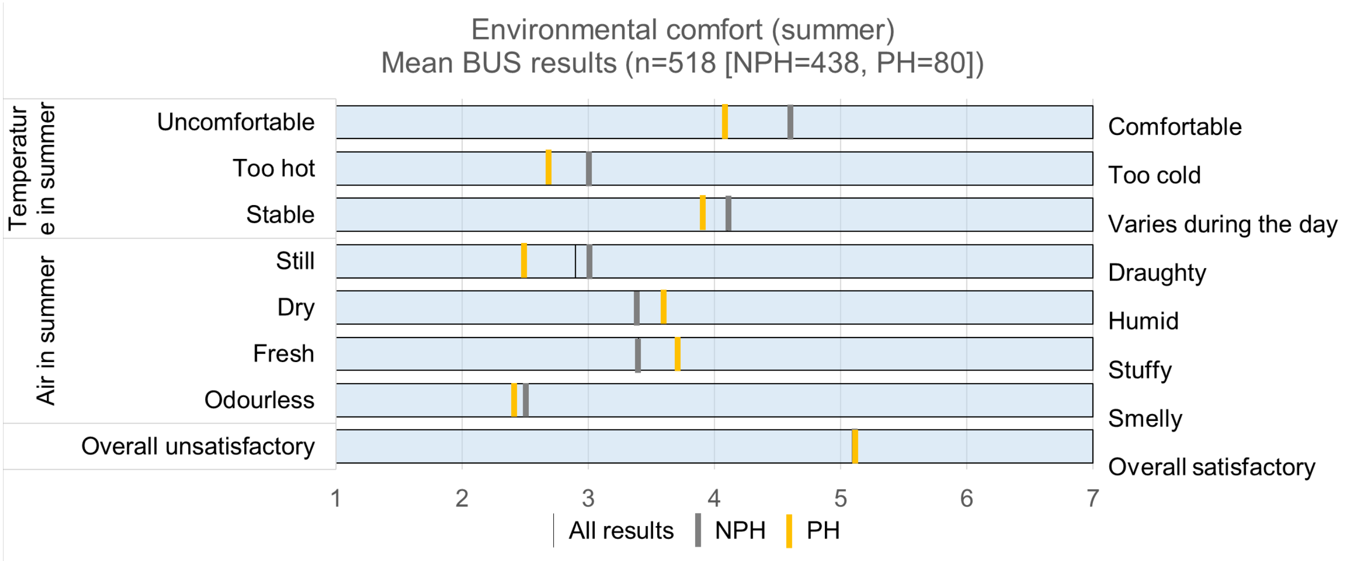


Figure 28. Summer comfort and satisfaction with air quality results (PH & NPH)

PH dwelling residents appear to perceive less control than their NPH counterparts on aspects that matter most in the purpose of designing PH dwellings. That is, PH dwellings residents perceive less control over heating, cooling and ventilation of their dwellings. The differences are, however, not unacceptable on average (Figure 29).

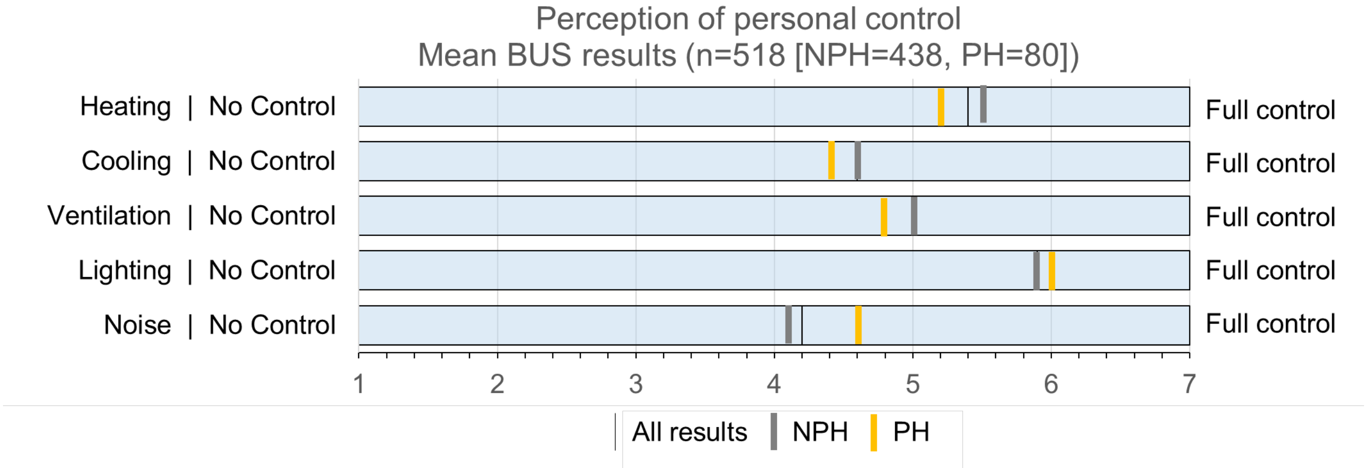


Figure 29. Perception of personal control (PH & NPH)

4.4.2 Difference in resident perception between ventilation types

Figure 30 below shows the BUS results for winter based on ventilation type. Dwellings with MVHR appear to be performing best with the greatest overall satisfaction and comfort in winter but not as well in summer. Though the difference is not significantly large, naturally ventilated dwellings are most satisfactory in summer (Figure 31). This is most likely the obvious perception of greater personal control as the resident gains from the traditional practice of opening windows for ventilation. This perception of control can be seen in Figure 32.

Note in the graphs, where there is overlap it is always 'MVHR' overlapping other types.

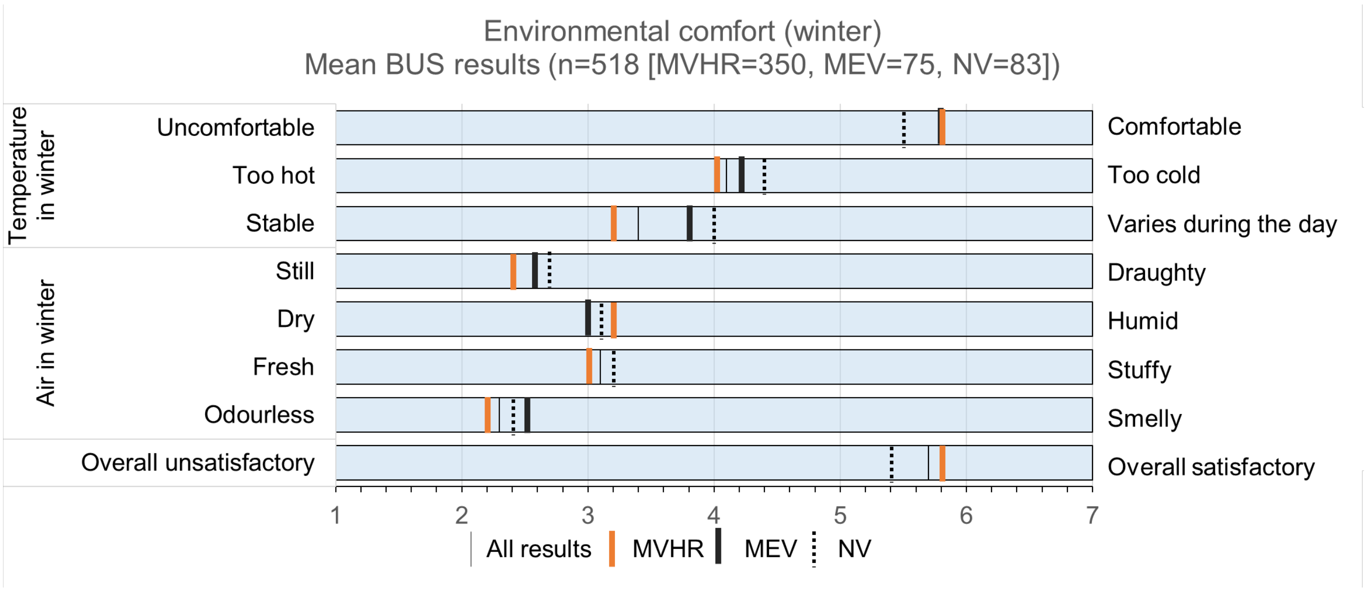


Figure 30. Winter comfort and satisfaction with air quality results (ventilation type)

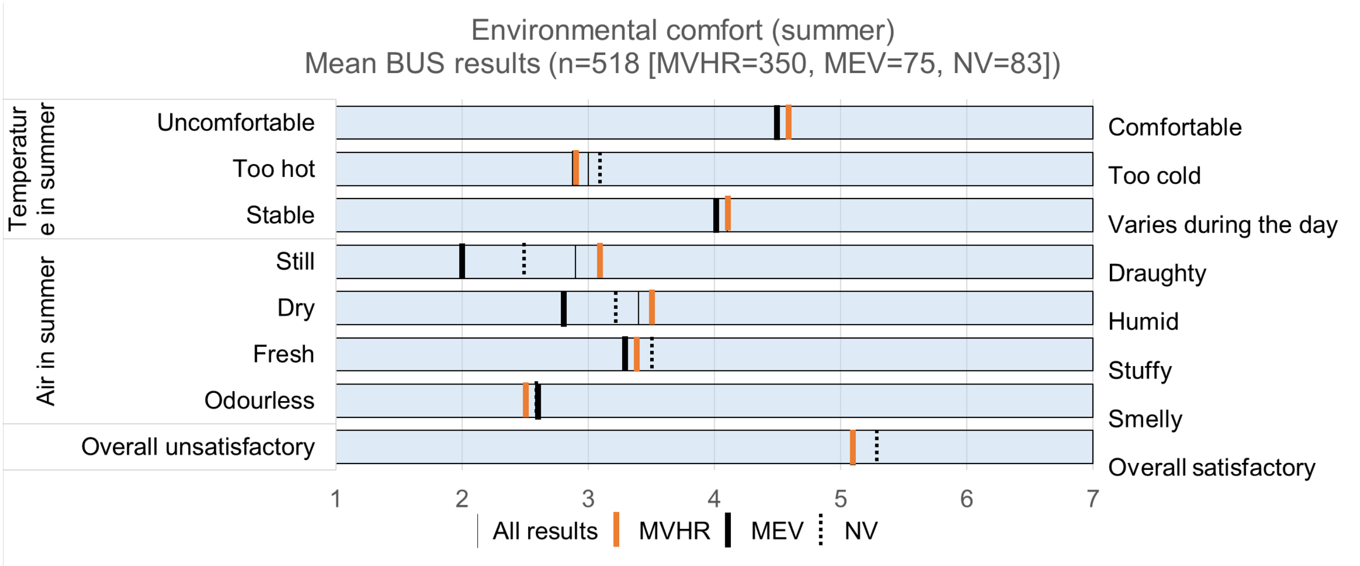


Figure 31. Summer comfort and satisfaction with air quality results (ventilation type)

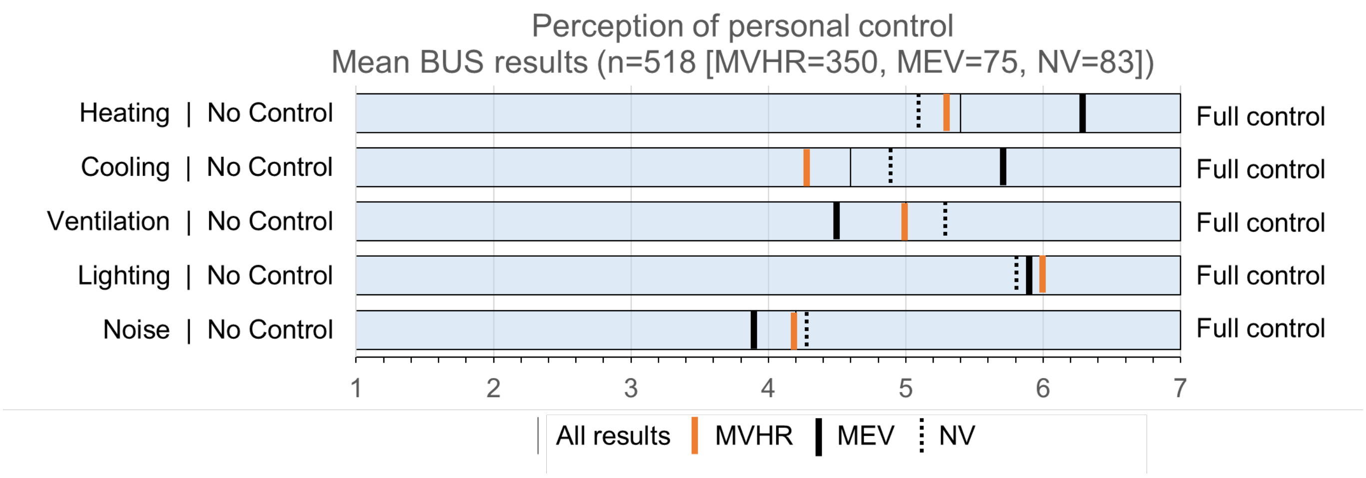


Figure 32. Perception of personal control (ventilation type)

Table 30 shows the relationship between perception of seasonal temperature, IAQ & health and the perception of heating control & ventilation control for design type and ventilation type.

Though the correlation is highest among the ventilation types it is still moderately weak overall. Correlations are overall moderately weak to negligible, but the strongest relationship for most categories is seen in MVHR dwellings. The weakest relationship appears to be in NV dwellings for heating and MEV dwellings for ventilation.

Table 30. BUS perception of control and environment correlations

	Control over heating					
	All	PH	NPH	MVHR	MEV	NV
Health	0.20	0.24	0.20	0.25	0.03	0.19
Overall comfort	0.50	0.47	0.51	0.57	0.50	0.21
Winter temp. overall	0.43	0.51	0.42	0.48	0.24	0.42
Summer temp. overall	-	-	-	-	-	-
Winter IAQ overall	0.46	0.28	0.49	0.54	0.35	0.28
Summer IAQ overall	-	-	-	-	-	-
	Control over ventilation					
	All	PH	NPH	MVHR	MEV	NV
Health	0.25	0.19	0.26	0.28	0.25	0.13
Overall comfort	0.51	0.49	0.50	0.59	0.29	0.37
Winter temp. overall	0.33	0.21	0.35	0.41	0.18	0.18
Summer temp. overall	0.47	0.32	0.50	0.56	0.23	0.31
Winter IAQ overall	0.37	0.26	0.39	0.49	0.00	0.37
Summer IAQ overall	0.54	0.31	0.57	0.63	0.24	0.39

- >7 Strong
- >6 Mod. strong
- >5 Moderate
- >4 Mod. weak
- >3 Weak
- <3 Negligible

The meta-analysis of BUS survey data showed that:

- Passivhaus developments were associated with higher levels of perceived control and higher levels of resident satisfaction with the environmental conditions as well as with lower utility costs, particularly heating energy cost.
- The relatively low score of the “temperature too hot/too cold” variable in summer could imply some issues with summertime overheating in both Passivhaus and non-Passivhaus dwellings.

Chapter 5: Future of housing performance

5.1 Policy landscape and housing performance

The 2019 Consultation on changes to the UK Building Regulations for new dwellings (Ministry of Housing Communities and Local Government, 2019) set forth the commitment that, by 2025, the UK government will introduce a Future Homes Standard for new build homes to be future-proofed with low carbon heating and world-leading levels of energy efficiency[12]. The expectation is that an average semi-detached home built to meet the Standard would produce 75-80% less carbon dioxide emissions than one built to the 2013 Part L requirements.

Two options were suggested for an uplift in energy efficiency standards in Part L to be brought in during 2020

1. 'Future Homes Fabric': 20% improvement on the current Part L standard. To be delivered predominantly by very high fabric standards.
2. 'Fabric plus technology': 31% reduction in CO_2 from new dwellings, compared to the current standards. Likely to encourage the use of low-carbon heating and/or renewables. (less stringent fabric requirements than option 1).

The new standard would require minimum fabric standards (e.g. improve on the U-value minimum for each building element) and proposes the removal of the Fabric Energy Efficiency Standard. The Proposed minimum standards are listed in Table 31 alongside 2013 BRUKL limiting fabric parameters.

Table 31. Building regulation fabric parameters

Fabric parameter	Future homes standard	BRUKL 2013 (2016 amends.)
External walls ($W/m^2.K$)	0.26	0.30
Party walls	0.20	0.20
Floor	0.18	0.25
Roof	0.16	0.20
Windows	1.60	2.00
Roof-lights	2.20	-
External doors	1.60	-
Air permeability ($m^3/m^2.K$ at 50Pa)	8.00	10.00

As fabric standards are tightened in the new decade, wider policy goals on energy demand reduction and climate change mitigation require that the standards are met in reality, not only in models. This is important as these models have been shown to be incorrect and or often outdated by the time a house is finally completed, misrepresenting efficiency (BEIS Committee, 2019). A new prescriptive nature of fabric standards or other energy related system efficiency would suggest that additional

[12] CIBSE (2019) released a briefing on August 12th stating that: *Recent work by the Committee on Climate Change (CCC) and BEIS Select Committee make clear the urgent need to reduce emissions from buildings, in order to meet the new statutory target of net zero carbon UK by 2050. The Part L trajectory must respond to this requirement for action... Given the scale of the ambition and the limited time available, this needs to begin now, and not be left to another review of Part L. …this should translate into the following overarching objectives: all new buildings to be net zero carbon in operation from 2030, including all energy uses; and to allow this, all new buildings to be designed as net zero carbon from 2025.*

methods of housing performance evaluation are essential to demonstration of compliance just as stair measurements, for example, need to be verified for compliance. Under the proposed regulations, it will become increasingly important to evaluate not only the real performance of the fabric, but other areas of the building's performance.

Furthermore, CIBSE produced a useful briefing paper (2019) which sets out a possible timeline for the phased transition of the compliance to UK Building Regulations more focused on real performance, as set out below. We agree with this type of approach, and would envisage working with the Government, CIBSE and others to develop the plan in more detail.

1. Introduce clear (phased in over time) targets for the operational performance of buildings,
2. from 2020 provide incentives to adopt operational targets,
3. from 2020 introduce mandatory disclosure of energy performance, and
4. from 2020 strengthen and expand as-built checks and commissioning for all buildings, piloting the more extensive proposals in "Building a Safer Future"

According to Committee on Climate Change (2019), closing the energy use performance gap in new homes could save between £70 and £260 in energy bills per household per year. Furthermore, BEIS Committee (2019) magnifies this point by stating that there are larger carbon savings in closing the performance gap than making standards more onerous. *This is not a reason against raising standards; rather it underlines what can be gained by eradicating the discrepancy.*

Though this report focuses on new housing, to amplify the need for housing performance evaluation some mention should be made of the need to improve existing housing in the UK also. If the housing stock is to be decarbonised, and if the vulnerable population is to be protected from rising fuel prices, almost every home will need some energy efficiency improvements (BEIS Committee, 2019). Housing performance evaluation can provide greater detail on the real performance of the dwelling before and after retrofit, which can also inform energy models.

5.2 Future of housing performance evaluation

As explained above, the proposed policy changes expose the importance to evaluate not only the real performance of the fabric, but other areas of the building's performance. This places performance evaluation in an essential position to both

1. verify that the required fabric standards are met to justify low carbon systems and
2. quantify the cost-effectiveness of low carbon systems in general so that policy recommendations can be continually improved.

To provide more accurate predictions which would minimise the performance gap between modelled and actual performance, housing performance studies are needed to produce calibrated prediction models (using test data and where possible actual occupancy details).

Housing performance evaluation can also provide the following benefits:

- Energy efficiency investments need to be targeted correctly. Housing performance evaluation should be a government tool used to assess the effectiveness of energy efficiency policy for the improvement of funding direction and effectiveness.
- Materials and methods may fail due to common mistakes and misconception during both construction and in-use stages. Performance evaluation is the only route to deciphering these issues (e.g. gain greater insight into the resident's interaction and use) and correcting them so that the building industry can quickly improve use and integration of new materials, systems and methods and improve educating residents on proper use and maintenance.
- Housing performance evaluation as a tool to verify workmanship, e.g. verified installer / builder
  - Example: a specified number of performance evaluations should be performed to verify a builder's work; they would be certified by a 3rd party and subject to a certain number of evaluations per year to retain certification.
  - This primarily to verify quality of workmanship and correct operation of systems and materials as past scams and poor standards of workmanship have blighted confidence in energy efficiency installations. If there is limited trust in energy efficiency schemes, there will be limited progress in housing decarbonisation and fuel poverty alleviation (BEIS Committee, 2019).
  - An added benefit would be the collected data to feed into other purposes listed above, e.g. improvement of funding effectiveness.

The Mineral Wool Insulation Manufacturers Association (MIMA) recommend that by 2025 to meet new efficiency and carbon standards:

- Government mandates the use of digital technologies (or other means) to "track and trace" the installation of energy efficiency products in newly constructed homes, and other products relevant to the health and safety of future residents, creating a "golden thread" of information and accountability.

- Government mandates the verification of as-built performance of new homes against key metrics developed with industry, to check the performance of new housing schemes matches the design intent. Government incentivises and regards organisations who go further to verify that the in-use performance aligns with the design.

What will government need to do to encourage and support the integration of performance evaluation into the house building industry to avoid the specification / performance gap?

- Immediately incentivise real performance of current and greater rewards for proven performance of future proposed standards.
- Incentivise performance verification techniques and technologies to decipher which ones work in order to create a proven log of methods going into 2025.

Additionally, the Committee on Climate Change (2019) recommend the following which are highly relevant for the future of housing performance evaluation:

- Overhaul the compliance and enforcement framework so that it is outcomes-based (focussing on performance of homes once built), places risk with those able to control it, and provides transparent information and a clear audit trail, with effective oversight and sanctions. Fund local authorities to enforce standards properly across the country.
- Reform monitoring metrics and certification to reflect real-world performance, rather than modelled data (e.g. SAP). Accurate performance testing and reporting must be made widespread, committing developers to the standards they advertise.
- Review professional standards and skills across the building, heat and ventilation supply trades with a nationwide training programme to upskill the existing workforce, along with an increased focus on incentivising high ‘as-built’ performance. Ensure appropriate accreditation schemes are in place.
- Undertake a large-scale study to provide robust quantification and benchmarking of the performance gap for energy, water and ventilation.

5.2.1 Data privacy and ethics in housing performance studies

The Data Protection Act of 2018, the UK’s implementation of the General Data Protection Regulation (GDPR), controls how personal information is used by organisations, businesses or the government. According to the Act, entities that have access to personal data have the responsibility to follow ‘data protection principles’. That is, to ensure personal information is:

- used fairly, lawfully and transparently
- used for specified, explicit purposes
- used in a way that is adequate, relevant and limited to only what is necessary
- accurate and, where necessary, kept up to date
- kept for no longer than is necessary
- handled in a way that ensures appropriate security, including protection against unlawful or unauthorised processing, access, loss, destruction or damage

Housing performance studies are a kind of an experiment that is conducted in a real world setting, wherein the residents become the subjects. Since the home environment is one where individuals are entitled to privacy and safety, an evaluation will necessarily impinge on this. Sharpe (2019) presents the following ethical challenges that may arise in HPE studies:

- *Non-maleficence* – The principle is to do no harm. Potential aspects of harm may need to be considered:
    - Could monitoring that revealed patterns of resident behaviour be used to disadvantage occupants?
    - Could monitored data be used to identify patterns of lifestyle or occupancy that could be exploited?
    - Would showing when houses are empty present a security risk?
- *Research conduct including honesty and integrity* – errors in data collection and use; concerns over the risks and liabilities that may be revealed by BPE studies are often major barriers to the adoption of BPE.
- *Lack of coercion* – occupants may feel that their tenancy or relationship with the landlord is under threat if they do not participate.
- *Informed consent* – sufficient information needs be provided to enable an informed decision to be made but there is a concern over participant bias and the Hawthorne Effect. As an example, would telling participants that a study was evaluating how frequently they opened their windows affect their window-opening habits?
- *Confidentiality*
- *Equality and diversity; and*
- *Data protection*

By adopting ethical procedures and data protection principles, the above challenges should be addressed in HPE studies that involve residents.

5.3 Enhancing performance evaluation with emerging technologies

With decarbonisation of heating and electricity, it will become important to assess not only the thermal performance of the building fabric but also energy demand profiles and resident health and wellbeing. Emerging technologies and tools can enhance the process of delivering housing performance, as explained below.

Building Information Modelling (BIM):

Evaluators utilizing BIM will be equipped to access better design and construction documentation where available. This would enable all parties to obtain documentation on the intended material or system, their specification and their intended integration in one place. These data provide highly detailed insight into as-designed and as-built changes.

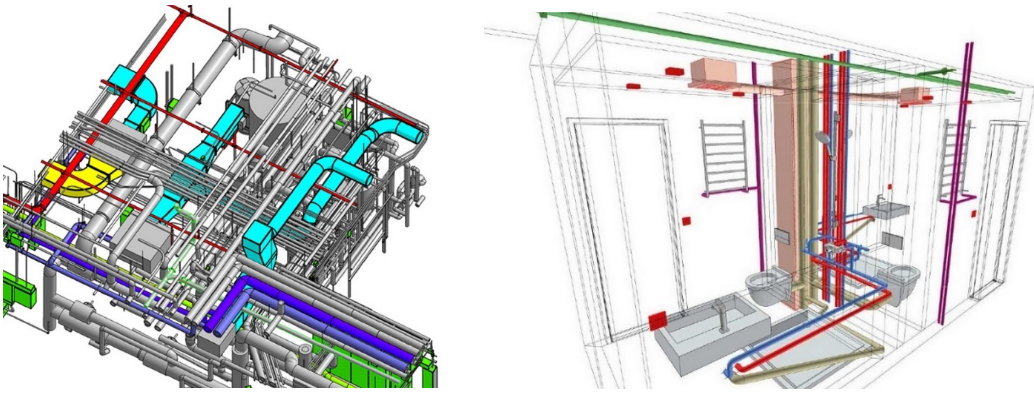


Figure 33. Images of BIM – left: mechanical integration[13]; right: bathroom plumbing modelling[14]

Low-cost non-invasive building fabric performance tests:

- New low disruption methods may allow effective fabric assessment during occupation. One method, *Pulse* (BTS, 2019), is a portable compressed air based system which is used to measure the air leakage of a building or enclosure at a near-ambient pressure level (4Pa). A concept originally pioneered by the University of Nottingham, the system releases a small burst of air which generates a flow rate through the gaps and cracks in the building. The change of internal pressure of the building due to this flow is seen as a 'pulse' and its representation is characteristic of the building's leakage. Pulse dynamically measures building air leakage directly at low pressure providing an air change rate measurement that is representative of normal inhabited conditions, helping to improve understanding of energy performance and true building ventilation needs. The test is quick, less susceptible to wind disruption, and requires no envelope penetrations for the test to run.
- An additional tool which works with *Pulse* is *Leak Checker*. The tool is a fan designed to be window mounted, runs from a mobile phone app and can be used as an air leakage diagnostics tool. The fan creates a pressure difference large enough so that air leakage paths can be felt with your hand of visualised with a smoke pen or thermal imaging camera. Though the fan is not intended as a measurement instrument and cannot be used for compliance. It can provide an indication of overall leakiness and level of progression made by your sealing interventions.
- Another tool, *Surface thermal properties measuring system (STPSYS05)* from Hukseflux[15], allows the measurement of thermal conductivity and an estimate of thermal diffusivity. The measurement process involves placing the sensor on a smooth flat surface of the material in question and allowing it to stabilize for five minutes. After this, a reading is provided. For higher accuracy results, glycerol is suggested as a thermal contact fluid to ensure minimal interfacial thermal resistance between the sensor and the material.

[13] https://vibim.com.vn/
[14] https://www.tzb-info.cz/
[15] https://www.hukseflux.com/products/thermal-conductivity-sensors/thermal-conductivity-measuring-systems/stpsys05-system

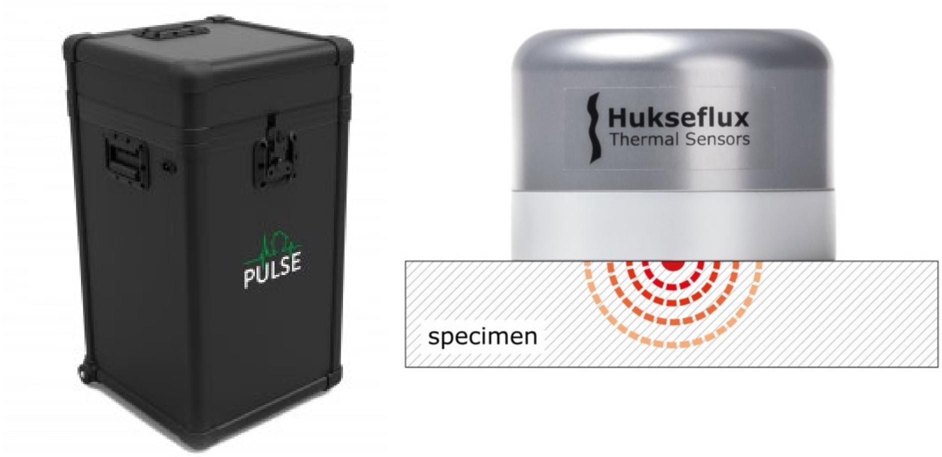


Figure 34. Pulse[16] (left); Surface thermal properties measuring system[17] (right)

Internet of Things (IoT) based sensing

Internet of Things (IoT) based home energy management systems and low-cost sensors can not only manage energy use but also continuously monitor indoor environment.

Systems like Hive Active Heating, Ecobee and Nest, smart home energy management systems, are a wireless thermostat control device that communicates with a hub that is connected to the home's broadband router, and the receiver which allows the thermostat to communicate with the heating system. Smart thermostats allow for more detailed control over the heating system while at home or away.

Many of these smart heating systems also include or work with 3rd party smart home accessories that can also be controlled via apps such as lighting, plug controls, window and door sensors, and occupancy sensor. The data from these devices are potentially useful for post-occupancy evaluation.

Figure 35. Smart home system from left to right: occupancy sensor, smart plug, active heating, smart bulb, window and door sensors[18]

16 https://buildtestsolutions.com/
17 https://www.hukseflux.com/
18 https://www.hivehome.com/

Personal monitoring devices

Personal monitoring devices, also called as wearable technology can gather data for assessing the health and well-being of residents seamlessly.

With the diffusion of wearable technologies such as Fitbits and numerous other smart watches, health measurements of residents can be easily assessed through heart rate, heart rate variability, activity levels and sleep quality. A correlation between such physiological data and environmental monitoring data can be undertaken to identify the relationship between health conditions of the occupants and indoor environmental conditions. Wearable technology is already being used in the health and insurance industry for physical and behavioural evaluation. In 2015 the NHS announced the roll out of wearables as a revolution in self-care. The British Council for Offices (BCO) (Taub, Lockhart, & Clements-Croome, 2016) reported on the potential impact of wearables in the evaluation and improvement of health, wellbeing, and productivity in the office environment. By extension many of these are useful in the home environment. Examples include:

- Air quality: personal environmental monitors and air purification devices. Wearable environmental monitoring devices can map air quality or 'air pollution mapping' as an individual uses a space. Device example: *CleanSpace*
- Water: drinking water quality assessment. Water consumption may be tracked to correlate with overheating in homes. Device example: *WaterMinder*
- Light: monitoring of lighting properties. Device example: *SunSprite*
- Comfort: Individual control of local thermal conditions which can provide a wealth of information on at the time environmental conditions and preferred conditions as on changes their environment in response. Device example: *Thermodo.*
- Well-being: measure physiological aspects of humans - heart rate, activity levels, sleep quality that can be used to cross-relate with indoor environmental data to see how the indoor environment is affecting residents' well-being. Device examples: *Fitbit* & *Polar*

Figure 36. Wearables from left to right: Fitbit[19], SunSprite[20], Thermodo[21]

[19] https://www.fitbit.com
[20] https://www.sunsprite.com/
[21] https://thermodo.com/

Smart meters

As we enter a world of smart meters and smart homes, individuals will be better able to understand how their homes perform – this could revolutionise and mainstream the measurement and evaluation of housing performance. Smart meters are being rolled out to all homes and small businesses by 2020 (though this may be more ambitious than realistic). The rollout is central to the energy system transformation under-pinned by the three drivers of digitalisation, de-centralisation and de-carbonisation. There are several suggested benefits to smart-metering for the consumer such as greater visibility and awareness of energy use and, better use of and accessibility to time-of-use tariffs. For government, there is strong interest in the use of data to improve the delivery of services and to aid public policy making, in the context of the growth of big data and artificial intelligence. Examples of use include, producing official statistics and undertaking statistical research that meets identifiable user needs for the public good.

In terms of enhancing performance evaluation, smart metering will increase the availability to high granularity of energy consumption / generation / export data. However, third parties will have to gain customer consent and subject to signing up to certain privacy protections as Smart Energy Code (SEC) signatories, including arrangements for customer authentication and information provision before they can collect customer data. This is likely not a problem since any invasive post-occupancy evaluation methods will require consent.

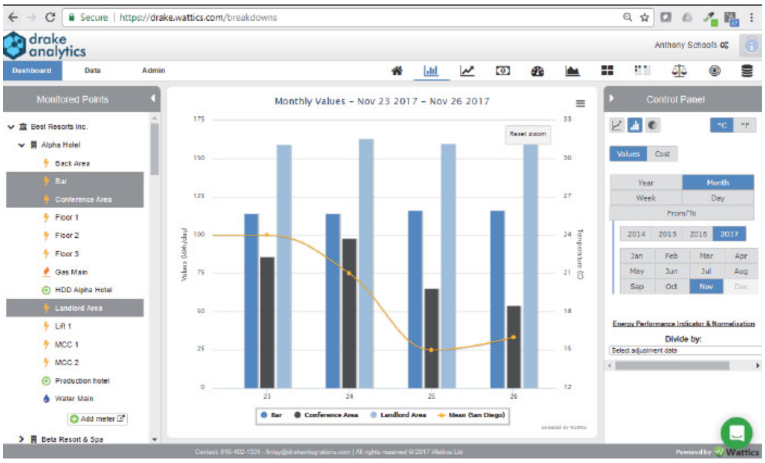


Figure 37. Smart meter[22] (left); Online data portal[23] (right)

To move from a modelled to measured approach, BEIS[24] has been supporting a programme of research to develop and commercially deploy methods for measuring the thermal performance of homes using smart meter data. The methods could use smart meter and weather data, and potentially other measurements (e.g. indoor temperature and home survey data). These products have been collectively termed 'Smart Meter Enabled Thermal Efficiency Rating' (SMETER) products. The thermal performance measurement provided by a SMETER (i.e. the HTC) could be fed back into the SAP model to enable a more accurate assessment of annual building energy performance for policy use.

If housing performance evaluation is to become common practice for new build schemes, such emerging technologies and tools need to be available and market ready to support this change.

22 https://www.greentechmedia.com/
23 https://www.wattics.com/
24 https://www.gov.uk/guidance/smart-meter-enabled-thermal-efficiency-ratings-smeter-innovation-programme

References

Alzetto, F., Farmer, D., Fitton, R., Hughes, T., & Swan, W. (2018). Comparison of whole house heat loss test methods under controlled conditions in six distinct retrofit scenarios. *Energy and Buildings, 168*, pp. 35-41.

ATTMA. (2016). ATTMA Technical standard L1: measuring air permeability in the envelopes of dwellings.

Baborska-Narożny, M., & Stevenson, F. (2019). Service controls interfaces in housing: usability and engagement tool development. *Building Research & Information, 47*(3), pp. 290-304.

BEIS. (2018). *Clean Growth Strategy: Leading the way to a low carbon future*. London: HM Government Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/700496/clean-growth-strategy-correction-april-2018.pdf.

BEIS Committee. (2019). *Energy efficiency: building towards net zero*. London: https://publications.parliament.uk/pa/cm201719/cmselect/cmbeis/1730/1730.pdf

Bordass, B., & Leaman, A. (2005). Making feedback and post-occupancy evaluation routine 1: A portfolio of feedback techniques. *Building Research & Information, 33*(4), pp. 347-352.

Bordass, B., Leaman, A., & Bunn, R. (2007). *Controls for End Users: A guide for good design and implementations,* .

BTS. (2019). Build Test Solutions (BTS), innovators in building performance measurement. Retrieved Date from https://buildtestsolutions.com/.

Carfrae, J., De Wilde, P., Littlewood, J., Goodhew, S., & Walker, P. (2009). Long term evaluation of the performance of a straw bale house built in a temperate maritime climate. *RCOM A*, p 23.

Cartwright, P., & Gaze, C. (2013). *Lessons from AIMC4 for cost-effective, fabric-first, low-energy housing: Part 1: Introduction to AIMC4*.

Chapman, J., Lowe, R., & Everett, R. (1985). *The Pennyland Project*. http://oro.open.ac.uk/19860/1/Pennyland_report_Jan_10.pdf

CIBSE. (2015). Environmental design: CIBSE Guide A (pp. 402): CIBSE.

CIBSE. (2019). CIBSE briefing: Steps to net zero carbon buildings. In CIBSE (Ed.), (1 ed.). London: CIBSE.

Committee on Climate Change. (2019). *UK housing: Fit for the future?* : https://www.theccc.org.uk/wp-content/uploads/2019/02/UK-housing-Fit-for-the-future-CCC-2019.pdf

DCLG. (2008). Code for Sustainable Homes—Technical Guide. *London: Department for Communities and Local Government*

EST. (2009). Enhanced Construction Details: Thermal bridging and airtightness (Vol. CE302, pp. 21). London: Energy Saving Trust.

EST. (2010). *Getting warmer: a field trial of heat pumps* London: DECC. http://hydrocarbons21.com/files/energy-saving-trust-heat-pump-trial-uk.pdf

Everett, R., Horton, A., & Doggart, J. (1985). *Linford Low Energy Houses*. http://oro.open.ac.uk/19861/1/Linford_report.pdf

Forster, L. M., Randall, T., & Churcher, D. (2014). *GCB Project 430 Knowledge Capture and Dissemination*. G. C. Board.

Gallardo, A., Palme, M., Lobato-Cordero, A., Beltrán, R. D., & Gaona, G. (2016). Evaluating thermal comfort in a naturally conditioned office in a temperate climate zone. *Buildings, 6*(3), p 27.

Gaze, C. (2014a). *AIMC4 Information paper 5: lessons from AIMC4 for cost-effective fabric-first low-energy housing Part 5: As-Built performance and Post Occupancy Evaluation*.

Gaze, C. (2014b) *How did the homes perform? The data.* Paper presented at the Proceedings of final AIMC4 conference.

GHA. (2019). Resources. Retrieved Date from http://goodhomes.org.uk/resources.

Gill, Z. M., Tierney, M. J., Pegg, I. M., & Allan, N. (2010). Low-energy dwellings: the contribution of behaviours to actual performance. *Building Research & Information, 38*(5), pp. 491-508.

Godefroy, J., & Etude. (2019). *Buildings Energy Mission 2030: Background Report to Recommendations from the UK Green Construction Board in response to the 2030 Newbuild Challenge*. London: http://www.constructionleadershipcouncil.co.uk/wp-content/uploads/2019/05/GCB-Energy-Mission-Report-300419-FINAL.pdf

Good Homes Alliance. (2019). OVERHEATING IN NEW HOMES: Tool and guidance for identifying and mitigating early stage overheating risks in new homes (pp. 48). London: Good Homes Alliance.

Gorse, C., Glew, D., Johnston, D., Fylan, F., Miles-Shenton, D., Smith, M., . . . Fletcher, M. (2017). *Core cities Green Deal monitoring project–Leeds*.

Gupta, R., & Chandiwala, S. (2010). Understanding occupants: feedback techniques for large-scale low-carbon domestic refurbishments. *Building Research & Information, 38*(5), pp. 530-548.

Gupta, R., & Dantsiou, D. (2013). Understanding the gap between 'as designed'and 'as built'performance of a new low carbon housing development in UK *Sustainability in Energy and Buildings* (pp. 567-580): Springer.

Gupta, R., Eyre, N., Darby, S., Lucas, K., Barnfield, L., Hamilton, J., . . . Irving, B. (2015). *Evaluating the impacts, effectiveness and success of low carbon communities on localised energy behaviours (EVALOC)*. Oxford: O. I. f. S. D. Low Carbon Building Group, Oxford Brookes University & Environmental Change Institute, University of Oxford. http://docs.wixstatic.com/ugd/caf2de_7e26026ae8c9492ca5b32ade0b4dac7a.pdf

Gupta, R., Gregg, M., & Bruce-Konuah, A. (2017) *Assessing the occurrence of summertime overheating in occupied and unoccupied low energy homes*. Paper presented at the PLEA, Edinburgh. https://plea2017.net/

Gupta, R., Gregg, M., & Cherian, R. (2013). *Tackling the performance gap between design intent and actual outcomes of new low/zero carbon housing.* ECEEE Summer study proceedings.

Gupta, R., Gregg, M., & Cherian, R. (2019). Developing a new framework to bring consistency and flexibility in evaluating actual building performance. *International Journal of Building Pathology and Adaptation*

Gupta, R., Gregg, M., Manu, S., Vaidya, P., & Dixit, M. (2019). Customized performance evaluation approach for Indian green buildings. *Building Research & Information, 47*(1), pp. 56-74.

Gupta, R., Gregg, M., & Salvati, A. (2020). Performance evaluation based claims process for insuring energy performance of new dwellings. In S. Lloyd, M. Dastbaz & C. Gorse (Eds.), *Sustainable Ecological Engineering Design: Selected Proceedings from the International Conference of Sustainable Ecological Engineering Design for Society (SEEDS)*. Switzerland: Springer International Publishing.

Gupta, R., & Kapsali, M. (2014). *How effective are 'close to zero' carbon new dwellings in reducing actual energy demand: Insights from UK.* 30th International PLEA Conference.

HM Government. (2010). Approved Document F 2010 edition with 2013 amendments *Approved document F: Ventilation* (pp. 63). London: NBS.

HM Government. (2011). *The carbon plan: Delivering our low carbon future*. London: D. o. E. a. C. Change.

Jaggs, M., & Scivyer, C. (2009). *A practical guide to building airtight dwellings*. Amersham: http://www.zerocarbonhub.org/sites/default/files/resources/reports/A_Practical_Guide_to_Building_Air_Tight_Dwellings_NF16.pdf

Jradi, M., Arendt, K., Sangogboye, F., Mattera, C., Markoska, E., Kjærgaard, M., . . . Jørgensen, B. (2018). ObepME: An online building energy performance monitoring and evaluation tool to reduce energy performance gaps. *Energy and Buildings, 166*, pp. 196-209.

Lowe, R., Bell, M., & Roberts, D. (2003). *Developing future UK energy performance standards: St Nicholas Court Project (Final Report)*. Leeds

Lowe, R., Wingfield, J., Bell, M., & Bell, J. (2007). Evidence for heat losses via party wall cavities in masonry construction. *Building Services Engineering Research and Technology, 28*(2), pp. 161-181.

Miles-Shenton, D., Wingfield, J., Sutton, R., & Bell, M. (2011). *Temple Avenue Project* Leeds: https://www.leedsbeckett.ac.uk/as/cebe/projects/tap/tap_summary_report.pdf

Ministry of Housing Communities and Local Government. (2019). *The Future Homes Standard 2019: Consultation on changes to Part L (conservation of fuel and power) and Part F (ventilation) of the Building Regulations for new dwellings*. London: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/843757/Future_Homes_Standard_Consultation_Oct_2019.pdf

Monahan, S., & Gemmell, A. (2011). How occupants behave and interact with their homes. *The Impact on Energy Use, Comfort, Control and Satisfaction. HIS-BRE Press on behalf of the NHBC Foundation, Milton Keynes*

NHBC Foundation. (2016). Air leakage services. Retrieved Date from http://www.nhbc.co.uk/ProductsandservicesConsultancyandTesting/Airleakageservices/FAQs/.

Ozturk, Z., Arayici, Y., & Coates, S. (2012). Post occupancy evaluation (POE) in residential buildings utilizing BIM and sensing devices: Salford energy house example.

Palmer, J., Godoy-Shimizu, D., Tillson, A., & Mawditt, I. (2016). Building Performance Evaluation Programme: Findings from domestic projects Making reality match design. Innovate UK.

Palmer, J., Terry, N., Johnston, D., Miles-Shenton, D., Gorse, C., & Pope, P. (2019). *Cavity Party Walls: Measuring U-values*. London: BEIS. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/788575/Cavity_party_walls_measuring_u-values.pdf

Preiser, W., Rabinowitz, H., & White, E. (1988). *Post-occupancy evaluation* New York: Van Nostrand Reinhold.

Preiser, W., & Vischer, J. (2006). The evolution of building performance evaluation: An introduction. In W. Preiser & J. Vischer (Eds.), *Assessing building performance* (pp. 3-14): Routledge.

Ridley, I., Clarke, A., Bere, J., Altamirano, H., Lewis, S., Durdev, M., & Farr, A. (2013). The monitored performance of the first new London dwelling certified to the Passive House standard. *Energy and Buildings, 63*, pp. 67-78.

Ross, J. (2014). *Cavity wall insulation inspection report*. N. I. H. Executive. https://www.nihe.gov.uk/getmedia/7138f205-c8fb-408b-974e-626ed394e472/cavity-wall-insulation-inspection-report.pdf.aspx?ext=.pdf

RPA & LMU. (2012). *Temple Avenue Project*. York: JRF. https://www.jrf.org.uk/sites/default/files/jrf/migrated/files/energy-efficient-refurbished-homes-report.pdf
Satre-Meloy, A., Diakonova, M., & Grünewald, P. (2019). Daily life and demand: an analysis of intra-day variations in residential electricity consumption with time-use data. *Energy efficiency*, pp. 1-26.
Seguro, F. (2015). *Building Performance Evaluation Meta-Analysis: Insights from Social Housing Projects*.
Sharpe, T. (2019). Ethical issues in domestic building performance evaluation studies. *Building Research & Information, 47*(3), pp. 318-329.
Sian. (2013). Rory Bergin reflects on the psychological changes already developing for residents of VELUX and HTA's CarbonLight Homes. Retrieved Date Accessed, 2019 from https://www.worldarchitecturenews.com/article/1513330/other-peoples-houses-feel-caves#sthash.zteJ1s70.dpuf%20http://www.hta.co.uk/projects/velux-carbonlight-houses.
SMG. (2019). AIMC4. Retrieved Date Accessed, 2019 from https://www.stewartmilnetimbersystems.com/why-us/aimc4
https://www.hhcelcon.co.uk/resources/sustainability/aimc4.
Spataru, C., Gillott, M., & Hall, M. R. (2010). Domestic energy and occupancy: a novel post-occupancy evaluation study. *International Journal of Low-Carbon Technologies, 5*(3), pp. 148-157.
Stevenson, F. (2019a). Embedding building performance evaluation in UK architectural practice and beyond. *Building Research & Information, 47*(3), pp. 305-317.
Stevenson, F. (2019b). *Housing fit for purpose: Performance, feedback and learning.* London: RIBA Publishing.
Stevenson, F., & Baborska-Narozny, M. (2018). Housing performance evaluation: challenges for international knowledge exchange. *Building Research & Information, 46*(5), pp. 501-512.
Stevenson, F., & Leaman, A. (2010). Evaluating housing performance in relation to human behaviour: new challenges. *Building Research & Information, 38*(5), pp. 437-441.
Stevenson, F., & Rijal, H. (2008). *The sigma home: towards an authentic evaluation of a prototype building.* Proceedings of the 25th International Conference on Passive and Low Energy Architecture.
Sutton, R., Gorse, C., Shenton, D., Bradley, J., Thomas, F., Bell, M., & Glew, D. (2016). *Stamford Brook: Exploration of energy data*. Leeds: https://www.leedsbeckett.ac.uk/as/cebe/projects/stamford/pdfs/stamford_brook_inuse_final_report.pdf
Taub, M., Lockhart, V., & Clements-Croome, D. (2016). *Wearables in the workplace*. London: BCO. http://research.bco.org.uk/resources/clients/3/user/resource_785.pdf
Thompson, P., & Bootland, J. (2011). GHA monitoring programme 2009-11: technical report results from Phase 1: post-construction testing of a sample of highly sustainable new homes. *Report, Good Homes Alliance*
TSB. (2010). *Building performance evaluation, domestic buildings: Guidance for project execution* (Guidance No.: TSB.
TSB. (2012). Building Performance Evaluation competition brief. Retrieved Date Accessed, 2018 from https://webarchive.nationalarchives.gov.uk/20130102174011/http://www.innovateuk.org/content/competition/building-performance-evaluation-.ashx.
TSB. (2014). *Retrofit Reavealed: The Retrofit for the Future projects–data analysis report* T13/28). Swindon: T. S. Board.
USGBC. (2016). LEED credit library. Retrieved Date from http://www.usgbc.org/credits/homes/v4.
Whale, L. (2016). *Thermal bridging guide–an introduction to thermal bridging in homes*. London: Z. C. Hub. http://www.zerocarbonhub.org/sites/default/files/resources/reports/ZCH-ThermalBridgingGuide-Screen_0.pdf
Williamson, T., Soebarto, V., & Radford, A. (2010). Comfort and energy use in five Australian award-winning houses: regulated, measured and perceived. *Building Research & Information, 38*(5), pp. 509-529.
Wingfield, J., Bell, M., Miles-Shenton, D., & Seavers, J. (2011). *Elm Tree Mews Field Trial–Evaluation and Monitoring of Dwellings Performance (Final Technical Report)*. http://www.leedsbeckett.ac.uk/as/cebe/projects/elmtree/elmtree_finalreport.pdf
Wingfield, J., Bell, M., Miles-Shenton, D., South, T., & Lowe, R. (2008). *Evaluating the impact of an enhanced energy performance standard on load-bearing masonry domestic construction: Understanding the gap between designed and real performance: lessons from Stamford Brook* 1409828913).
Yao, R., Li, B., & Liu, J. (2009). A theoretical adaptive model of thermal comfort–Adaptive Predicted Mean Vote (aPMV). *Building and Environment, 44*(10), pp. 2089-2096.
Zero Carbon Hub. (2014). Closing the gap between design and as-built performance. *End of term report*

Research sponsored by