“The Thermal Energy Performance of Domestic Dwellings in the UK”

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PhD by Published Works

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Acknowledgements

My supervisor Professor Will Swan, and my mentor Professor Nigel Mellors have been crucial to the completion of the body of work presented. I also thank my wife Emma for support and patience during this long process. I would also like to thank my colleagues at the Energy House, in particular Moaad Benjaber for his support and help over the past few years.

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Abstract:

The central contribution of this work is concerned with the understanding of the real performance of domestic retrofit measures in terms of whole house energy efficiency. The researcher has undertaken studies in a whole house test facility in a climate controlled chamber, which has allowed for work to be undertaken that challenges the existing assumptions within regulatory steady state models, such as the Standard Assessment Procedure, something that is not easily undertaken in field-based and occupied properties. The two studies, around controls and curtains indicate that relatively small changes to the building can have potentially significant impact on the performance of the building, something that is poorly addressed within the models.

This work focuses on the performance gap, the difference between modelled and measured performance is investigated. As such, supporting work discusses the relationship between measured data and regulatory models, as well as considering issues with existing and the development of new methods for measuring performance in the field. These studies are undertaken within a contextual understanding of the current retrofit field from a policy and market perspective; this work is essential in terms of positioning the work in terms of ensuring it applicability and implications for the sector.

The main findings indicate that the one factor at a time approach, facilitated by the controlled environment within the facility, reveals significant differences between the measured values and the regulatory models. This is demonstrated in research on building controls and window coverings.

1 - Introduction

1.1 Introduction to the Research

This PhD by publication presents a body of work related to understanding the energy performance of domestic buildings in the UK. The central focus of the work is to challenge the assumptions of performance of buildings found within statutory models and so contribute to a better understanding of the performance gap. This work is mainly, although not entirely, based around work undertaken in the Salford Energy House, a unique whole house test facility within a climate controlled lab. This approaches addresses some of the difficulties found in the literature of field testing, which can be complex due to the high numbers of uncontrolled variables, and element or individual system tests, which often do not take into account the interactions of these measures within a whole building context. This provides a core contribution to knowledge of this work of providing improved datasets around real building performance of specific measures.

This work is bounded by an understanding of wider issues. The boundaries of the research (Figure 1) mean that contributions have been made to issues around both statutory and dynamic modelling, as well as methodological issues that surround tests both within the field and lab based conditions. In addition, the work is further bounded by a contextual understanding of where the work sits in terms of the policy and industry context, which is essential when considering potential impact and engagement with wider stakeholders.

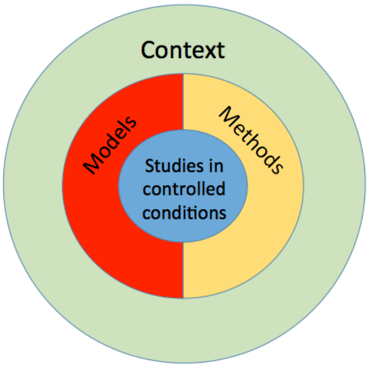


Figure 1 Bounding of Research

1.2 Aims and Objectives

The aim of this research in the main is to highlight issues with the current steady state energy modelling tool used in the UK for regulatory purposes, the Standard Assessment Procedure (SAP). This steady state tool is used to predict energy consumption in domestic properties, using a method which avoids the dynamic characteristics found in dwellings (in systems/fabrics and occupancy variation) and the boundary conditions that surround them (BRE 2012). Whilst of course this abstraction is useful as it allows comparisons to be made of similar buildings, the research presented here states that some of these simplifications could be reconsidered to provide a more accurate tool, and also suggests that a dynamic methodology may be more useful in some circumstances. Full aims and objectives are outlined in Section 3.4.

1.3 Core research and main contributions

The core research aims to provide detail about the dynamic effects of two measures that are often retrofitted/added to buildings to aid energy efficiency and levels of thermal comfort: Window coverings and heating controls. This work is detailed in Section 4.4 of this thesis. While only two technologies are addressed here, the trajectory of the work suggests an ongoing engagement with this main area of research, which is the assessment of real performance of retrofit measures.

The research found considerable differences between the values in SAP and the values measured under controlled conditions. When the steady state conditions found in SAP were represented in the house with no variations in temperature or without the radiators being below the windows, model values were very similar to the modelled and measures found by other researchers in the field (Baker 2009; Garber-Slaght & Craven 2012; Lunde & Lindley 1988). However, when the dynamic elements were introduced the measured values were significantly different, and higher rates of savings were found in some cases where the heat emitter was located below the window and, subsequently, lower savings where the emitter was placed away from the window. The variances in predicted savings from steady state to dynamic was in the order of +/- 12%. When this is considered over a full house it becomes significant.

The level of data presented and analysis presented in the paper offers a solution to energy modellers: where dynamic models are used this data can be used to make calibrations and perform verification (Marini et al. 2016; Pan et al. 2007), and where steady state models are used this data can offer a "factor" which may help in the accurate predictions in the savings made by various types of window coverings, according to the placement of heat emitters.

Localised controls have been shown to make significant savings under controlled conditions, when compared to savings predicted by an RdSAP calculation in **Publication 1**. When a calculation is made using SAP we expect the savings in the order of 2-3% in the heat demanded by the dwelling by adding TRVs to a building exactly the same as the Energy House, however **Publication 1** measures these savings at 33%. This leaves a performance gap of around 27% in terms of the energy savings offered by controls. It is observed that this measured performance gap is largely due to the dynamic effect of the system which appears to be overly simplified in SAP model in such a way that incorrect savings are generated.

This contributes knowledge to the modelling sector who can use the published measured data to generate more accurate dynamic models. It also gives the opportunity to improve predictions offered by steady state models

Although these are only two studies, the findings are clear: when predicting energy savings figures, or building performance figures, it is clear that steady state models do not accurately the true savings that can be found under dynamic and real world conditions. This viewpoint is shared by others in the research community who find the tool to be lacking in areas around accuracy. (Kelly et al. 2011).

1.4 Methodological work and main contributions to knowledge

The methodological work is centred around attempting to resolve difficulties from both a research design and pragmatic delivery of research. Initial work **(Publication 6)** investigated the methodological issues with fieldwork, ranging from issues with technology to non-co-operative occupants. All these issues have implications for research design, execution and results. Next **(Publication 7)** is an initial attempt to support effective research design in addressing some of these problems.

Prompted by the discovery of significant issues in the measurement of energy performance in buildings, which was also highlighted by the Zero Carbon Hub report on the performance gap (Zero Carbon Hub 2010), led to the creation of a new sensor for measuring u-values in buildings this is now submitted as a patent (**Publication A2**), as well as working on a new international standard **(Publication A1)** for measuring the thermal performance of foil based insulation which also filled a knowledge gap on the measurement of this material which has been the subject of much dispute in the construction industry concerning its measured performance (Hauser et al. 2013)

Whilst elemental performance of dwellings remains important, many researchers (Jack 2015; Stamp 2016; Butler & Dengel 2013; Siddall et al. 2013; Johnston et al. 2015) have recently focussed on the performance of an aggregated energy performance of dwellings, relying on long term test known as the Whole House Loss Methodology, created by Leeds Becket

University (Johnston et al. 2010). A new method known as the QUB method (Mangematin et al. 2012) was validated under controlled conditions in the Energy House **(Publication 8).** This method is designed to provide a rapid diagnostic test of a dwelling in as little as 48 hours, when compared to approximately 2 weeks for other whole house methods (Johnston et al. 2012). The contribution here was to provide a robust, repeatable and statistically valid comparison between the Whole House Heat Loss methods and the QUB method. Both of these methods allow for a building to be testing in real world conditions with the dynamic effects of the external boundary conditions and the fabric of the dwelling including infiltration heat loss.

1.5 Modelling work and main contributions to knowledge

The core work of providing more robust data has implications for the modelling community, thereby improving the assumptions within both static and dynamic models. However, this effective modelling also relies on effective characterisation of the modelled building, which should also be considered when analysing energy modelling work.

Publication 4, provides an example of this type of work. Here, the detailed data was gathered from the Energy House to provide a model to investigate potential overheating of retrofit solutions for solid wall dwellings. This is detailed in Section 4.3 of this thesis. This work is unique, as the model created was a representation of the Energy House, which was also validated using test data collected under dynamic internal conditions. This data was used to calibrate the dynamic energy simulation. This modelling work predicted significant overheating in both the living room and bedrooms before 2050, this is a significant contribution for two reasons, this is the one of the first times that a dwelling has been successfully calibrated using test data at this scale, and it also breaks ground in predicting with significant accuracy, where and why a home can overheat in the future if retrofitted and also suggests ways that this can be mitigated.

Publication 3 highlights ways that errors in data collection and negligent action can seriously affect the outcomes of energy performance certificates in the UK. This is important as this mechanism is used to make decisions on retrofit options and also to make financial calculations for energy savings products. While this focus is on the statutory model for Energy Performance Certificates, it also has implications more widely; the effective characterisation of the building is one of the essential first steps in developing accurate models and this requires a detailed understanding of built form.

1.6 Summary and Future Work

The work here represents a point in time in addressing the research areas outline above. Additional work is currently being undertaken in the following areas

1.7 Purpose of Report

The purpose of this report is to present a body of work undertaken for submission for the PhD by published works. The core body of work is focused on the thermal energy performance of domestic buildings, which is driven by boundary conditions, fabric, systems, controls and occupants. The work, while aware of the wider socio-technical context of energy and buildings research, takes a largely positivist approach, with a focus on building physics. The work covers three core areas; methodological issues, modelling and experiments. A secondary contextual area of work concerning the wider implications and boundaries of the central work is also discussed.

The report covers work from 2011-2016, and has the following structure;

- Chapter 1 – Introduction
- Chapter 2 – Research Context and State of the Art
- Chapter 3 – Researcher Context and Methodological Position
- Chapter 4 – Paper Narratives
- Chapter 5 – Impact and Contribution to Knowledge
- Chapter 6 – Discussion
- Chapter 7 – Summary and Conclusion
- Annex A – Publications

This report demonstrates the core skills and competences that have been developed by the researcher to achieve a PhD by publication. These competences, as defined by the Quality Assurance Agency for Higher Education (QAA) (QAA 2014):

- The creation and interpretation of new knowledge, through original research or other advanced scholarship, of a quality to satisfy peer review, extend the forefront of the discipline, and merit publication.
- A systematic acquisition and understanding of a substantial body of knowledge which is at the forefront of an academic discipline or area of professional practice.
- The general ability to conceptualise, design and implement a project for the generation of new knowledge, applications or understanding at the forefront of the discipline, and to adjust the project design in the light of unforeseen problems.
- A detailed understanding of applicable techniques for research and advanced academic enquiry.

Typically, holders of the qualification will be able to:

- Make informed judgements on complex issues in specialist fields, often in the absence of complete data, and be able to communicate their ideas and conclusions clearly and effectively to specialist and non-specialist audiences.
- Continue to undertake pure and/or applied research and development at an advanced level, contributing substantially to the development of new techniques, ideas or approaches.

And holders will have:

- The qualities and transferable skills necessary for employment requiring the exercise of personal responsibility and largely autonomous initiative in complex and unpredictable situations, in professional or equivalent environments.

1.8 Evidence Presented

The evidence presented in this report is split into three sections:

Published Works

8 publications are peer reviewed and published as defined in the Research Award Regulations published by the University of Salford. The work also includes one publication (**Publication**

2) that has been accepted with changes; these have been submitted are waiting to be approved.

Publications Submitted Awaiting Acceptance

These publications have been submitted to journals, and are awaiting acceptance. These have been presented to illustrate the current research taking place, and they also help set context for some other papers.

Supplementary Publications

These supplementary publications have all been peer reviewed and published into the public domain as either standards/patents or formal guidance from industry authorities and chartered bodies.

Outline of Work

Figure 2 below illustrates the structure of the work presented.

Background Issues

Adoption of Sustainable Retrofit in UK Social Housing

Understanding our Heritage: Monitoring of energy and environmental performance of traditional terraced houses of Northern England

Methods	Modelling	Experiments
Energy monitoring in retrofit projects: Strategies, tools and practices A UK practitioner view of domestic energy performance measurement Zero Carbon Hub: Closing the gap between design and as built performance BS EN 16012:2012+A1: Patent Application (GB1609035.9) QUB: Validation of a Rapid Energy Diagnosis Method for IEA Annexe 58 Final Report: Logic and use of a Decision Tree	The Variability of UK domestic energy assessments RICS Article: Performance gap in domestic retrofits Assessing overheating of the UK existing dwellings – A case study of a replica Victorian end terrace house	Assessing the Performance of domestic heating controls in a whole house test facility A Study into the Effect of Curtains and Blinds as Energy Savings Measure, Under Controlled Conditions

Figure 2 Structure of work presented as evidence

2 - Research Context and State of the Art

2.1 Domestic Energy context in UK

This thesis focuses on the existing domestic housing sector in the UK, which makes up a significant proportion of the final energy consumption of the UK. This sector accounts for 27% of final energy consumption (Palmer & Cooper 2012). This means that the CO_2 produced by domestic buildings in the UK currently accounts for more than that produced by road transport or industry. (Palmer & Cooper 2012). The following section outlines the scope and scale of the problem of energy efficiency within the domestic stock.

The total stock of UK domestic properties is approximately 27.3 million dwellings. A relatively small number of new properties are being constructed, at around 180,000 per year (Palmer & Cooper 2012). The rate at which properties are currently being newly constructed and existing ones demolished, establishes that by the year 2050 that between 60 and 87% of the housing that existed in 2006 is likely to be still in use (Sustainable Development Commission 2006; Ravetz 2008; Boardman 2008). It is for this reason that the author has focused largely on the existing stock rather than the new build sector.

2.2 Sources of Energy Loss in Dwellings

There are many sources of energy loss in dwellings; fabric and systems for example. Work based on the English Housing Survey (DCLG 2011) is used to provide energy efficiency data of the housing stock. The survey consists of 17,556 sample archetypes reflective of England's 22.3 million homes and has been analysed through the Cambridge Housing Model (CHM), which assigns energy consumption to various elements of the dwelling (Hughes 2011).

Figure 3 illustrates the broad results from the CHM model to give an overview of domestic energy consumption by category; the majority of the energy used in the average UK dwelling is overwhelmingly for space heating which accounts for over 66% of the final energy consumption. This evidence forms the backdrop for the author's choice of topics and subsequent research. It is clear that, given the energy efficiency landscape in the UK, an investigation of space heating and heat losses in dwellings, addresses a central issue for the UK.

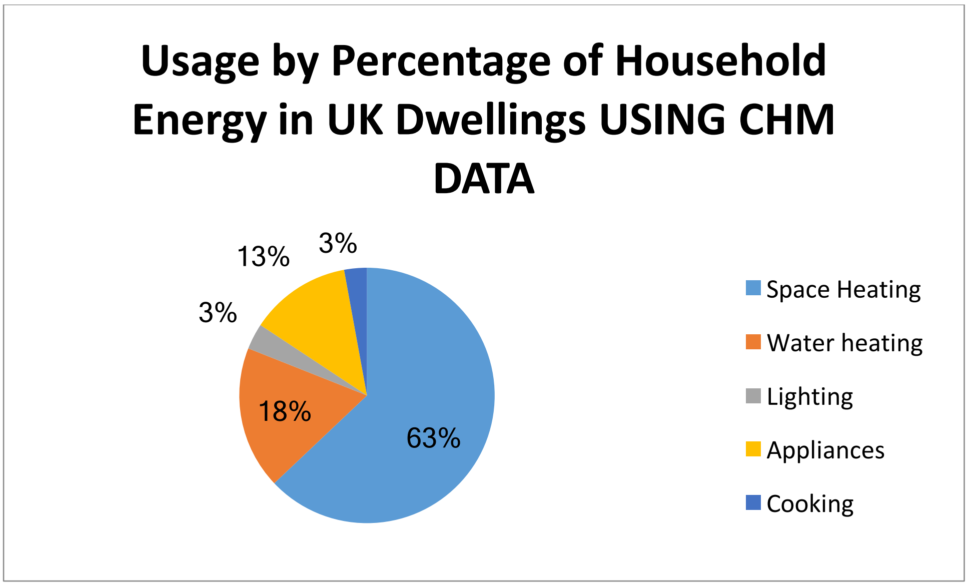


Figure 3 Usage by percentage of household energy (DCLG 2011)

The core research position is to take a building physics approach, a fundamentally positivist stance, to understand how buildings perform, as well as investigating ways in which this performance can be improved.

2.3 Energy Policy

Energy policy in the UK, has changed multiple times since this body of work was commenced, with some publications referring to defunct/out of date policies. The body of work is only 3-4 years old at maximum. It is for this reason that this section will encompass an overview of current policy as affects the domestic sector.

Background:

UK energy policy has been driven by the energy trilemma; climate change, fuel poverty and energy security (World Energy Council & MacNoughton 2016). It could be viewed that energy policy as applied to the domestic sector during 2011-16 has largely been driven by climate change, as enshrined in the Climate Change Act (2008) and fuel poverty, which was previously defined using a 10% threshold of income to heat the home to a defined comfortable threshold (Boardman 1991), but which was revised to a more complex approach under the Hills Review (Hills 2012).

Energy Company Obligation

The Energy Company Obligation (ECO) is a supplier obligation and replaced the Carbon Emissions Reduction Target (CERT) (OFGEM 2016) and the Communities Energy Savings Programme (CESP) (OFGEM 2016). It can be viewed as a "tax" on energy bills, which is then used to fund improvements in dwellings for carbon emissions reductions, area based schemes similar to CESP and fuel poverty. The Governments ECO policy is currently under review following a consultation period.

Green Deal

The Green Deal (DECC 2010) was a programme initiated through the Energy Act 2011 and was designed to allow occupants to fund the up-front capital cost through loans which would then be paid off through payments based on the energy savings. It was predicted that the Green Deal would attract £1.3 billion per annum of investment by suppliers through the ECO scheme and £200 million in private sector investment to carry out work under the Green Deal (Palmer & Cooper 2012). The Green Deal relied on several "rules", the main one being that the finance for the measure meets the "golden rule". This is defined as "the expected financial savings must be greater than the costs attached to the energy bill". This must be the case for each Green Deal measure or combination of measures proposed. (DECC 2010). The Green Deal failed to deliver major improvements, with low consumer awareness and uptake being one of the main causes for its lack of success (Pettifor et al. 2015), together with assessment costs having to be paid up front by the consumer and interest cost added to the loan (Marchand et al. 2015)

Minimum Energy Standards

An additional part of the Energy Act (2011) introduced Minimum Energy Standards (DECC 2015) applicable to the growing private rented sector, representing some 18% of the current stock (Office of National Statistics 2015). This identified that properties rated F or G under the Energy Performance Certificate (see below), would not be eligible for rent. The landlord would be required to bring them up to the required energy efficiency standard to bring the property back to market. This comes into force in 2018 for dwellings.

Energy Performance Certificate

Underpinning many of the policy initiatives, such as Green Deal, ECO and Minimum Energy Standards, the Energy Performance Certificate (EPC) which is required to be produced when renting, buying and selling new or commercial property has been in place since the Housing Act 2004 provided the enabling legislation for the document. This was renewed in 2008 under The Energy Performance of Buildings Regulations Directive in 2007, which introduced the requirement for the Energy Performance Certificate to be provided to any would-be buyer or renter of a property. The EPC has been criticised by many researchers for its lack of flexibility and often inaccurate estimates of a buildings consumption compared to real life monitoring data on the same building. (Wingfield, 2011).

The overview of policy is brief, as it does not form the core focus of the work presented here. However, awareness of the policy context is essential in understanding how improvements are being delivered, as retrofit of existing dwellings may be viewed as largely policy driven. At the time of writing, policy with regards to energy efficiency in domestic properties is undergoing a major review known as Every Home Matters (previously the Bonfield Review) to which the author has contributed. This will be published in 2016 and may lead to a new policy landscape for the sector.

2.4 Building Physics and Building Performance

Thermal performance of a building chiefly concerns the building in relation to boundary conditions. In this section we discuss the basic theories underpinning building physics and their application to understanding the thermal performance of buildings.

Heat in a gas, solid or liquid will flow from hot to cold and will carry on flowing until equilibrium is reached (Burberry 1997). There are three ways in which a building can lose or gain heat: Conduction, convection and radiation:

Conduction - As temperature increases in a material so does the kinetic energy contained within it. This results in activity in the molecules of the fabric. These molecules then act on one another; this has the effect of transferring heat through the solid (Smith et al. 1983). When thermal conductance takes place though a solid, the more energetic molecules pass energy to less energetic molecules, thus the heat transfers from hot to cold. Some materials such as metals allow for the conductance of heat at a high rate, whereas materials with a low conductivity such as polystyrene, which are used as insulators, slow down the rate of heat flow through an element.

Convection - Convection is generally applicable to fluids and gases such as air, and is the way in which transmit heat by circulation. This can take effect in places such as ventilated roof spaces, where the heat transfer is proportional to the movement of air in the space. The more air movement, the greater the heat transfer is in the fluid. It is also the mechanism that gives rise to heat travelling upwards in an open space, as the hot air is displaced by the colder denser air that sinks naturally to the bottom of the space (Burberry 1997)

Radiation - Radiation is emitted from all materials that contain some form of kinetic energy, i.e. anything with a temperature of greater than -273.15K or absolute zero. This transfer of heat is in the form of electromagnetic waves. The rate of transfer depends on the surface of the material, a shiny surface can be found to be a poor emitter of radiation, whilst dark matt coloured surfaces emit radiation at a higher rate (Smith et al. 1983)

With this understanding of the methods of heat loss a picture can be built up of the issues, in terms of heat loss these can be broadly broken down into 2 distinct areas: fabric losses and ventilation losses through unintended ventilation (Johnston et al. 2010). And whilst radiative losses in a building are important, they are not covered to a great extent in this body of work. In Figure 4, the Cambridge Housing Model (Palmer & Cooper 2013) is applied to show the conduction heat losses through each of the elements, with ventilation losses considered separately.

The largest proportion of heat loss is from fabric heat losses and further to this, walls are greatest heat loss path in the average UK domestic house.

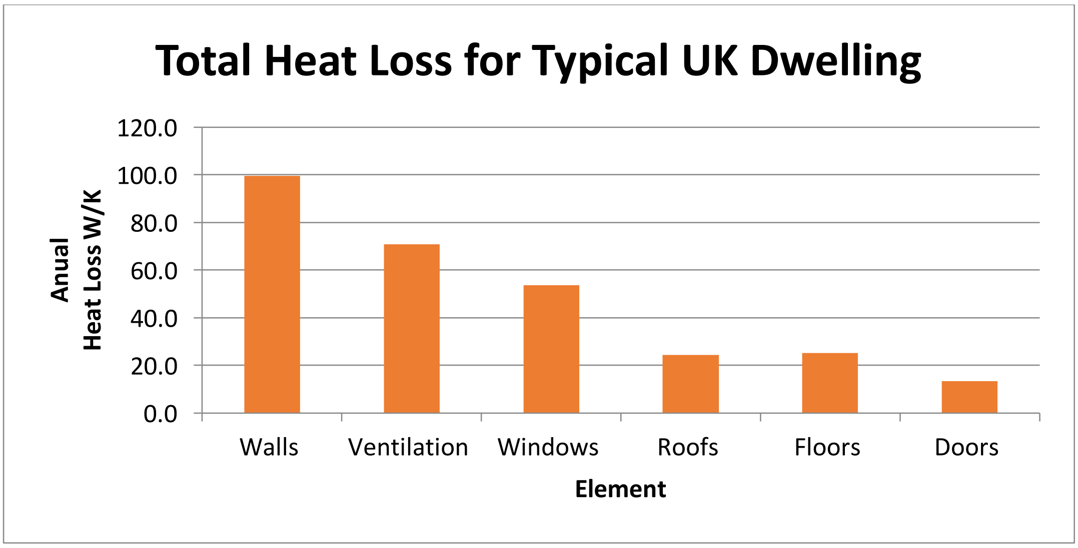


Figure 4 Heat loss figures for typical UK dwelling (Palmer & Cooper 2013)

In terms of costs, an average UK dwelling has a space heating consumption of 14400 kWh (Boardman 2006), assuming the building has gas central heating, as found in 90% of homes (DCLG 2011). This equates to an average heat loss through an average property’s external wall over 1 year a figure of 35% of 4900 kWh. At the current standard tariffs rates for gas of 3.6 pence per unit (British Gas 2016), then a breakdown can be built up with costs apportioned is shown in Figure 5.

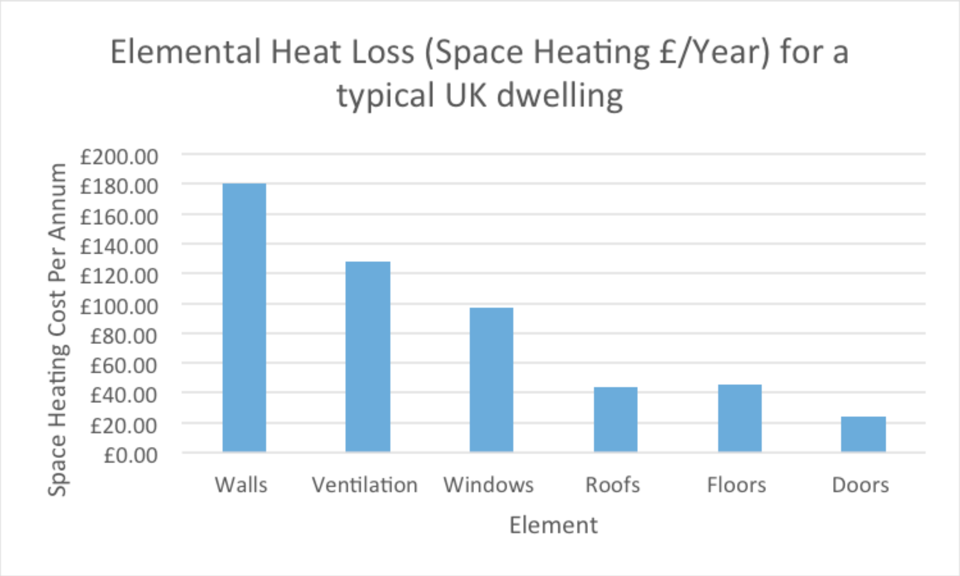


Figure 5 Elemental heat loss with associated space heating costs

The data within the Cambridge Housing Model identifies that in terms of heat loss, and sub sequentially financial terms, fabric losses form the major element of energy consumption in the domestic sector. In addition to the fabric losses, the heating and controls systems in the dwellings themselves are needed to be function efficiently; this requires controls and efficient heating apparatus. In addressing both the fuel poverty and climate change goals of the UK government, from an impact position, improving the fabric and heating efficiency of homes is a necessary policy goal.

This data provides the basis for an argument for sustainable retrofit (Marchand et al. 2015) with a focus on fabric, and potentially heating systems improvement. This retrofit approach has been supported through policy mechanisms such as Green Deal and ECO, but the policy review currently underway has identified that this is a complex problem, with many technical and social elements, or socio-technical issues (Lomas 2010).

The retrofit industry in the UK has many stakeholder groups that are required to drive change in the physical performance of the stock (Tweed 2013). Tweed defines this as a process that involves the technical nature of retrofit as a main component, but also identifies the requirement of an understanding of the needs and drivers of the occupants and their decisions. Leaman et al go on to further detail this requirement on the topic of examining buildings after completion in the occupied stage, where they validate a requirement to not only study the effects of the building on the occupant and the efficiency issues alongside, but also to feedback to the stakeholders involved. (Leaman et al. 2010a) The stakeholders in retrofit however are very disparate as described by (Brown & Swan 2012) who laid out the stakeholders in a series of 7 regimes, which are illustrated in Figure 6

Figure 6 Socio-technical regimes for domestic retrofit sector (Brown & Swan 2012)

While the work takes a positivist approach, focusing predominately around building physics, the positioning of the research has been in the context of a wider socio-technical understanding of the problem. This is an essential approach when considering applicability and impact of the findings from the work, as the focus of the wider research unit is concerned with the applied nature of the problem and effective engagement with the wider stakeholder groups described above. This issue is discussed in more detail in the next section regarding researcher position.

3 - Researcher Context and Methodological Position

3.1 Researchers Background

The author was a building surveyor and building physics practitioner for 10 years prior to becoming an academic. This role covered sustainable retrofits on commercial and domestic retrofit work, as well as a significant amount of building physics work.

3.2 Researchers Current Role

Currently, the author is Research Lead for the Salford Energy House. While building physics is a widely practised field, this facility provides a unique approach to work, as it is carried out at system (whole-building) level under controlled conditions. The Salford Energy House (University of Salford 2016), is an end terrace Victorian property, with a similarly constructed conditioning void to replicate an adjoining property. The houses are traditionally constructed, with solid brick walls, suspended timber floors, lath and plaster ceilings and single glazed windows. In its base state, it is uninsulated. The heating is provided by a wet central heating system, fired by a gas condensing combination boiler. All of this can be changed to suit different testing requirements

The dwellings are both located inside a large climatic chamber: The external environment surrounding a dwelling can potentially make a significant difference to how much energy is required to heat the building. It is for this reason that the chamber was developed to recreate a series of external weather conditions; such as temperatures from -10 degrees Celsius to 30 degrees Celsius, wind, rain, solar radiation and snow.

The authors’ role at the Energy House is to manage all the research programmes at the facility from inception, including experimental design, to completion. The research carried out at the Energy House is around 60% commercial research and 40 % academic research. These projects concentrate mostly on retrofit solutions, although some methodological work has also been undertaken. Examples of some of the experiments are illustrated in Table 1

Table 1 Recent Experiments completed at the Salford Energy House

Organisation	Product tested
BEAMA Heating Controls Group	Room thermostats and thermostatic radiator valves
Saint Gobain Recherche	Validation of the QUB whole house test methodology
Yorkshire Electric Radiators	Comparison of electrical heating vs. gas central heating
Viessman	Study of the effectiveness of weather compensation on a gas boiler
Thermaskirt	Measuring the temperature distribution of skirting board heat emitters on a wet system
PES Voltage Optimisation	Measuring the effect of a voltage optimisation system under controlled conditions
Clo-I	Measuring the thermal performance of several different curtains using the heat flow meter method.
XEFRO Infrared Heaters	Comparing electrical infrared heaters to a wet central heat system in terms of energy performance
Stelrad Radiators	Testing the performance of a serial feed radiator on a whole house scale
Stormgaurd Window Coverings	Study on the thermal performance of a proprietary secondary glazing product
Alertme (British Gas)	Study to disaggregate energy use: domestic hot water vs. central heating
Saint Gobain UK	Whole house retrofit, carried out element by element
Leeds Beckett University	Validation of coheating whole house test methodology
University College London	High resolution heat flow mapping of suspended timber floors

These experiments range from small experiments lasting a few days, valued at around £10,000, to larger research projects for multinational companies lasting for several months at a time, valued at around £200,000. In some cases the research has been developed commercially, but permission has been given to publish the results in academic journals, subjecting the findings to peer review as seen in **Publications 1, 8 ,S1 and S2.**

In addition, the approaches and learning from the Energy House has been applied to a wide variety of fieldwork. This includes whole house monitoring for projects such as Green Deal Go Early and Green Deal Communities for DECC, as well as other smaller field trials and building tests for grant funded and commercial clients.

The author contributes to CEN/BSi/ISO groups on several panels working groups: Contributions were made to the authorship of a European Standard concerning the measurement of performance of multifoil insulations; BS EN 16012 (British Standards Global 2012). The author also represents the University of Salford on International Energy Agency Annexe 58 where amongst other things, contributions were made to one of the final reports recently on the subject of selecting appropriate building testing methods for energy performance research the output of this report was an extremely useful tool for practitioners wishing to find the most appropriate way of testing a building's performance (Erkoreka et al. 2016). He is also sub task leader for a newly formed International Agency Annex 71, which proposes to characterise a dwelling's thermal performance using smart meter data, and small amounts of other data.

3.3 Research Paradigm

A paradigm of research is characterised by 3 variables according to Guba, these three variables are ontology, epistemology and methodology (Guba 1990)

Ontology

Ontology is concerned with the philosophical assumptions with regards to the form and nature of reality and what can be known about it (Guba and Lincoln 1994). While, as stated previously, there is a wider socio-technical stance for the research group in which the author is a member, the core of the work takes positivist ontology. This accepts knowledge as knowable and objective (Guba & Lincoln 1994)

Epistemology

Epistemology is concerned with the relationship between the knower and what can be known. The scientific method drives this relationship between the researcher and the objective reality is defined in the ontology. As a positivist, the scientific method (i.e. quantitative) governs the relationship between the knowledge and the researcher in an attempt to investigate and objective reality. This leads to the research having a linear structure as it follows the scientific method (Figure 7): hypothesis, data collection, analysis and conclusion and discussion (Creswell 2009). The emphasis in the research is on the accurate data collection of the variables in order to either test a hypothesis or find a causal link between the primary data that is collected and the observed effect. (Kothari 2004)

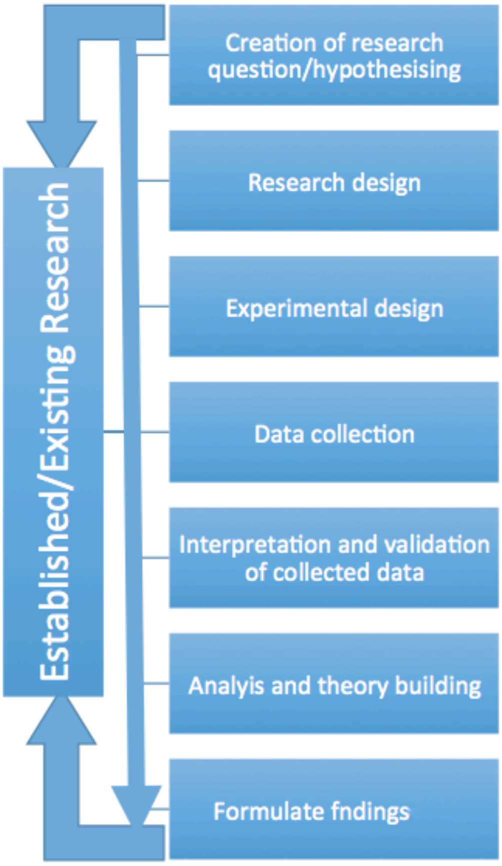


Figure 7 Flow of scientific method process

Methodology

As stated previously, the work follows the scientific method. The papers where experimental work has been carried out makes attempts to ensure that the work is transparent and able to be subject to external scrutiny through the peer review process and in-line with the scientific method and experimental design good practice (**Publication 1 and Publication 2**). Key issues for consideration in experimental when carrying out the experiments in the Energy House for example are:

- Variables: Energy House (EH) experiments are designed to deal with specific issues, this is often to measure the performance of a system, or intervention. To maximise the measurement accuracy, an OFAT is used (one factor at a time). This has been proven by other researchers to provide accurate results. OFAT ensures that all variables are kept to a minimum (Xu et al. 2015). EH experiments will only generally alter one variable at a time. An example of this is given in **Publication 1** where the only variable that changes is the setup of the heating system, all other variables are kept identical, such as chamber temperature, boiler flow set point etc.
- Uncertainty of measurement: This is a factor of experimental design, which is exceptionally important. No measurement is exact, it a consequence of the measurement system itself (Joint Committee For Guides In Metrology 2008). This system includes measurement apparatus, operation of equipment and variances in environments. If we consider the measurement of u-value data as an example the margin of error can be up-to ±28% according to ISO9869 (ISO 2014) other authors haves suggested that this figure can be even higher, an error of up to 46% was found examining data from a 4 year field trial (Cessarato & De Carli 2012), with errors originating from; sensor placement, stratification of air in the room being measured, contact with sensor to the fabric being measured, instrument precision. Some of these errors can be reduced by taking longer-term measurements or by carrying out measurements with less variation in conditions. (Taylor 1983). With uncertainties of such magnitude, two major points should be raised; every effort should be made to reduce these figures, and also they should be declared properly within the results of the experiment.
- Data Analysis: data analysis is crucial to the work within the Energy House. As mentioned above, the data capture process is sensitive to uncertainty, and the data must be analysed in bearing this in mind. Using u-value estimation as an example the ISO 9869 (ISO 2014) standard gives 2 ways of calculating the u-value from raw values, the averaging method and the dynamic method. It is suggested by Meng et al

that the difference between these different methodologies can have an effect on the u-value of up to 20% (Meng et al. 2015) We have used both methods in the EH and tend to find that the averaging method suits the OFAT methodology as there are no dynamics at play, the tests are carried out under quasi steady state conditions. However, when we have dynamic factors as part of our variables (thus not OFAT) then the dynamic method can be used, an example of this is when we operate the chamber using diurnal cycles or when we add wind or rain to the environmental conditions.

3.4 Summary of Research Aims:

The core research work being undertaken is to address three issues within the sector of building performance in particular retrofit: i) Methods of measurement, ii) Experimental work and iii) Accurate modelling using in situ data. The hypothesis which binds these topics together is:

> *"Is the performance gap a combination of other gaps, such as the measurement gap, and the data gap in modelling?"*

The core of this question is outlined in Figure 8, which highlights the different elements of the problem. This diagram identifies the key contributory elements of the performance gaps and leads to the development of the following objectives.

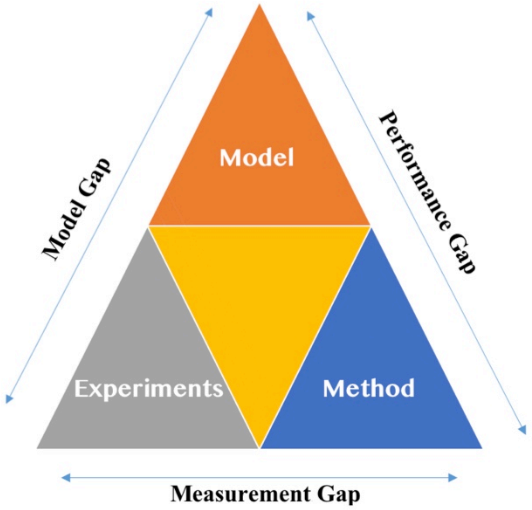


Figure 8 The hypothetical gaps contained within the performance gap

The objectives of the body of work are:

- Identify and investigate the contributory factors that drive the performance gap
- Understand and critique building performance methodologies in evaluating building performance
- Identify and explore the assumptions with regulatory and dynamic models in establishing modelled building performance
- Design and conduct experiments to better understand actual performance of retrofit products within a whole house context
- Provide insight and recommendations for better understanding of the performance gap at product and system level

The body of research is concerned with these areas and as such makes an original contribution to knowledge in the following areas:

- Development and validation of new and existing building performance methods
- Design and experimentation of product testing at the whole house level under controlled conditions
- Consideration of the modelling assumptions and their contribution to the performance gap, based on this data

The next section highlights how the development of the research builds the area, covering contextual information, but also work that addresses each of these areas.

4 - Paper Narratives

4.1 Background Publications

4.1.1 Section Introduction

The following papers are concerned with the wider context of buildings retrofit, providing the researcher with a wider context in which the scientific building physics work takes place. The papers are cover the following topics; the heritage aspect of retrofitting older dwellings, the uptake of specific retrofit measures and barriers in pace which are preventing this.
This paper was awarded 2014 Literati Award for Outstanding Paper of the Year in Structural Survey Journal.

4.1.2 Adoption of Sustainable Retrofit in UK Social Housing (Publication 5)

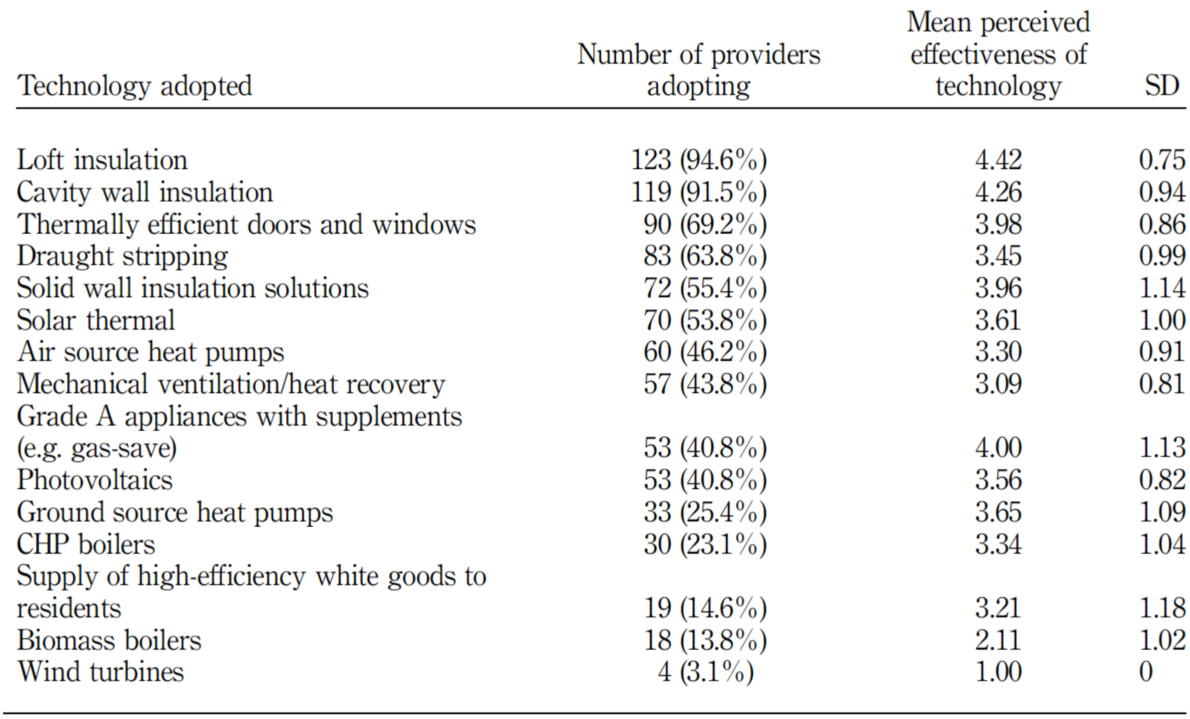
Swan, W., Ruddock, L., Smith, L., & Fitton, R. (2013). Adoption of sustainable retrofit in UK social housing. Structural Survey, 31(3), 181–193. http://doi.org/10.1108/SS-12-2012-0039

Introduction

This paper focuses on the take up of retrofit measures in social housing stock in the UK. The aims were to examine the take up of measures, but more importantly to provide details of the decision making process.

Main Outcomes

The study highlighted several important findings that helped guide the author's further research, firstly and most importantly the adoption of measures ranked in order of take up. This is illustrated in Figure 9 where there appears to be a correlation between perception of effectiveness of a measure and the number of providers adopting them (although the term effectiveness is a term that can be interpreted in several ways)



Technology adopted	Number of providers adopting	Mean perceived effectiveness of technology	SD
Loft insulation	123 (94.6%)	4.42	0.75
Cavity wall insulation	119 (91.5%)	4.26	0.94
Thermally efficient doors and windows	90 (69.2%)	3.98	0.86
Draught stripping	83 (63.8%)	3.45	0.99
Solid wall insulation solutions	72 (55.4%)	3.96	1.14
Solar thermal	70 (53.8%)	3.61	1.00
Air source heat pumps	60 (46.2%)	3.30	0.91
Mechanical ventilation/heat recovery	57 (43.8%)	3.09	0.81
Grade A appliances with supplements (e.g. gas-save)	53 (40.8%)	4.00	1.13
Photovoltaics	53 (40.8%)	3.56	0.82
Ground source heat pumps	33 (25.4%)	3.65	1.09
CHP boilers	30 (23.1%)	3.34	1.04
Supply of high-efficiency white goods to residents	19 (14.6%)	3.21	1.18
Biomass boilers	18 (13.8%)	2.11	1.02
Wind turbines	4 (3.1%)	1.00	0

Figure 9 Adoption of retrofit measures in ranked order

The results highlight several important points that were taken forward for future research: The five most common measures were fabric interventions; they also have the greatest perceived effectiveness. These five measures also have some of the lowest standard deviations amongst the sample indicating a strong agreement in the sample. However, this paper also highlights the difficulties some organisations had in identifying and evaluating successful retrofits. Another key finding related to the authors work was that the source of information that that retrofits decision makers used least of all the options was from universities/academics, which identified an important gap in work being undertaken by University research teams in promoting their work.

Limitations

There are some interpretive issues with this research: the term “effectiveness” is subjective, and leaves room for interpretation, which may be considered a generic issue within survey type work. For instance, comparing energy savings and CO_2 savings is not possible, for example electrical heating maybe more efficient, but when we examine this using energy models such as SAP then the energy efficiency does increase but the CO_2 levels associated with heating the dwelling increase. If the survey were adjusted to allow for carbon effectiveness/energy effectiveness, then this could have led to different results.

This type of survey can only ever be seen as a single data capture point; it does not attempt to spot trends or make future predictions. However, the future work will address this issue, as it will be able to analyse differences between periods.

Research Updates

The same data collection survey has been carried out twice since this original publication, the results are due to be published in 2017, where trends will be analysed for the first time and future prediction scenarios examined. This however still remains by far the largest data collection of stockholder information on retrofit measured in the UK.

Summary

This paper sets the scene for the author's research aims and objectives, giving information on the key retrofit measures used, in a large section of the UK housing sector. This allows for research efforts to be focussed in the correct direction for maximum impact for both industry and academic researcher

4.1.3 Understanding our Heritage: Monitoring of energy and environmental performance of traditional terraced houses of Northern England (Publication 9)

González, A. G., Roberts, B. I., Fitton, R., Swan, W., & Elkadi, H. (2016). Understanding Our Heritage: Monitoring of energy and environmental performance of traditional terraced houses of. In Energy Efficiency and Comfort of Historic Buildings. Brussels. Retrieved from http://www.eechb.eu/eechb-2016/

Introduction

The aim of this paper was to detail the issues around retrofitting solid walled terraced buildings, although the project that this data was extracted from covered all element of building performance measurement, the aim of this study was to provide u-value measurements of solid wall terraced properties and compare them to other studies in the field. Six properties were subject to u-value measurement.

Main Findings

Using the u-values measured in this trial a comparison was made to a study carried out by BRE in solid wall properties (Hulme & Doran 2015) both of these studies were carried out in accordance with ISO9869 (ISO 2014), so a comparison is possible. u-values ranging from 1.3 to 2.38 W/m^{2}K were found in this publication.

Hulme and Doran, using a sample of 300 buildings, found the u-value to be on average 1.57 W/m^{2}K. Both of the studies agreed that in terms of an average u-value of around 1.6-1.7 W/m^{2}K . This highlights the fact that the current u-value for solid walls used in the RdSAP calculation of 2.1 W/m^{2}K is not representative of the buildings that were measured in both of these trials. These findings are backed up by other researchers who have made similar findings (Rye & Scott 2012; Baker 2011).

Limitations

The BRE study is large and concise and the methodology is well documented, however **Publication 9** had an imposed word/page count had to be concise, as such details such as error analysis are omitted, although the ISO9869 process was followed, also the opportunity to make a comparison against the design u-value for the walls was excluded. This does not therefore give the opportunity to examine any performance gap issues that exist in the studied dwellings.

Summary

The author's main research topic of performance gap is illustrated in its most basic form in this paper. These results, together which other researchers work is compelling evidence that one element of the performance gap (poor characterisation of building elements in models) is now beyond doubt where solid walls are concerned. This leaves the requirement for greater investigation into this field to allow realistic u-values to be applied in the UK for energy models.

Section Conclusion:

In this section two papers were examined. These papers provide an important base to the author's body of work. The scene is set for the retrofit interventions that are popular in the UK. Fabric measures are seen to be the most popular measures across a large part of the UK stock in **Publication 5**. And yet we find that the results in **Publication 9**, backed up with findings for larger studies, suggests the tool that is used for policy decisions in the UK concerning insulation, RdSAP, has a significant error in predicting the effectiveness of solid wall improvements. This finding helps to contextualize the remainder of the body of research presented: We can illustrate that models themselves have errors; from here other elements of performance gap and performance measurement are investigated for similar issues.

4.2 Methodological Publications

Section Introduction

In this section the area of the methods of measuring the performance of buildings will be discussed. This section covers several different ways of measuring the energy performance of element of dwellings, such as walls and windows, and at the whole dwelling level, using approaches such as QUB and coheating. Firstly, the proposition of why there is a need to measure performance is discussed, then follows a précis of the state of the art of building monitoring, giving details of how practitioners currently work on this subject are, both within academia and industry. Methods of measuring construction materials at a lab level are then briefly discussed. New and state of the art measurements will then be discussed at a whole house level and then at an elemental level.

4.2.1 A UK practitioner view of domestic energy performance measurement Publication 6

Swan, W., Fitton, R., & Brown, P. (2015). A UK practitioner view of domestic energy performance measurement. Proceedings of the Institution of Civil Engineers - Engineering Sustainability, 168(3), 140–147. http://doi.org/10.1680/ensu.14.00056

Introduction

This paper aims to fill a significant gap in knowledge about a small, but growing group of practitioners in the area of building performance evaluation. Semi structured interviews were carried out to elicit views and opinions on working practices, guidance used, issues encountered, client perception of works and current and state of art techniques.

Main Outcomes

Building performance field trials are taking place in significant numbers (Gupta & Gregg 2012), with the following research projects currently underway or completed:

- Futurefit: 102 dwellings (Affinity Sutton 2016)
- Retrofit for the Future: 100+ dwellings (Sweett 2014)

- Green Deal Go Early Manchester: 35 dwellings (AGMA 2012)
- Green Deal Go Early Leeds: ~100 dwellings

This is combined with a developing viewpoint that completed buildings often do not perform as modelled, whether new build or retrofit (Leaman et al. 2010b; Wingfield et al. 2011; Jaffe & Stavins 1994). There was however little literature found on the experience of the individuals involved in measuring these issues.

The client's knowledge of how to commission and specify performance measurement works was often incomplete and it was identified by several interviewees that the clients were often underfunded to carry out an acceptable standard of evaluation. A lack of planning led to clients placing all the onus of evaluating homes only in the post retrofit stage, with the failure to measure the buildings performance before the work had been started, this leaves no opportunity carry out a pre-post comparison, essential in understanding the performance of retrofit.

All participants reported difficulties with the area due to lack of guidance in the industry, although standards such ISO9869 may exist for specific measurements, no holistic guidance or methodologies in terms of planning a successful monitoring project.

All of the participants reported significant issues with the equipment currently being used to carry out BPE.

While this work follows an interpretivist research paradigm, it is largely concerned with scientific practice. It indicates the types of errors and issues that can hamper building physics research and, as such, provides an important contribution to issues of experimental design at the practical level.

Limitations

This paper had a low number of respondents, and more would have been needed for the research to be more significant. However, these low numbers are also indicative of a small community of practice, and a profession that is its infancy, which concurs with comments made by several of the participants of the industry just in its early stages of becoming a formalised profession/vocation.

Research Updates

This research is still recent, and to date this knowledge has not been updated or added to. However recent updates to techniques and methods (**Publication 8** for example) are filtering through to these practitioners, and the number of practitioners in this field is expected to grow. As such the author will review these findings with another set of interviews in 2017.

Summary

The lack of guidance and some substandard equipment leads to several issues:

- Tacit practice, where practitioners in the field are creating their own methods of measurement, these methods are not documented, referenced or shared with others:
- Imperfect data sets; where data dropouts are experienced researchers will at times fill these gasp with assumed/predicted data, whilst this may be acceptable of done to a set standard over short periods, these procedures need to be well documented.
- Inconsistency in measurements can lead to a lack of repeatability in measured data, this does not allow for measurements to be repeated, or compared across multiple scenarios.

When we consider this within the practice of performance gap, another variable comes into play; that of the measurement gap. Some of these issues are addressed in the next publication presented.

4.2.2 Energy monitoring in retrofit projects: Strategies, tools and practices Publication 7

Fitton, R. (2013). Energy Monitoring in Retrofit Projects. In Retrofitting the Built Environment (p. 256). Wiley.

Introduction

This was an edited book that selected several papers and outputs from the Retrofit 2012 conference (University of Salford 2012) The chapter investigates the stages of carrying out a monitoring study of typical retrofit scenario, including; selection of equipment, data collection and analysis as well as advice on what stages to monitor. This text, although in conference proceedings and academic in its nature, is pitched towards a practitioner in the field of retrofit.

Main Outcomes

This book chapter addresses some of the issues and problems in building performance evaluation, understood anecdotally at the time of writing, and further explored and also confirmed in the interviews contained in **Publication 6**. It draws together practice guidance and reference materials in to one source, considering the key issues of experimental design, recording of data and also guidance on how to procure these types of services externally, by identifying existing standards and key questions, to ensure a constant degree of quality across a project.

Limitations

This publication was one of the authors first peer reviewed publications. One of the issues with this chapter is that the content tends to be more guidance material rather than purely academic research. Given the research work since this publication and the constant changes in technologies, methodologies and policy, an updated version would be useful.

Research Updates

The methodologies and standards mentioned in this publication are still valid, and as much of the rest of the publication is based around assessment and building physics, nothing new has been developed that is relevant, with the exception of some of the new test methods such the QUB (**Publication 8**) and the Arcada u-value meter mentioned in Chapter 5. There is a possibility that these measurements could be rolled out in the UK/EU sometime in the future.

Summary

This book chapter brings together guidance, both strategic and practical for building performance practitioners to use as a reference. In a landscape that is rapidly changing with increasing numbers of field trials, both grant funded and commercial, a set of principles is seen as a step forward in terms of gaining accuracy, and equally as importantly comparability and repeatability between one trail and another. This will allow for more statistically significant and sensible conclusions to be drawn.

4.2.3 Zero Carbon Hub: Closing the gap between design and as built performance

Publication A4

Zero Carbon Hub. (2014). Closing the gap between design and as built performance. London. Retrieved from ttp://www.zerocarbonhub.org/sites/default/files/resources/reports/Design_vs_As_Built_Performance_Gap_End_of_Term_Report_0.pdf

Introduction

This research was contributed to by the author over a period of 18 months. The aim of the publication was to collect the opinions and views from a group of building performance experts in the UK, with a view to providing a report to DCLG and DECC containing the main issues, causes and solutions to the performance gap issue in new build properties.

Whilst there is much research focussed around the performance gap in retrofitted buildings, there is also a growing concern, particularly in the UK that the performance gap is being found in new build properties (Johnston et al. 2010; Wingfield et al. 2008)

Main Outcomes

The author sat on the Testing work group committee and contributed to the final report (Zero Carbon Hub 2014). The group's recommendations are contained as follows: -

- Diagnostic tests are needed by industry to understand why a finished house, system or element might not be achieving the designed performance.
- Protocols of existing tests be refined and standardised to be more useful, useable and consistent in assessing the energy and carbon performance of homes
- New and emerging test methods also need to be developed by research organisations and commercial groups

- Existing assessment methods, such as thermography, heat flux testing and elemental laboratory tests, need refining and standardisation of protocols to improve consistency and robustness of results is urgently needed.

Limitations

The limitation with this work is that it only concerns the new build housing sector. However, many members of the committee were also professional in the area of evaluating energy performance of retrofit solutions as well as new builds, and this comes across in the report itself and many of the tests/measurements that are referred to and suggested for improvement are ones that are also used in retrofit studies.

Research Updates

Unfortunately, due to recent changes in low carbon legislation (HM Treasury 2015), the ZCH ceased to operate in March 2016. However, it is still hoped that the relevant stakeholders will act upon the recommendations listed above.

Summary

All the outcomes in this report are currently being worked on by the author and are represented in this body of work: new test methods in **Publication 8**, new test protocols are being developed as part of the authors CEN work. Existing methodologies are also being worked onto to streamline these approaches. This work has formed the grounding to the performance gap issues in all sectors of the construction industry, and where testing is involved, has given outputs to build on. It has also guided the development of new, quicker, easier and more accurate testing methods.

4.2.4 BS EN 16012:2012+A1: 2015 Publication A1

British Standards Global. (2012). BS EN 16012:2012+A1:2015 Thermal insulation for buildings. Reflective insulation products. Determination of the declared thermal performance. London: British Standards Institute. Retrieved from http://shop.bsigroup.com/ProductDetail/?pid=000000000030294320

Introduction

The aim of this standard was to provide a new set of methods for the testing of reflective insulation products, as no standard was deemed suitable to test products with low emissivity including airspace. The measurement of the performance of these products, at laboratory level and dwelling level has been debated for over 50 years (Hnilicka 1960).

The author was one of the members of the committee from the UK, and focussed on the measurement characteristics of the experiments. This was published as BS EN 16012:2012+A1:2015 *Thermal insulation for buildings. Reflective insulation products. Determination of the declared thermal performance* (British Standards Global 2012) .

Main Outcomes

This was a new standard and is now deemed compulsory for national standards bodies in each of the EU countries to implement. The standard lays out laboratory testing and calculation methods for any thermal insulation product that derives a proportion of its insulative properties from the one or more reflective or low emissivity layers and airspaces.

This new standard allows the standardised testing of an insulation products' measured performance at laboratory level. Previous methods did not allow for the testing to be carried out with this air cavity included. This new standard does allow for this and manufacturers can declare this as part of their declared thermal resistance for the product.

The author is listed as a contributor in the document itself. This is a large and complex document, then author contributed only on the section regarding heat flow meter testing, measurement and labelling.

Research Updates

This is a relatively new standard, and is being actively used now in the insulation industry, no further changes are expected in the next several years. However, the subject of multifoil and low emissivity insulation continues to develop with other test methods declaring higher values, this tends to focus on disagreements around test method, with the multifoil industry suggesting that whole house testing proves the actual resistance of the product where a hotbox testing setup does not. Tenpieriek et al state that whilst manufacturer are routinely claiming resistance values in the region of 5 or 6 m^2K/W it is not feasible for this type of insulation to reach this level and 1.5–2.5 m^2K/W is a more likely level of performance. (Tenpierik & Hasselaar 2013)

Summary

Low emissivity insulations have been debated for some 50 or more years, and this continues to be the case. Radiative barrier insulation works in a different way than bulk fibre insulation, which relies on air entrapment. It also has different installation requirements with air gaps needed on a least one side. This new standard does go some way to determining the resistance characteristics of the product under controlled conditions, these values can then be input into models to allow comparisons to made against other calculations. This again leads back to performance gap issues, if manufacturers are making a claim that their product may be superior to what it actually is and this is entered into energy models then this also creates a performance gap.

4.2.5 Patent Application (GB1609035.9) Publication A2

Fitton, R., Busby, P., & Benjaber, M. (2016). Patent Filing for Heat Flux Sensing Device. UK. Retrieved from https://www.ipo.gov.uk/pro-types/pro-patent/pro-p-os/pro-p-journal/p-pj?lastResult=250&perPage=10&startYear=2016&startMonth=July&startDay=06th+-+6633&endYear=2016&endMonth=July&endDay=06th+-+6633&filter=&sort=Publication+Date&status=undefined

Introduction

The aim patent was to claim the rights to an invention that came from the author and his colleagues Moaad Benjaber and Paul Busby. With the author's extensive industry knowledge and experience in building physics, coupled with the results from **Publication 6** a decision was made to develop a system which would make the measurement of u-values in walls an easier, cheaper and more accurate process. The research and development for this unique product is the output of over three years' work.

Main Outcomes

Publication 6 highlights issue with the measurement of u-values in dwellings: Equipment cost, the amount of cabling involved, the appearance, stability unreliability and the appearance (Figure 10). Several of the interviewees also stated that many people do not want such cumbersome equipment in the living area of their home. The equipment also being so expensive (a typical rig would cost ~£3500) is at risk of theft, this is particularly true when void properties are measured. **Publication A4** also states that more research into new testing methods and instruments are required.

Figure 10 Typical layout of existing u-value measurement equipment

In reaction to these documents and our own requirements, the Energy House team (lead by the author) developed a new type of sensor where all the sensors and logging technology is built into one custom unit (Figure 11). This houses the heat flux sensor, a contactless infrared sensor for surface temperature measurement and an air temperature sensor. The unit also logs data internally and also send data to a cloud server for backup or dynamic analysis. An external unit records external climatic data required for the u-value calculation.

Figure 11 New u-value measurement sensor with data logging device

This sensor is uniquely designed to act as an all in one sensor and also has a unique "quick fix" mechanism that allows the device to be attached and detached from the element without damaging the decoration. The system is now at the 2nd iteration of a prototype and is being discussed with potential development partners. The device has had a patent filed at the UK patent office.

Limitations

The device is currently awaiting a field trail to be undertaken by an independent party to validate its accuracy, and the team are also validating the approach with the use of CFD.

Research Updates

New measurement methods for heat flux measurement have been given in recent publications. Paronen describes a rapid u-value meter in his patent (Paronen & SKÖN 2013). The author has also worked on this project (see Chapter 5). However, this is a dynamic tool for taking rapid measurements and not logging over long periods in accordance with current standards. Calculation methods have been developed using Bayesian techniques to take data from heat flux sensors (like the one proposed in this patent) and accurately predict u-values up to 3 times quicker than using traditional methods of averaging heat flux and temperature readings (Biddulph et al. 2014) . This method will be examined by author with a view to potentially embedding this methodology into the sensor itself.

Summary

The development of this technology has been created through necessity and input from others. Addressing the performance gap takes careful and accurate measurement, more accurate assessments of elements can be made if the equipment is more affordable, as more spot measurements can be taken, the new equipment is less intrusive so engagement with study participants may be improved and, finally, with an easier and more systematic approach of measurement his may help further improve consistency and comparability across studies. All of these will lead to less "gaps" occurring in measurement. UOS are currently in discussions with a large manufacturer to bring this device to market.

4.2.6 QUB: Validation of a Rapid Energy Diagnosis Method for Buildings Publication 8

Pandraud, G., & Fitton, R. (2014). QUB: Validation of a Rapid Energy Diagnosis Method for Buildings. In International Energy Agency Annexe 58 (pp. 1–6). International Energy Agency.

Introduction

The aim of this paper was to produce a peer reviewed paper to present to the International Energy Agency Annexe 58 members. The paper presents a unique and patented method for measuring the whole house heat loss of a building, in an accelerated way. Currently, these measurements are carried out use the Whole House Heat Loss Methodology, created by Leeds Becket University (LBU) (Johnston et al. 2012). This is known colloquially as the coheating method. This test, although well validated and backed up with extensive field trials take around two weeks to complete and requires a vacant property. The QUB methodology can be completed in two days.

Main Outcomes

The researchers at Saint Gobain Recherché (SGR), developed and patented the QUB method in 2012.(Mangematin et al. 2012) It aims to measure the whole house heat loss of a single building in 48 hours or less. Following a field trail by SGR in France, it was deemed necessary to validate the method under controlled conditions, and also make a comparison to the most commonly used existing method developed by LBU. The main outcomes of this work were:

- Prior to this experiment LBU had carried out a quasi-steady state coheating test of the building and the results were made available. A close match was found between the two methods.
- Two test sessions were carried out to obtain the repeatability which was found to be ~4% in terms of variance. The HLC found was to be in agreement with the LBU value within ±7%
- There was a significantly reduced timescale when compared to coheating ~48 hours, reflecting two nights testing, dusk till dawn.
- The tests can be carried out with lower temperature differentials between internal and external temperatures,
- The temperatures involved are not excessive, the testing temperature is ~19-20 degrees Celsius. This avoids risks to newly constructed dwellings
- The level of uncertainty is ~10-15%, which is comparable to the LBU methodology.
- The QUB test can give other outputs aside from the HLC such as the capacity of the structure and information regarding time constants of the building
- The faster method allows for more tests to be carried out in quick succession, to reduce error and also to measure retrofit interventions at staged points

Work is still underway to estimate the uncertainty of the QUB method, but given the above results and work that SGR have carried out in the field, the uncertainty is likely to be ± 10-15%

Limitations

It should also be considered that a sample of one building does not give solid evidence that a test method is valid or accurate, however the SGR team are currently trialling this method in the field in a larger sample of different buildings to add to their research data.

Research Updates

The majority of research around whole house heat loss testing has two strands, cost effectiveness/ease of use and test duration. Stamp concludes that the standard coheating method, given the correct analysis and favourable conditions can be reduced to 3 days in total (Stamp 2016). The ISABELLE methodology claims to be able to shorten the duration of testing between 5-15 days, as the test is dependant on the weather conditions (Brun et al. 2014). Research carried out by Farmer identifies alternate methods to reach the whole house loss figure, where the central heating system is fitted with a heat meter to give an energy input figure, so the home's central heating system is used rather than additional apparatus. This gives comparable results of the standard LBU methodology, with the added advantage of providing data on the performance and set up of the heating system itself, which may prove useful. However, Farmer does not appear to investigate the shortening the duration of the test, and it is assumed that due to the uplifted temperature of 25 degrees Celsius that the building should be unoccupied (Farmer et al. 2016)

Summary

This research illustrates that, under controlled conditions, short terms tests are possible to measure the heat loss characteristics of a dwelling. The accuracies and repeatability are within acceptable boundaries of other types of measurement in this field. Additional work to validate the accuracy and to carry out sensitivity analyses, will help to gain further information on the limitations of the test method, such as times of year when it can be performed. A significant finding of this research is that if a building can be tested in 48 hours then more tests can be conducted along the process of a retrofit and, as such, this could take the part of a stage-based quality approach, checking the retrofit as it is being completed. This was carried out in **Publication S1** where the Energy House was retrofitted in 6 different scenarios and QUB/coheating was used to measure the results. There are also drawbacks with the QUB method; where coheating heats the building for approximately 2 weeks, this gives the researchers time to carry out heat flux and u-value measurements, the QUB does not. Also the equipment used for the QUB is not significantly less in size or cost than that used in the coheating method.

Section Conclusion

This section opened with a discussion around the numbers of studies currently taking place in the UK, and the fact that this figure is growing all time, next **Publication 6** gave an insight into the day to day issues encountered by these individuals, suggestions were made on how

BPE could be improved. **Publication 7** is also aimed toward the practitioner who is embarking on a monitoring or testing regime, in particular retrofit projects to dwelling. This chapter contains evidence and practical guidance for these individuals, before this chapter was written it is believed that all of this advice had not been gathered together into one publication, and certainly not one that was up to date.

The ZCH Performance Gap Report **Publication A4** then highlighted the significant gaps in knowledge behind new build performance measurement and stated that new technologies were required to assist with this problem, as well as further research into accuracy of these methods and new methodologies in order to discover where the performance gap was originating, and thus minimise it. In response to this, several new testing/measurement techniques are discussed; the new testing methodology for reflective foils **(Publication A1),** which previously did not have a standard, the new u-value sensor **(Publication A2)** co-developed by the author which aims to make the process of u-value measurement easier, more accurate and more accessible. The QUB method (**Publication 8)** offers a quick, convenient and accurate method to measure the whole house performance of new buildings and retrofit scenarios.

4.3 Data Led Modelling Publications

Section Introduction

Building energy models are used for many different reasons: design, operational management, lifecycle assessment, and retrofit analysis. Given a series of inputs, depending on the model type, they can be used to predict energy consumption, thermal comfort levels and other outputs, such as element heat flux and airflow in rooms. (Li et al. 2015). They rely on assumptions being made in most cases on items such as u-values, air permeability and thermal capacity of the building. (DesignBuilder 2016). Two different methods will be discussed in this chapter; quasi-steady-state methods such as SAP and dynamic methods such as IES and Designbuilder.

It is also important to note that almost every UK performance gap/whole house heat loss study and report uses SAP/RdSAP as a benchmark, so some credence must be given to the tool even if just for its qualities as a steady state physics modelling tool (Zero Carbon Hub 2014; Johnston et al. 2015; Pandraud & Fitton 2014; Farmer et al. 2016)

4.3.1 The Variability of UK domestic energy assessments Publication 3

Gledhill, T., Kempton, J., Swan, W., & Fitton, R. (2016). The variability of UK domestic energy assessments. Journal of Building Survey, Appraisal & Valuation. Retrieved from http://www.ingentaconnect.com/content/hsp/jbsav/2016/00000004/00000004/art00009

Introduction

This paper examines the use of RdSAP for carrying energy performance certificates, carbon savings calculations and energy savings calculations. Focussing on how user error or even intended malpractice can affect the outcome the calculation

Main Outcomes

A typical property was used as a baseline. A series of “errors” were inputted into the model:

When a 5% measurement error was made in the site measurements and a generic boiler type is used (a common error), rather than inputting the actual model, then the outcome of the EPC in terms of CO_2 generated by the building is a 20% over estimation in terms of carbon saved by loft insulation and 21% for cavity wall insulation. (Absolute values of +0.8 and +0.7 TonnesCO_2/annum).

Although not mentioned in published literature it is well known in industry that some SAP/RdSAP users have been known to misuse the tool to their advantages to make some carbon savings measures more attractive to would be funders of the measures. For instance, where electrical heating is recorded as secondary heating in the case highlighted above then the carbon savings offered by loft insulation and cavity wall insulation are increased by 30% and 36% respectively. Some users of the tools have been known to do this simply where they see signs of an electrical heater but know that it is not being used formally as secondary heating.

Limitations

The research takes the form of a position paper based on anecdotal evidence from the field in order to further investigate the impact of practices on model outcomes. However, further work should be undertaken in the following areas; the number of variations modelled is low, and the variables have been mixed for brevity (the use of a standard boiler AND mis-measurement). This does not allow for a complete sensitivity analysis to be carried out. From a performance gap point of view the research does not help, as it focuses mostly on carbon counting and SAP ratings, energy performance information would have helped pin down some of the causes of performance gap in the retrofit sector.

Research Updates

This is a fairly recent publication, however, further research work has been undertaken to validate the anecdotal evidence through interviews with practitioners with regards to error in the RdSAP process. This work is due to be published in spring 2017.

Summary

This research has shown that this figure can be subject to incorrect measurement, and even mis-measurement by 5% can have a significant effect. However, this paper has only a small number of variables over one type of property and does not provide a full sensitivity analysis of the tool.

4.3.2 RICS Article: Performance gap in domestic retrofits Publication A3

Fitton, R. (2016). "Performance gap" in domestic retrofits. Retrieved August 19, 2016, from http://www.isurv.com.salford.idm.oclc.org/site/scripts/documents.aspx?categoryID=1349

This is not technically research published in the academic field, so will not be narrated in full. It also crosses many of the topics already covered. It has been included to demonstrate the linkages of the research with practice and the author's wider engagement.

Summary

This is a guide that was written directly for the RICS (Royal Institution of Chartered Surveyors). The author is a Chartered Building Surveyor, and thus saw the demand to create practice guidance on the subject of performance gap in domestic retrofits. This work builds on **Publication 7.** The work was published directly to surveyors using the RICS' digital platform iSURV. This work is peer reviewed by the Education Standards Board of the RICS, made up of industry specialists and academics in the field. The paper addresses several topics: Performance gap and common causes, when to monitor and how, fabric investigations such as u-value measurement and air tightness testing and interpreting collected data.

4.3.3 Assessing overheating of the UK existing dwellings – A case study of a replica Victorian end terrace house Publication 4

Ji, Y., Fitton, R., Swan, W., & Webster, P. (2014). Assessing overheating of the UK existing dwellings – A case study of replica Victorian end terrace house. Building and Environment, 77, 1–11. http://doi.org/10.1016/j.buildenv.2014.03.012

Introduction

This paper deals with the dynamic modelling of the Energy House in predicted future climate scenarios. A validated model was created in IES VE (IES 2016). This was achieved using a comparison between accurate data gathered experimentally and a simulated version of this experiment, knowledge of the materials and properties of the EH were inputted to make the model as accurate as possible.

Main Outcomes

A layer of External Wall Insulation (EWI) was added to the model to represent a basic retrofit in the form of a 45mm EPS slab. This may be argued against in terms of breathability and aesthetics, but ultimately EPS is homogenous and has a well characterised R-value and is not significantly affected by moisture compared to other materials, so this variable becomes of less concern. (Jerman & Černý 2012).

Morphed climatic models with data taken from UKCIP02 (Hulme et al. 2002) were used (Belcher et al. 2005) leading to the following analysis of overheating. Following the retrofit, the living room will take until 2050 to start overheating for significant periods, and the bedroom will start to overheat in 2020.

The bedroom is a sensitive area as people spend up to 33% of their time sleeping, are more prone to sleep disturbance at high temperatures (Wang et al. 2015). Lack of sleep has also been shown to have significant effects on health of humans in particular young adults. (Roberts et al. 2009).

The paper is focussed on excess summer temperatures but also considers that whilst overheating is a consequence of the average temperature increase, the model also identified that space heating demand would significantly reduce under the morphed weather data set with a reduction of 30% from 2005 figures to 2080 figures.

Limitations

Due to limitations of the article in terms of size, a number of issues that could have been investigated were not covered. These issues would have been:

- A comparison is not made to the original building, what would happen to energy performance and thermal comfort where the dwelling is kept in its unmodified state. This business as usual or retrofit question is one asked by many researchers, and policymakers. Also the original model was validated on the untreated EH not an insulated one so some very accurate future predictions could have been made.
- This study is also limited to one geographic area, other areas such as southern England have similar types of stock and are likely to have greater changes in average

temperature so it would have been interested to see where the greatest were and to see them quantified.

- No mitigations or limitation methods are suggested to overcome the overheating issues found.

Research Updates

Many publications have been published since this one on the topic of overheating, however most of them consider new builds rather than retrofit. Research that relates directly to this topic is found to agree with the finding of this paper: Psomas et al declare that most energy renovations for single-family dwellings in moderate climates (central and northern Europe) will overheat. This is particular pronounced when floor insulation and airtightness measures are increased. This can be mitigated by including window upgrades and decreasing the window g-value. (Psomas et al. 2016)

Summary

While this work does provide some detailed understanding of overheating within the Salford Energy House, the major consideration for the wider work is the relationship between the models and measured data. This modelling exercise is unusual, as the model has been calibrated using detailed in situ data. This is unusual as the process of calibrating a model to reflect an actual building is one that takes a significant data collection period, with many measurements required, such as u-values and air infiltration (Marini et al. 2016). This is made slightly easier in the Energy House as many variables can be taken away or added when needed. These calibrations allow for future environmental conditions to be predicted with a higher degree of accuracy.

Section Conclusion

In this section the performance gap issue is introduced showing areas where the performance gaps in terms of the modelling gap can be uncovered. Two types of energy models have been considered, steady state and dynamic. The steady state models are not complex enough to accurately predict actual energy usage in a dwelling, this is well referenced and justified; they are not designed for this purpose. Their use should be to compare buildings, and to *assist* in some basic design decisions, whilst also acting as a compliance-checking tool. These models are also susceptible to manipulation and error and can be extremely sensitive to errors in the input of variables such as materials or u-values. However, they are being used to calculate the modelled energy consumption in dwellings, and further used in studies to state whether there is a performance gap or not, this should not be the case. Next the implications of future overheating were analysed using predicated climate data for a building with EWI insulation added. This work was carried out using a calibrated model, thus making the work as accurate as is currently possible, given that the weather file uses predictions. If we consider these isolated pieces of research as a whole, then this leads to the conclusion that more accurate models should potentially be generated before we consider using these figures to calculate a performance gap.

4.4 Experimental Publications

Section Introduction

When addressing the performance gap, the argument often occurs “which is right the model or the reality?” This can be a difficult decision to make due to the large number of variables that can affect the performance of a building in the field; such as wind, rain, fluctuations in temperature, ground conditions, sky conditions etc. (CIBSE 2015). We also need to consider occupancy of the buildings and the impact the random nature of these effects on the energy performance (Janda 2011). All of this is confounded by the difficulty in measuring energy performance in the field as found in **Publication 6 and Publication 7.**

An alternative to field testing is laboratory testing, this has historically been carried out on building products such as heat flow meter tests for R-values of insulation products: BS EN 12667:2001 (British Standards 2001), or larger scale test on building elements such as windows and doors: BS EN 12667:2001 (British Standards 2001). However, dwellings operate as holistic systems and each retrofit measure can have an effect on another (Gustafsson 2000); no component or measure acts independently of the dwelling. It is for this reason that testing a whole house test of a dwelling is of benefit, as the full physical representation of a retrofit measure can be tested and studied for its effects across the complete building. Additionally, multiple retrofit measures can be installed to examine how they interact with one another. The EH is a facility where this type of experiment can be carried out under controlled conditions. As with other environmental chambers, the ability to run at constant temperature with little variation in temperature and humidity helps to produce more accurate results with a greater degree of certainty.

4.4.1 Assessing the Performance of domestic heating controls in a whole house test facility Publication 1

Fitton, R., Swan, W., Hughes, T., Benjaber, M., & Todd, S. (2016). Assessing the performance of domestic heating controls in a whole house test facility. Building Services Engineering Research and Technology, 0143624416634070-. http://doi.org/10.1177/0143624416634070

Introduction

The BEAMA Controls Group (British Electrotechnical and Allied Manufacturers Association) represent the manufacturers of heating controls in the UK, commissioned a large research project with the University of Salford (5 phases valued at over £300,000), with the goal of defining the energy/carbon savings and comfort benefits of domestic heating controls, in a controlled environment. The main output from the early phases of this research is **Publication 1,** although 2 other technical reports (BEAMA 2014; BEAMA 2013) are published as white papers.

The publication gives a background around central heating systems in the UK: this type of heating system is present in 90% of homes in England (DCLG 2011), it also accounts for over 20% of the final energy used in the UK (Palmer & Cooper 2013). Heating controls in new build dwellings are covered by the building regulations and it is mandatory to provide time and zone controls (DCLG 2013), therefore most new dwellings will have thermostatic radiator valves (TRV) and room thermostats installed. However, these regulations are not retrospective. According to the English Housing Survey, around 5 million homes could benefit from improved heating controls (either TRV, room thermostats, or timers) (DCLG 2011). With the potential for major impact on UK energy consumption, it is important to understand the *actual* savings offered by domestic heating controls. Previous research has been carried out around this area, however it is lacking in terms of empirical evidence for energy savings: Munton et al make the following points in the key findings section their recent literature review of this topic (Munton et al. 2014):

- Little research has been undertaken in this domain and much of what is available comes from small scale case studies, most of which were not conducted in the UK.
- Research from the UK and USA has largely failed to provide a consistent body of evidence as far as the capacity of improved heating control technology to contribute to energy savings is concerned.

Main Outcomes

Three separate experiments were carried out to reflect typical scenarios:

Experiment 1 found that the heating setup with no installed controls, simply controlled using the factory settings on the boiler led to overheating of the building, with the highest temperature reached being 31 degrees Celsius in the main bedroom. This illustrates the opportunity for significant overheating in the dwelling and could lead to energy inefficient practices such as window opening to cool the building, or manually switching the boiler off manually when overheating.

Experiment 2 has the most basic kind of local control, a room thermostat, in effect the Living Room acting as a proxy for the entire house. Even this most basic setup controlled the building significantly better and resulted in a 12% savings of fuel consumed.

Experiment 3 represents a house under full control. TRVs in controlled the temperature throughout coupled with the room thermostat in the Living Room. This lead to fuel savings of 42% fuel savings again by reducing the temperatures throughout to those found in SAP and also again by engaging condensing mode in the boiler even more frequently.

Limitations

Whilst this case study cannot, and does not claim to, accurately predict energy savings in an occupied building in the field, it does meet the original aims of the study, which is to provide data on the savings offered by a simple package of controls. These explicit figures can now be used in more sophisticated energy models to make accurate predictions of savings made by controls over a year/ lifetime of the device.

Research Updates

Beizaee et al have carried out a similar study, but more in depth, looking at time and temperature (zonal controls) in an experimental; matched pair setup (two adjoined houses) they found savings of 12% over an 8 week period when zonal time and temperature controls were used (Beizaee 2016; Beizaee et al. 2015) . This is inherently a different type of test, but can be used in conjunction with **Publication 1** to define savings contributed to occupancy times rather than just internal setpoint conditions.

Summary

This series of experiments although straightforward in their approach allowed a comparison to RdSAP and the findings did not concur with the building when modelled using RdSAP. This is currently under further investigation at the Energy House with BRE, DECC and UOS working together to amend the values included in SAP, which deal with TRVs and room thermostats. This data will hopefully now be used in future energy models, and by researchers to inform their work, as it a significant piece of research carried out to a high degree of accuracy, consistency and repeatability. This evidence of controls savings simply did not exist before this work was published. It is also featured in most recent DECC sponsored literature review as a piece of evidence. (Munton et al. 2014) Savings made by heating controls are quoted on this report as having a significant gap in knowledge and research. This publication fills a significant part of this gap.

4.4.2 A Study into the Effect of Curtains and Blinds as Energy Savings Measure, Under Controlled Conditions. Publication 2

Submitted to Journal of Energy Efficiency

Note: This paper has been accepted with changes, and was resubmitted in Spring 2016 for further review. It has been included as it provides a narrative for other papers.

Introduction

This paper is concerned with the possible existence of a performance gap when modelling the performance of window coverings compared to measurements made in a controlled environment. The work contrasts two methods of testing the performance and likely energy savings of window coverings in dwellings. The savings made are currently modelled by SAP and dynamic models such as IES and Designbuilder. However, these values represent savings that can be made at stable homogenous temperatures in a room. This does not replicate the reality of the savings are possible in certain other situations commonly found in UK dwellings: It has been common practice since central heating systems were first installed to install radiators directly below windows, and current guidance issued by the Chartered Institution of Building Services Engineers (CIBSE) continues to recommend this practice in new and existing dwellings (CIBSE 2013).

The window, therefore, is in an area of increased heat flux density. As such, the steady state/ simplified way that SAP/RdSAP deals with the savings offered by curtains may not be accurate in real world scenarios, and was the subject of this experiment.

Main Outcomes

Test 1 collected steady states R values (resistance of the element with and without curtains applied) measured in accordance with ISO9869 and in line with other recent work carried out (Wood et al. 2009). These u-values were in close agreement with the values in SAP, within ±0.02 m^2K/W. Given the degree of accuracy of the experiment these values are close.

This test highlighted savings when using curtains to around 12-24% for curtains and 26-27% for blinds. Given that blinds form more of a seal around the perimeter of the glazing and thus create an extra layer of resistance these results are comparable to other studies (Fang 2001).

Test 2, rather than dealing with u-values/ R-values, investigates the absolute heat loss through the window. This allowed a comparison between each of the windows. The windows that were located directly above the radiators had higher heat flux density than the remaining windows when no coverings were present; also they were the windows that had the most significant savings figure when the coverings were added with savings of 28-29%. The other windows had savings when covered of between 5-12%. The absolute savings were also consistently higher in this location.

Limitations

The process of measuring in-situ heat flux/and u-values in single glazed window panels is not covered formally by any national or international standard, Transparent elements are usually affected by heat loss and heat gain due to solar radiation, so more vigorous analysis is generally required, or specific lab testing using the hot box methodology (Asdrubali & Baldinelli 2011), due to this missing standard and the fact that the author chose another standard to follow which is aimed at opaque elements rather than transparent caused many issues during the 1st review of this paper, and caused it to be accepted but with changes. This has now been justified, and the paper resubmitted.

The chamber had no significant radiative heat gains in this experiment, so ISO 9869 (ISO 2014) is now deemed suitable by the author. Another issue with this paper was the decision to try and quantify the actual fuel/cost savings generated by blinds and curtains using a degree-day calculation, the reviewers deemed this not to be accurate enough. This section was removed prior to resubmission.

Summary

In summary this paper provides new knowledge on two topics, firstly the steady state values in SAP are broadly in line with the findings made, but these are only able to make accurate predictions when the dwelling is not heated by radiators that are located beneath windows. As this scenario is the current Government recommendation in the England and Wales Building regulations, this leaves the calculation somewhat lacking. Secondly, in terms of absolute heat loss, the most significant driver for this figure is the location of the heat emitter in the room rather than the type of window covering.

These results have significant implications for those looking to predict energy savings for window coverings, whilst steady state measurement/calculations will arguably give an accurate u-value/ R-value it is not possible to estimate energy loss through these units until the location of the heat emitter in the room is known. The research suggests that 3D computational fluid dynamics (CFD) modelling could be used to predict heat loss in window covering measures, rather than SAP/steady state, although more accurate results in SAP could be achieved if a “heat emitter location factor” were considered.

The next stage of this research will develop a dynamic calculation using the calibrated Energy House model from **Publication 4**, this will also allow for a through comfort assessment to made in line with CIBSE Design Guide A (CIBSE 2015) Operative temperature, and the Fanger PMV Scale (ISO 2005). This will also provide actual fuel savings made over an annual period, attributable to the usage of window coverings.

Section Conclusion

This section has examined two common energy saving measures. The first looked at the heating controls used in dwellings that may consider to be a retrofit measure, whilst the second paper measured the actual performance of a passive measure, which most dwellings have in place already; window covering. The two measures may seem distinct in kind but commonality is found between these measures in that they are dealt with poorly in standard energy models.

The observations of the savings offered by window coverings were examined and the steady state test did not find any significant deviation from the modelled value found in SAP. However, this was not the case when the real world situation was observed. When heat emitters are placed near or under windows, as recommended by Government guidance, we find that window coverings perform much better than modelled in terms of energy savings. These finding suggests that dynamic modelling should be used, or a different approach should be taken in SAP, to correctly estimate the savings made by window coverings. This may encourage designers to think differently about window coverings as a design solution to heat loss in windows, particularity in retrofit projects.

Both of these experiments conclude that there is a modelling gap; what we generate in models, in particular SAP, is different to what we find when experiments are carried out under controlled conditions. This may be challenged by those who argue that this type of chamber-based test does not perfectly replicate the outdoor environment. However, the counter argument to this is that the measurement uncertainty in the field is far greater than found in controlled conditions. The differences found in these two tests cannot be attributed to external variables. However, these experiments should be seen as snapshots in time rather than an annual/ long term saving prediction. The future research will improve on this using calibrated dynamic of the house (accurate to within 3%) to scale these experiments in to an annual prediction of energy demand and cost savings along with payback times.

5 - Impact and Contribution to Knowledge

Impact of Research

The Applied Buildings and Energy Research Group (ABERG) aims to create knowledge for practitioners and public as well as for academic research. It is for this reason that our impact is particularly important; the group is also fortunate to work with large product manufacturers/organisations that also benefit from impactful research that is well read and well received. To do this we have several outlets that we use for our work:

1. Publication through academic channels (most of the clients that we work with give permission to publish the research that we carry out for them).
2. Conference presentations, the group attends as many conferences as possible to disseminate work, as well as ABERG events such as the successful Retrofit 2012 conference
3. Networking and trade events, the author and other ABERG members frequently act as keynote speakers at events such as Ecobuild, Greenbuild, Retrofit Live and Innovate UK events.
4. CPD Events, the author holds frequent CPD events on Retrofit at Energy House for RICS, RIBA and CIBSE.
5. The work of the Energy House is featured in a large array of trade publications putting the research directly into the hands of those with a vested interest from all levels of the construction industry.
6. The author's work is directly relevant to the module that he leads on the topic of retrofitting domestic buildings on the BSc Building Surveying programme. The students benefit from cutting edge research in the topic and also extremely relevant and practical guidance on industry issues around the topics.
7. The work of the EH is also distributed throughout various international standards groups:
    - International Energy Agency Annexe 58,70 and 71
    - CEN (European Committee for Standardization) group Working Group 13 Sub task 4 looking at developing EU standards for coheating methodologies
    - British Standards groups concerning the testing of multifoil insulation

Awards

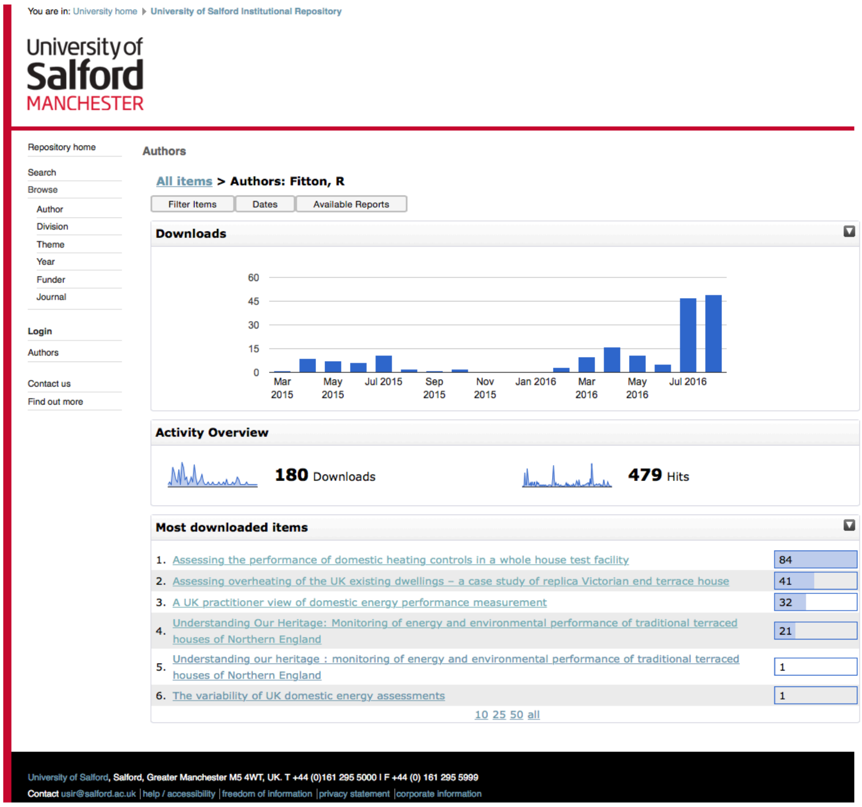
The author has also been formally recognised for his research with a number of different awards:

- Rising Star Award (Building Magazine 2014) This award placed the author in the top 50 professionals in the area of sustainability, for the research carried out at the EH
- Green Gown Award (EAUC 2014) Environmental Association for Universities and Colleges judged the EH to be the leading research and development project in the energy and sustainability sector in 2011.
- Travis Perkins Innovation Award (Travis Perkins 2016) The author has been shortlisted for an innovation award sponsored by Travis Perkins for the work on the wireless HFT mentioned in **Publication A2**
- BRE Innovation Award (BRE 2016). Working together with the Arcada University in Finland, the author and Arcada were awarded a prize fund of £50,000 for their development works on a sensor that rapidly measures u-values in dwellings; the testing and development work in on-going.
- Literati prize for outstanding paper in Structural Survey journal for **Publication 5**

Presence and Citations

Two sources have been chosen to illustrate the researcher's presence in this area: Google Scholar (GS), which will demonstrate how many citations that the work has received, and USIR (the University of Salford Institutional Repository) which will demonstrate the amount of downloads and views they individual pieces of research have had. The author is an early career researcher; the research published is generally limited to the publications contained within this report. Several papers have been published only recently and others only 2-3 years ago.

The area of energy performance of dwellings is still a growing research topic and has only a small number of active researchers. To expect large numbers of citations or downloads/views may be optimistic. According to GS however the number of citations is rising quickly with 2015 (9 citations) already nearly doubled half way through 2016 (16 citations). Also many publication have been published this year so will take time to be cited.



All items > Authors: Fitton, R

180 Downloads

479 Hits

Most downloaded items

1.	Assessing the performance of domestic heating controls in a whole house test facility	84
2.	Assessing overheating of the UK existing dwellings – a case study of replica Victorian end terrace house	41
3.	A UK practitioner view of domestic energy performance measurement	32
4.	Understanding Our Heritage: Monitoring of energy and environmental performance of traditional terraced houses of Northern England	21
5.	Understanding our heritage : monitoring of energy and environmental performance of traditional terraced houses of Northern England	1
6.	The variability of UK domestic energy assessments	1

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Figure 12 USIR profile statistics

The USIR data (Figure 12) are more detailed and of a higher resolution than that found in GS, however only the number of downloads are shown rather than whether a paper has been used as a citation. However interesting data still exists:

- Monthly downloads have increased significantly from 2015 to 2016.
- The most popular paper (even though available for only two months) is **Publication 1**; this is felt to be down to a significant gap in this research in this area and a lot of publicity around this work. This has influenced the increase in downloads in July/ August 2016.
- During 2016 the majority of views come from the UK, which is expected as all of the research has specific UK content, the growing surge in Chinese research in the energy sector has had an impact also with the second largest section of viewers coming from China.

6 – Discussion

The aim of this body of work is to answer the following question:

> *"Is the performance gap a combination of other gaps, such as the measurement gap, and the data gap in modelling?"*

This is a complex question to answer in several pieces of work. However, the work presented here gathers a forming body of evidence and directions for further research:

Performance gap is seen as two inputs: measured performance vs. model, and yet both of these inputs may be incorrect. The HLC is generated invariably using an inaccurate model (SAP) with proven deficiencies in this thesis (**Publications 1, 2 and 9**). Additionally, the current industry/skillset of the building performance measurement in the domestic sector is in its infancy and requires further development, with the levels of skills being diverse and the lack of the standard guidance and protocols as shown in **Publication 6**. This leaves a situation where the modelling gap and the measurement coincide; this leads to two errors in the performance gap measurements.

If we consider that when calculations are undertaken with imprecise numbers, then the resulting numbers will also be imprecise. Given that the two inputs to the equation may be incorrect then the error will be difficult to identify. This can have different effects, one value may cancel the other one out, or both errors can be compounded. For example, the HLC is inaccurately calculated to be too high and a very high accuracy measurement is taken then this will lead to a negative performance gap, the building is shown to be performing better than it should be. Conversely, if the HLC is accurate and a poor measurement is completed that underestimates the energy performance of the building (for instance not properly accounting for solar gains) then this lead to a positive performance gap in as much as the building is shown to be performing better than it should. In terms of improving the accuracy of measurement of energy performance, several pieces of work presented if consulted should assist those carrying out these measurements:

From a laboratory standpoint the measurement of insulations containing foil can now be modelled more accurately and thus the values that are used for modelling will now be to an agreed standard **Publication A1**, this will lessen the gap in performance from the modelling point of view.

On site measurement guidance is contained is contained in **Publication 7.** This will introduce new entrants to the field in terms of strategy, guidance, and if outside the scope of their work, how to select people to do the work to an agreed standard. These items are crucial to forming a measurement that can be relied on when making assumptions about the performance gap.

Two innovative new tools are covered in this work, to aid in the assessment of building performance, one at whole dwelling level (QUB in **Publication 8**) and the Heat Flux measuring device in **Publication A2.** The QUB method is an alternative to the longer in duration, but much wider researched coheating method. The duration needed to vacate a property for a coheating test is a significant negative issue; the QUB takes a step to improve on this, with its claim to reduce the time taken by coheating to 2 days. This work progresses at speed to try and validate this work in the field. Measurement at an elemental level can be improved with new technology, such as the new heat flux sensor; due to its ease of use and standardised software embedded within the sensor, it will be possible to calculate u-values to current standards with little intervention from operators. This will minimise user error, and its appearance and cost will make u-value measurement more acceptable to occupants. As more consistent and comparable data is collected and shared, this will assist experts in the area. When we compare this to the current way that u-values are measured using different equipment, differing methodologies, and different analysis techniques it is clear that this may contribute to a measurement gap.

Several new pieces of evidence concerning the operation and accuracy of models are provided in the works. There is a clear gap between the actual thermal performance of window coverings under certain conditions and also the energy savings attributed to basic heating controls in SAP. These issues are worthy of attention to lessen the gap between actual performances and predicted in SAP and also other models. We have also seen that models are open to accidental and intentional errors that can cause substantial errors in the output of the models. The positive side of modelling has also been illustrated; with a well-calibrated model we can examine scenarios that would be impossible to measure in the field.

This is necessary as the evidence is now clearly indicating that the UK climate is certain to change, with heat waves to become more frequent and for the average temperature to rise in general (Committee on Climate Change 2016).

Planned further research:

Further work is needed to make headway in the area of performance gap studies: the new testing methods mentioned in this works and others require further research into their levels of accuracy. Guidance and standards for these new methods also require preparing preferably in line with new recognised standards. The models that are used to provide the predicted values for performance gap studies need to be fully understood. They should not be used as the de-facto assumptions for a building's performance without being subject to scrutiny. It is also important to realise the effects of thermal comfort in the area of performance measurement; energy consumption should not be considered in isolation. The author will be embarking on a study to bring together thermal comfort and energy measurement together to validate comfort levels in retrofitted buildings, at a lab level in the EH and in dwellings in the field.

3-5 Year Future Research Plan:

There is an increasing demand for off-site construction (Monahan & Powell 2011) and other innovative methods of construction. This will become more apparent in the short to medium term, these units will require different types of performance testing, discussion are currently in place to discuss factory level testing on heating equipment and also dwellings that are constructed in full in a factory level environment. The author also plans to embed sensors into elements at a factory level; this allows the dwelling to be monitored discretely for the entire life of the building. This will be key in longer term energy studies for research but also for financial arrangements such as guaranteed energy performance contracts which are increasing dramatically in numbers (Deng et al. 2015)

Another topic to be researched is that of the urban heat island effect, this has been well studied in larger cities (Skelhorn et al. 2016) and has been shown to have a significant effect on cooling loads of between 9-12%. The author intends to examine the alternative perspective of examining collected environmental conditions in areas from the centre of Manchester to the rural areas. The conditions will be fed into dynamic models with houses of a similar type to the areas the conditions were collected in to examine the hypothesis of should energy savings campaigns be aimed at explicit geographic areas to achieve maximum energy/carbon savings. This will also be extended to a larger project to model stock across the UK. This has been done in a simplified way by Murphy et al, who found a gap between a standardised building in London to one in Glasgow of 30% due to external conditions (Murphy et al. 2013)

7 - Summary and Conclusion

7.1 Research Conclusions

As a body of work the research presented here is broad, to reflect the necessity of a wider understanding of the field. However, the core element of the work, as discussed in Section 1.1, is essentially concerned with understanding sometimes less understood, and certainly less well characterised by models, elements of buildings that contribute to their performance.

The main studies, of controls and curtains, are the early stages of understanding the performance of whole buildings and the impact of building elements in more detail than the current view. This opens up a wider range of future work to better characterise properties and associated elements. Controls, particularly, represent a major contribution to the better understanding of dwellings from a dynamic perspective. This work has further been extended in a joint project with BRE for BEIS (formerly DECC) to understand the impact of a range of environmental conditions, rather than at the single point presented here. Again, this contributes not only to understanding overall performance, but also performance under dynamic conditions. This underlying issue of poor or non-existent representation of certain elements is also addressed in the research on the performance of window coverings.

In understanding effective measurement and modelling, the work addresses the issues of assumptions within models and the importance of accurate data to inform those models. Accurate data collection is central to challenging assumptions around performance and this is largely driven by appropriate methodology, be it detailed building performance research or the methods of regulatory building assessment. In many respects both of these are driven by acceptable methods and a clear understanding of buildings. As highlighted, the practice of building performance research is even now developmental, as new approaches and technologies are introduced. Errors and risks in data collection have the capacity to undermine our understanding of the actual performance gap and, therefore, will be an ongoing area for investigation.

While comparing measured data against models, we can see that the performance gap covers three areas of research. By contributing to a better understanding of models in terms of their assumptions and the processes of effectively building the models to accurately reflect the built form. This work contributes to the development of both understanding the processes of regulatory frameworks, but also understanding the impact of these assumptions and processes on accurately representing buildings within different types of models.

The research has proven there to be a gap between measured and modelled performance and one of the significant reasons for this is the differences between steady state modelling and dynamic environments. The Energy House creates an opportunity to further explore this important relationship and understand the potential impacts this has for evaluating the energy performance of buildings.

7.2 PhD by Publication Objectives

This reports provides a narrative route through the body of linked individual research. And is a reflection on the *complete body* of research. This report has provided the opportunity to group the work into one body and provide a narrative to this work. The objective of the PhD by publication is to demonstrate that the research undertaken achieves the QAA descriptors appropriate for PhD level.

> *The creation and interpretation of new knowledge, through original research or other advanced scholarship, of a quality to satisfy peer review, extend the forefront of the discipline, and merit publication.*

The work presented has been undertaken with the researcher engaged in the design, delivery and analysis of the research work to deliver new knowledge. The work has been peer reviewed and has been successfully published.

> *A systematic acquisition and understanding of a substantial body of knowledge, which is at the forefront of an academic discipline or area of professional practice.*

The work focuses on the discipline of building physics, but connects with the identified actors within the “retrofit” sector in academia, policy and practice. The published works show significant structured engagement with the literature in the related fields, as well as strong engagement with industry.

> *The general ability to conceptualise, design and implement a project for the generation of new knowledge, applications or understanding at the forefront of the discipline, and to adjust the project design in the light of unforeseen problems.*

The research presented, as well as supporting research activity identifies the capacity to design and deliver independent research. This is demonstrated not only within the published works, but also the wider on-going research within the Salford Energy House and in the field, which form the basis of a substantive portfolio of research activity.

> *A detailed understanding of applicable techniques for research and advanced academic enquiry.*

The work identifies a number of activities which are concerned not only with the application of existing methods, but critiques and redesigns of approaches. This work has been undertaken as part of the wider research community (IEA Annexe 58), as part of an international research team (QUB) and individually within the University (u-value patent).

> *Make informed judgements on complex issues in specialist fields, often in the absence of complete data, and be able to communicate their ideas and conclusions clearly and effectively to specialist and non-specialist audiences.*

The communication of the work has been undertaken with a commitment to engaging with a wide range of audiences. Examples include,

- Accurate, cutting edge and industry led research has been delivered to students in the Building Surveying BSc on modules led by the author.
- The author regularly presents papers to conferences, he also presents at exhibitions and trade events, such as Greenbuild and Ecobuild.
- The is a member of the SAP Scientific Integrity Group, which oversees the scientific accuracy of changes and updates of the UK's standard energy model.
- Research carried out by the author has been presented at the House of Commons as part of a review into controls. Recently the work carried out by the author on heating controls has been requested by DECC to be used as scientific evidence to change the values found in SAP and other energy policy.

- The coheating and QUB works are currently influencing policy forming organisations: CEN as part of Working Group 13 Sub Task 4 looking at developing EU standards for coheating methodologies.
- The author has recently taken up a position to lead Sub Task 2 of the newly formed International Energy Agency Annexe 71, this task will research how to collect specific data on energy performance of buildings, using smart data and also sensor gathered data. This work will commence in Autumn 2016.

Academic guidance is rarely relied upon by clients of retrofit, this is evidenced in **Publication 5**. It is reasonable to assume that this may apply across the rest of the stakeholders in retrofit, although this is speculation, as no evidence exists. The aim of the researcher is to try and increase this figure, by distributing real world, comprehensive and impartial research as wide as possible.

This report is designed to not only demonstrate the development of the researcher and show that a recognised standard has been achieved, but also show a future direction for the research. This future work is not only based on new research opportunities and ideas, but a detailed critical reflection of the work previously undertaken. The researcher is in a unique position to engage with the retrofit community, looking to address the identified issues within the Performance Gap and improve our understanding of its constituent elements, as well as gaining a more complete understanding of how we might improve our housing stock for an understanding of energy efficiency that takes account of outcomes for the occupant.

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Annexe A

Overview of Papers & Declarations of Participation

Primary Published Works

Publication Number	Title	Participation Statement	Page Number
1	Assessing the performance of domestic heating controls in a whole house test facility	**Professor Will Swan (UOS)** This paper investigated the impact of different domestic control arrangements on energy consumption within the Salford Energy House. This work was based on work undertaken with the controls manufacturers association and represented the first work of this type. This was led by Richard as lead author who engaged with BEAMA and design the experiment and led the data collection and analysis. The literature review and writing was undertaken jointly with the authors, with Richard acting as lead author.	1
2	A Study into the Effect of Curtains and Blinds as Energy Savings Measure, Under Controlled Conditions	**Professor Will Swan (UOS)** This paper investigated the impact of window coverings under homogenous and heterogenous heating distribution within a domestic property, using the energy house. Richard is the lead author of this paper and designed the experiment, collected and analysed the data. The literature review was carried out mainly by Richard with the drafting and writing of the paper undertaken jointly with the team.	18
3	The variability of UK domestic energy assessments	**Professor Will Swan (UOS)** As the leading authority on the assessment of domestic properties within the team, Richard provided oversight	57

		in terms of the description of the models, relating RdSAP to the BREDEM family of models, as well as linking this to the assessment process from a training and practical perspective.	
4	Assessing overheating of the UK existing dwellings – A case study of replica Victorian end terrace house.	**Dr Yingchun Ji (UOS)** Richard's contributions for this paper are towards the creation of the Energy House model (i.e. the use of correct construction materials and their thermal properties) and the model verification with the real time measurements from the Energy House experiments. A verified model is the key element to perform further overheating analysis in this paper therefore Richard's contribution is significant for the publishing of this article.	74
5	Adoption of sustainable retrofit in UK social housing	**Professor Will Swan (UOS)** This paper reviewed the adoption of retrofit technologies for 130 social housing providers. This specifically looked at the different technical solutions adopted and the underlying reasons for their use. Richard provided technical input and literature review elements for the different technologies, applicable standards and issues of understanding perceived against actual performance.	86
6	A UK practitioner view of domestic energy performance measurement	**Professor Will Swan (UOS)** The paper was concerned with the practices of data collection for the energy performance of domestic properties and was initiated as an early sense making project for Richard's research work. The goal of the paper was to understand the	103

		practices of energy performance in terms of technical and pragmatic issues. The research question was initiated by Richard and the research was designed jointly between the two authors. The research was jointly designed and Richard undertook all of the data collection. The literature review was conducted jointly between the authors. The data analysis was jointly conducted, with the initial structuring of the paper also being undertook by the authors jointly. The drafting of the paper was undertaken between the authors.	
7	Energy Monitoring in Retrofit Projects: Strategies, Tools and Practices (Book Chapter)	Sole author	112
8	QUB: Validation of a Rapid Energy Diagnosis Method for Buildings	**Dr Guillaume Pandraud** (Saint Gobain Recherché) This paper describes energy performance measurements done at the Energy House in Salford with the QUB methodology. Although this methodology has been developed by Saint-Gobain, the success of the tests relied in large part on the experimental setup developed by the University of Salford. R. Fitton was in charge of everything related to the experimental installation, especially the maintenance and metrology, data acquisition and pre-processing, and also did the calculation of the theoretical performance and the review of the finished article.	128

9	**Conference Paper** Understanding Our Heritage: Monitoring of energy and environmental performance of traditional terraced houses of Northern England	**Aránzazu Galán González (Ecole Polytechnique De Bruxells)** Mr. Fitton provided a great help during the process of formatting and framing the paper topic. His vast experience in retrofitting, guided Mr. Roberts and myself to develop a very interesting paper that shows the first results of the aforementioned study as well as preliminary conclusions. Weekly meetings were held during a month with Mr. Fitton till the paper was drafted and he gave his approval. During the data processing, the help of Mr. Fitton was main. Several outcomes were unexpected and, due to his experience and knowledge of the matter, we were able to understand the reasons behind them opening some other doors to further research.	143

Supplementary Publications

Publication Number	Title	Participation Statement	Page Number
A1	European Standard BS EN 16012:2012+A1:2015 Thermal insulation for buildings. Reflective insulation products. Determination of the declared thermal performance	This was a committee document. The author contributed to the reviewing and sections on heat flux measurement. The author is listed in the document.	151
A2	Patent Submission for Heat Flux Sensor	**Moaad Benjaber (UOS)** Richard Fitton was part of the team who developed the new wireless u-value sensor, he provided his knowledge and expertise of building physics and u-value measurements to help design the casing of the sensor, to insure that accurate u-value readings are achieved. Richard was involved in outlining the calibration procedure of the wireless u-value sensor and how it compares with commercially available sensors. Moreover, also specifying the CFD analysis that is required to simulate the performance of the wireless u-value sensor while its installed on a wall.	188
A3	RICS Article 'Performance gap' in domestic retrofits	Sole author	209
A4	Zero Carbon Hub: Closing the gap between design and as built performance	This was a committee document. The author contributed to the reviewing and sections on whole house scale testing, heat flux measurement and lab measurement. The author is listed in the document.	226

Publications Accepted Awaiting Review

Publication Number	Title	Participation Statement	
S1	Comparison of whole house heat loss test methods under controlled conditions in six distinct retrofit scenarios (Energy and Buildings)	**Professor Will Swan (UOS)** Richard was responsible for parts of the experimental setup and design of the experiments, day to day running of the experimental facility and also data analysis of chamber and internal measurements. Background performance gap work was also provided in the paper.	307
S2	QUB: a fast dynamic method for in-situ measurement of the whole building heat loss (Energy and Buildings)	**Dr Florent Alzetto (Saint Gobain Recherché)** The involvement of Richard Fitton in this paper has been done through the bibliography on performance gap related studies performed in UK in addition to energy calculation procedures including SAP. His involvement has been done also through setting up experiments in the Energy House whatever it concerns the monitoring equipment inside the building or setting up the climatic chamber parameters to ensure that the required conditions are reached and steady. His involvement has also been in performing detailed thermal calculation of the building in its various states (baseline and retrofit stages) using SAP UK standard. In addition his involvement has been in performing data analysis of reference Heat Loss Coefficient using the static method including the uncertainty calculations.”	330

Assessing the performance of domestic heating controls in a whole house test facility.

Fitton, R., Swan, W., Hughes, T., Benjaber, M., & Todd, S. (2016).

Building Services Engineering Research and Technology,
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Assessing the performance of domestic heating controls in a whole house test facility

Richard Fitton, William Swan, Tara Hughes, Moaad Benjaber and Stephen Todd

Abstract

The energy consumed by domestic space heating systems represents a considerable share of the energy consumed in the UK. At the same time up to a quarter of English homes have inadequate controls on the central heating systems. Current modelling tools, and results from the limited field trials that have been carried out, are problematic due to the influence of the behaviour of occupants and variability of weather conditions. The Salford Energy House is a full-sized end terrace house built within a climate controlled laboratory. This allows a house of typical construction to be extensively analysed while completely disconnected from the unpredictability of weather conditions and human behaviour. This paper presents a series of tests carried out in the Salford Energy House into the effectiveness of installing room thermostats and thermostatic radiator valves. Savings of 40% in terms of energy consumption, cost and CO_2 were achieved. The results should be regarded with caution in terms of their extent and application to real homes, but represent a significant contribution to the gap in current knowledge due to the ability to isolate the performance of homes from uncooperative variables, and a potential base for the development of more effective modelling tools.

Practical application: This research provides evidence to support installation and use of room thermostats and thermostatic radiator valves as an effective means of reducing domestic energy consumption and overheating.

Keywords

Heating controls, space heating, thermostatic radiator valves, Salford Energy House

Introduction

Room space heating is a major source of energy use in the EU, accounting for approximately one-third of energy use when considering both domestic and non-domestic buildings.[1] In England, approximately 90% of homes use

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central heating,[2] usually fired by gas. Gas fired boilers are used for space heating, generally using a *wet* system of wall-mounted radiators, also providing hot water for cleaning and washing. These types of systems are the predominant heating system in the UK and their performance has a major impact on the amount of energy used for domestic space heating. Domestic energy demand in 2013 was 29% of the total UK final consumption of energy, with space heating accounting for more than 60% of this figure.[3] This means that approximately one-fifth of the energy consumed in the UK is by central heating boiler systems, making their effective performance an important part of UK energy policy. The English housing survey[2] indicates that 24% of homes in England (approximately 5 million) could benefit through the installation of improved heating controls.

Shipworth et al.[4] highlighted the shortage of data regarding the effectiveness of heating controls other than the existing models outlined in the standard assessment procedure (SAP).[5] The SAP is the UK regulatory assessment model to establish the projected energy performance of domestic properties. Shipworth et al.[4] conducted a study of 427 homes, and questioned the performance of controls in terms of energy saving. The study relied, to some degree, on householders to report information and install two temperature sensors. This resulted in a number of data collection risks that Shipworth et al.[4] clearly identified. A more recent study by the Building Research Establishment (BRE)[6] used a larger sample of 823 homes. Three temperature sensors and energy performance certificate ratings based on a model known as Reduced Data SAP (RdSAP)[5] were used to understand the properties. However, the focus of the BRE study was concerned with internal temperatures rather than controls. A record of the presence of wall thermostats and timers was taken, rather than a full description of the control system. While the BRE study is useful in challenging assumptions about internal temperatures held within the SAP model, its usefulness in the understanding of controls is more limited. It should be noted that, while closely aligned, internal temperatures are only be a loose proxy for actual energy consumption, as shown by Summerfield et al.[7] It is possible that other control methods may be used to manage the temperature in a property, such as building users opening windows. This can give rise to situations where the temperature declines, while energy continues to be consumed.[8] The gap in current knowledge with regard to the performance of controls is also addressed in Munton et al.[9]

The British Electrotechnical and Allied Manufacturers Association (BEAMA) heating controls study[10] was funded by the BEAMA Heating Controls Group that represents the association of controls manufacturing companies. This is of a different order of granularity to the large-scale studies previously discussed. It investigated the performance of controls in a highly monitored single test property within an environmentally controlled space, removing the impact of the additional variables such as external weather, solar radiation and occupant behaviour, which makes data analysis for individual measures in field trials difficult to isolate.[11] It should also be noted that through the control of the variables it does not directly reflect what may occur in an individual home. The control of variables to create benchmark testing in order to isolate the differences between control regimes does mean that findings may not be directly translated to consumer savings under a wider variety of conditions.

Understanding the performance of heating controls requires a detailed knowledge of internal and external environmental performance, the building and heat loads.[12] It also requires information about the interaction of the building, systems and controls with the occupants comfort objectives, habits and practices. While recognising that issues of housing and heating are socio-technical in nature,[13] by removing the variables of occupants and weather differentials, we can begin to unpick the potential factors underlying the results from field trials such as Shipworth et al.[4] and Huebner et al.,[14] as well as Heubner et al.'s[15] mixed methods study with a smaller sample. It also serves as a counterpoint to the social science studies on heating controls such as Peffer et al.,[16] Meier et al.,[17,18] Crosbie and Baker,[19] and Chetty et al.[20]

Relevant UK regulations relevant to heating and controls

The standard installation of heating system and controls is well described by Munton et al.[9] and identifies key elements such as boilers, tanks, emitters, controls and ancillary pumps and valves.

There are a number of boiler controls available, specified within the UK regulations. New dwellings in England are controlled by the requirements of Part L1A of the building regulations, which came into effect on 6 April 2014, covering the installation of heating controls. Schedule 1 highlights the regulatory requirement for new homes to be fitted with effective controls.

Part L1A of the building regulations[21] requires an assessment of the carbon dioxide emissions at an early stage of the design of homes. This is done using the standard assessment procedure (SAP 2012)[5] identified earlier as the standard regulatory modelling framework for UK domestic properties. The 2014 building regulations identify that a target emission rate (TER) is produced, which is referred to as a *notional dwelling*. This is a fully specified property in terms of the main energy parameters, including factors such as the fabric performance, the heating system and its controls. In terms of controls, the notional dwelling includes time and temperature zone control and a weather compensator, which is a sensor located externally that controls the performance of the boiler, and a modulating boiler with interlock.

The Domestic Building Services Compliance Guide[22] identifies minimum standards for the efficiency of boilers and other heating appliances, as well as the controls of heating and hot water systems.

The current UK building regulations identify that a set of controls is now a regulatory requirement. However, many properties have been built prior to the introduction of these more stringent building regulations, or may not have been effectively upgraded with new controls when heating systems have been replaced. The English housing survey: energy efficiency of English housing report[23] identified that 24% of 20.2 million English homes lack full heating controls, based on a study sample of 12,763 properties. It should also be noted that this was higher in the private rented (29%) and owner occupier sectors (26%), than in social housing (16%), probably due to renovation and energy efficiency programmes such as the Carbon Emissions Reduction Target, the Communities Energy Saving Programme,[24] Decent Homes[25] and Warm Front,[26,27] which were aimed at fuel poor homes. Currently, heating controls are supported through the green deal[28] and the home heating cost reduction element of the energy company obligation,[29] which is the supplier obligation that replaced CERT and CESP.

The Salford Energy House test facility

The Salford Energy House, Figure 1, is a full-sized test house, built within an environmental chamber. It is a test facility that bridges the gap between laboratory-based materials and product

Figure 1. The Salford Energy House.

testing and outdoor field trials, which may or may not include occupants.[30]

The house is a traditionally constructed Victorian end-terraced building, with a conditioning void to represent a neighbouring property. It has solid brick walls, suspended timber floors, lath and plaster ceilings and single glazed windows. In its base state it is un-insulated. It has a wet central heating system fired by a gas condensing combination boiler. All of this can be changed to suit the testing requirements. The conditioning void uses the same construction techniques and can be environmentally controlled to reflect different heating behaviours. Solid wall properties such as those represented by the Energy house currently number approximately 6.6 million in the UK.

The house is a traditional UK 'two-up, two-down' Victorian property, with the floor layout shown in Figures 2 and 3.

The external environment surrounding a dwelling can potentially make a significant difference to how much energy is required to heat the building. The chamber can recreate a range of external weather conditions: Temperature can be controlled from −12°C to +30°C (with an accuracy of ±0.5°C). Wind, both localised and chamber wide, of up to 10 m/s, and rain of up to 200 mm each hour can be applied. This controlled environment allows for consistent temperatures to be used. This is particularly useful for validating approaches such as co-heating, or whole house heat tests and in-situ U-values. Dynamic and random heating patterns can also be used which is valuable for research into transient effects in the structure or reflecting repeatable real world conditions.

Test methods

Overall Energy House set up

The study was split into three separate tests, described in the following section. Each test involved a single 24-h period of heating following a standard SAP heating pattern.[5] The

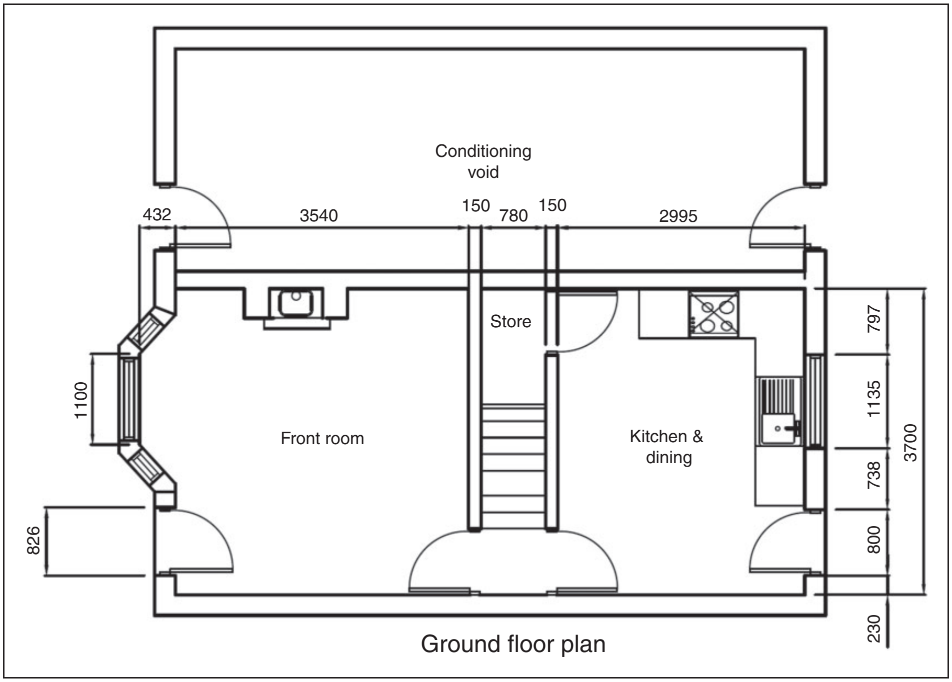

Figure 2. Ground floor layout.

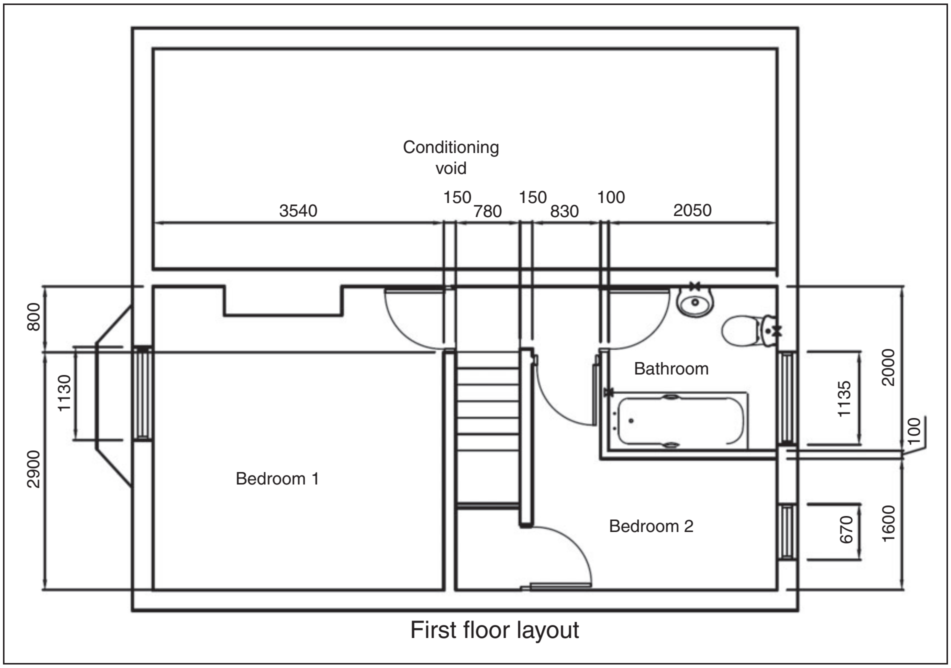

Figure 3. First floor layout.

property was heated from 7 a.m. until 9 a.m. in the morning and 4 p.m. until 11 p.m. in the evening. The target temperatures were 21°C for the main living area and 18°C in the other parts of the house. The experiment used three heating control configurations.

- Test 1 – Boiler thermostat at factory setting.
- Test 2 – Wall thermostat in main living area.
- Test 3 – Wall thermostat and thermostatic radiator valves (TRVs) on all radiators except living room.

Each test was run with the same experimental setup, described in more detail below. The only variables introduced were the changes to the controls in the building and the addition of set points for those controls. The environmental chamber temperature set point was an average of 5°C, with a variation of ±0.5°C during the study. The neighbouring property was not heated and designed to reflect a building that had no occupancy. This ruled out the variable of heat gain from a neighbouring property.

The heating system was a standard condensing boiler rated at 26 kW, a Veissman Vitodens V200 W. The heating system was designed and installed to the standards laid out in the CIBSE domestic heating design guide to remove the variable of different system sizing. The loads for each of the radiators and their outputs are shown in Table 1.

The system was re-commissioned and balanced by a heating engineer, both prior to initial testing and the installation of the TRVs. The room thermostat and TRVs were selected by BEAMA, the brand of which was not revealed to either the BEAMA members or the research team. The selected controls represent a mid-range set of *dumb* controls as might be found in a standard home. They were considered representative by the panel, which included members from BEAMA and the research team. They have not been identified in any part of the

Table 1. Loads and outputs for heat emitters.

Living room	Heat loss figure	Installed capacity	Percentage oversized (%)
Front room	2349	2464	5
Kitchen	2041	2187	7
Hall/Stairs Combined	420	456	8
Bedroom 1	1692	1791	6
Bathroom	868	980	13
Bedroom 2	1019	1117	10

study published by BEAMA[10] or within this study.

Before each test was carried out, the building was allowed to settle for a period of one week to acclimatise and avoid a cold start situation. This created a steady test environment, removing the impact of the building's thermal mass. Each phase consisted of a 48-h test, with the second day being used for data analysis. The 24-h period prior to the test was used as a settling day.

The chamber was sealed and no personnel entered the chamber during the test. All external windows and doors were closed and latched in the main house and the neighbouring property. The curtains remained open for the entire period. All internal doors were closed. It is recognised this reduces air exchange; however, for accuracy of temperatures and to accurate allow benchmarking between different scenarios, this was deemed to be appropriate. It should be noted that occupants may have any combination of open and closed doors in their homes, but this issue was not addressed by this test. It is recognised that this will lead to higher savings than an open door scenario. Appliances in the property were switched off to minimise incidental gains, again something that would not be found in the field. The heating pattern during the test was set according to the times laid out in the SAP guidance issued by BRE (from 7 a.m. until 9 a.m. in the morning and 4 p.m. until 11 pm in the evening).[5] A half hour heat up time was used before each heating period commenced to bring the building up to heat before the period began.

Sensors and data collection

A resistance temperature detector sensor, in a reflective housing, was used to measure the air temperature at the geometric centre of each room recording at 1-min intervals. The sensors perform to a resolution of 0.1°C and are accurate to ±0.5°C. The type T thermocouple temperature sensors are used to measure the feed and return temperature of the boiler. These have a range of -200 to 350°C, with a resolution of 0.1°C, with an accuracy of ±0.5°C. These are used to measure the temperature of the water coming in and out of the boiler.

The gas meter used in the Energy House was with a pulsed output. The gas consumption was monitored using a pulse data logger, reading the pulse output from the gas meter with 1-min intervals every 0.01 m^3, with an accuracy of ±1%. The electricity meter used to monitor the electricity consumption of the boiler is a single phase kWh meter with pulse output, with an accuracy of ±2%.

Description of the tests

While the previous section described the common test conditions and data collection for each test, this section covers the variable elements, which were concerned with the changing of control arrangements for the property.

Test 1 – Boiler thermostat only

Test 1 was designed to mimic the installation of a boiler into a home with no controls other than the boiler programmer, to maintain the heating pattern and the boiler thermostat. The settings of the boiler were unchanged from factory setting, giving a 74°C flow temperature. No hot water was drawn off during the course of the test. The heating time schedule was set following the standard pattern as defined earlier. The boiler flow temperature remained at 74°C for all following tests. The room thermostat was disconnected and TRVs in all room were placed to the fully on position to ensure they did not impact the study.

Test 2 – Living room thermostat

The base scenario for Test 2 remained the same as Test 1, but with a room thermostat added to the system. This device was a thermo mechanical thermostat representative of a mid-range of widely available domestic room thermostats. This was wired into the boiler in accordance with the manufacturer's instructions. The thermostat was located on an internal wall of the living room at the height recommended by the manufacturer (1200 mm). This thermostat was set to reach a set point of 21°C to reflect the standard SAP heating set points.[5] This could not be done using the device itself as the accuracy was not of an experimental quality so a calibrated air temperature gauge was used to ensure the thermostat reflected its actual set point rather than the numeric set point on the display. This is due to the fact that, while setting up the experiment, it was found that the device would give start signals to the boiler when at set points some considerable distance from the measured air temperature directly adjacent to the device. This gave more accurate control over the house. It also raises questions around how we might understand set points in the context of user behaviour, as highlighted by Peffer et al.[15] and Meier et al.,[16] and also how modelling assumptions of set points might need to be reconsidered.[31] This does not necessarily mean we need more accurate thermostats, because as both Shipworth et al.[4] and Nicol et al.[32] identify, the relationship between the individual, thermostats and comfort can be complex.

Test 3 – Living room thermostat and TRVs

In the final scenario, TRVs were added in all rooms apart from the living room, as this room already contained the room thermostat. As with the wall thermostat, the TRVs were initially set at steady state to 18°C. This was done using air temperature monitors to achieve the desired set point. All other factors remained the same. The TRVs were set at steady state, as this, under cycling or heating pattern conditions, is extremely difficult.

Results

The results describe the two main issues that were under consideration. The first is control of the internal temperatures and the second is the energy and cost savings made due the system being under different control regimes.

Control

For the purposes of the study, the internal temperatures were considered to be under control if they were within the boundaries described by SAP, 21°C in the main living area and 18°C in all other rooms.

During Test 1 the house exceeded the set point in most rooms, with the air temperatures at the geometric centre reaching up to 31°C in the bedrooms, as illustrated in Figure 4. The chamber temperature is shown in the bottom of the graph indicating a stable environment was achieved for the test. This was repeated for all of the subsequent tests.

Table 2 shows the maximum, minimum and mean air temperatures for each of the rooms during the test during the morning and evening periods.

The temperature passing the desired set point was caused by the heating system relying only on the boiler thermostat to control the heating system in the house. The boiler thermostat controls the temperature of the hot water fed to the radiators, rather than the air temperature as might be experienced by the occupant. This was set to 74°C as illustrated in the feed temperature graph in Figure 5.

It is also clear from the results that the flow feed temperature (Figure 5) reached maximum after a very short period and did not reduce in any significant way for the entire duration of the

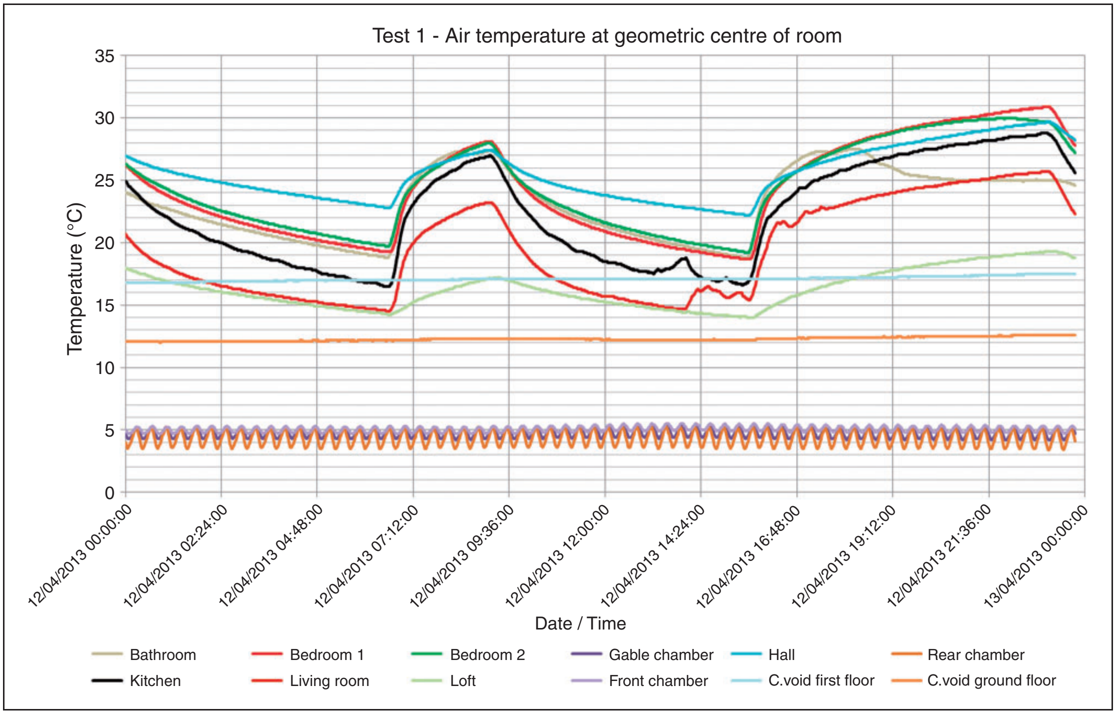

Figure 4. Room and chamber temperatures during Test 1.

Table 2. Temperatures during Test 1.

	Bathroom	Bedroom 1	Bedroom 2	Hall	Kitchen	Living room
Room temperatures between 6:30 and 9:00 at geometric centre						
Average temp °C	25.35	25.19	25.32	25.83	23.83	20.54
Max temp °C	27.3	28.1	27.9	27.4	26.8	23.2
Min temp °C	18.8	19.3	19.7	22.8	16.5	14.5
Room temperatures between 15:30 and 23:00 at geometric centre						
Average temp °C	25.50	27.99	27.85	27.39	26.08	23.39
Max temp °C	27.5	30.9	30	29.6	28.8	25.7
Min temp °C	18.8	18.7	19.2	22.2	16.7	15.4

period. The same can be said of the radiator surface temperatures, as shown in Figure 6.

However there are two exceptions; in both of the heating periods, the radiator in the bathroom begins to come under control, as does the radiator in bedroom 2. The temperature at the surface of the radiator, and therefore the room temperature, dropped. This may be due to an overheating fail-safe built into the TRV head itself, which according to the manufacturer's instructions, is engaged at around 26°C. It is not fully understood why this fail-safe did

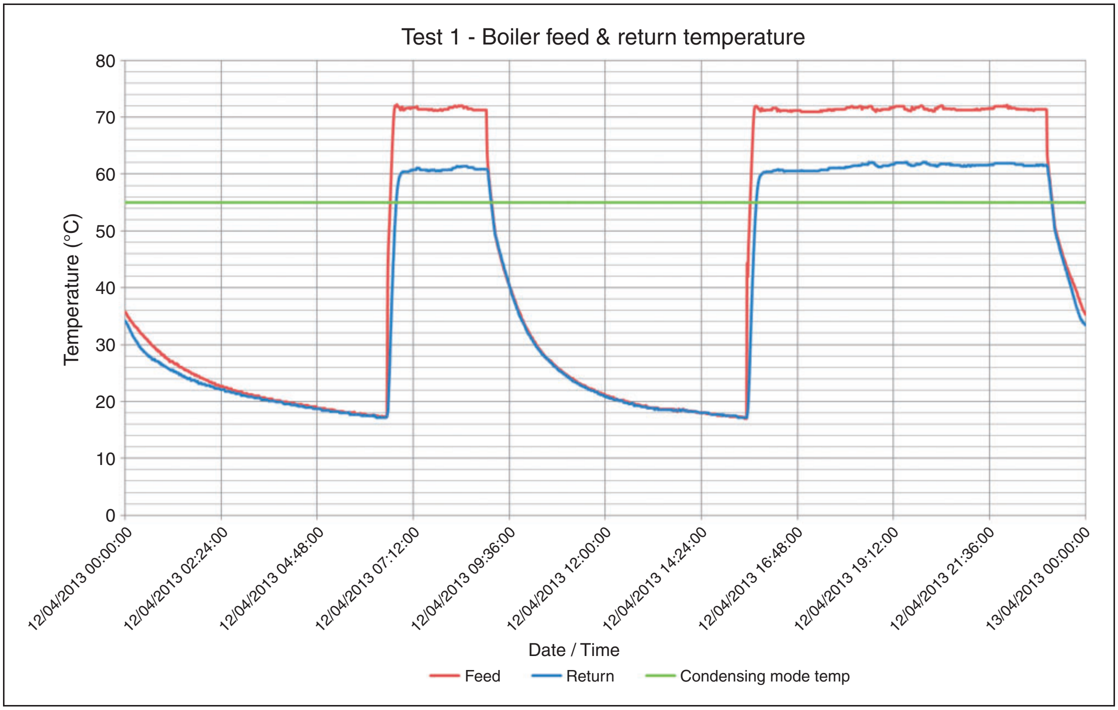

Figure 5. Test 1 feed and return temperatures.

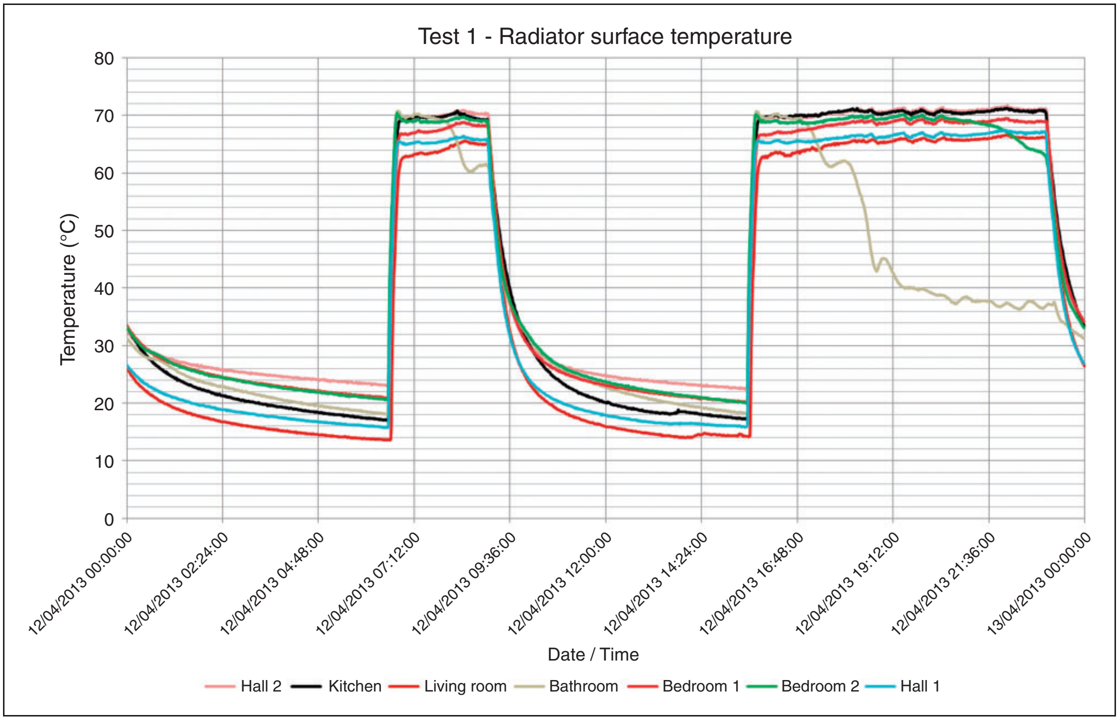

Figure 6. Test 1 radiator surface temperatures.

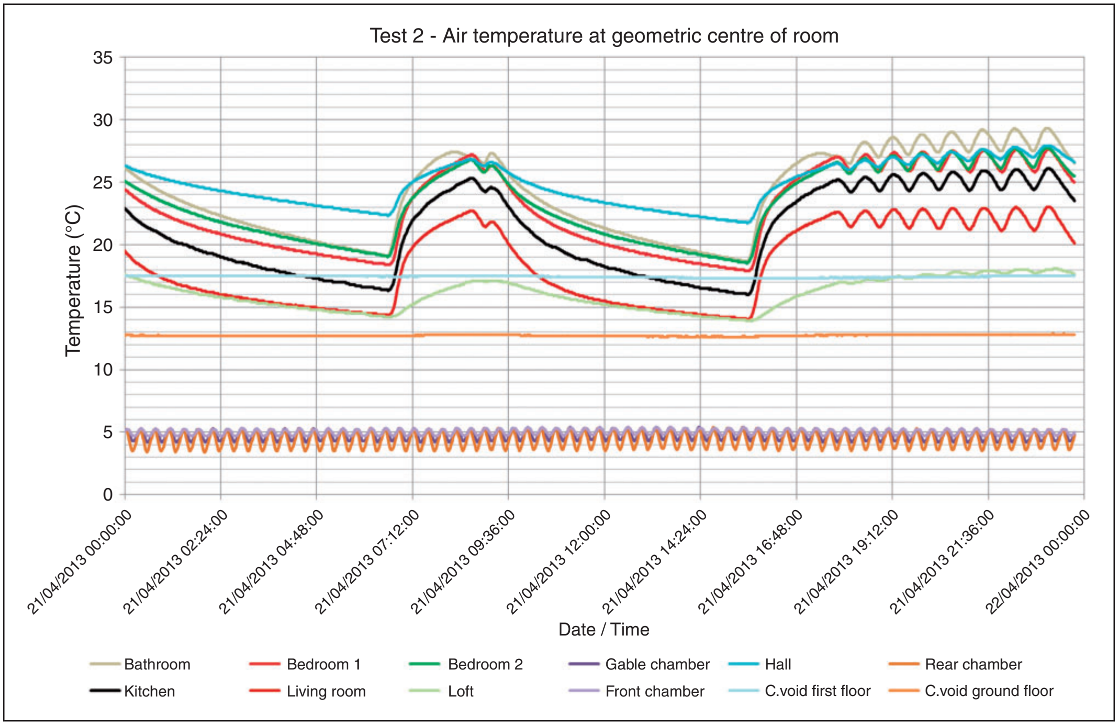

Figure 7. Room and chamber temperatures during Test 2.

not activate in the other areas. One reason for this could be the limited amount of airflow around the TRV heads, meaning that the increase in air temperature at the valve head that was far quicker than in the other areas.

The test shows that the lack of control in the property may lead to comfort issues from the perspective of occupants. Again, it is likely that the occupant would intervene through the use of heating controls or window opening, which would greatly influence the consumption figures. The maximum temperatures shown in Table 2, show that all of the rooms exceeded their set points. Due to the limited time of the heating periods (maximum duration of 7 h and 30 min), it is felt that these maximum room temperatures could reach even higher over a longer period, as the trend of the graphs appears to represent a significant rate of rise even at the end of the heating period. This could exacerbate overheating in buildings that are heated constantly; however, in a field scenario, it is likely that the occupants would intervene to address this issue.

During Test 2, as shown in Figure 7, the living room thermostat takes some control of the whole house, as indicated by the appearance of fluctuations in all of the room temperatures. This is due to the fact that the living room is now acting as a proxy for the rest of the dwelling. An oscillating cycle induced by the room thermostat has an influence on the rest of the building because the entire heating system is dictated by one room thermostat. This cycle is both very regular, and in certain rooms, very broad, with a ±1°C (a 2°C swing) taking in place in the living room, which was also reflected in the other rooms. However, this only occurs during the longer evening heating cycle, as the morning cycle only just enters the control band of the room thermostat as the heating cycle is drawing to an end.

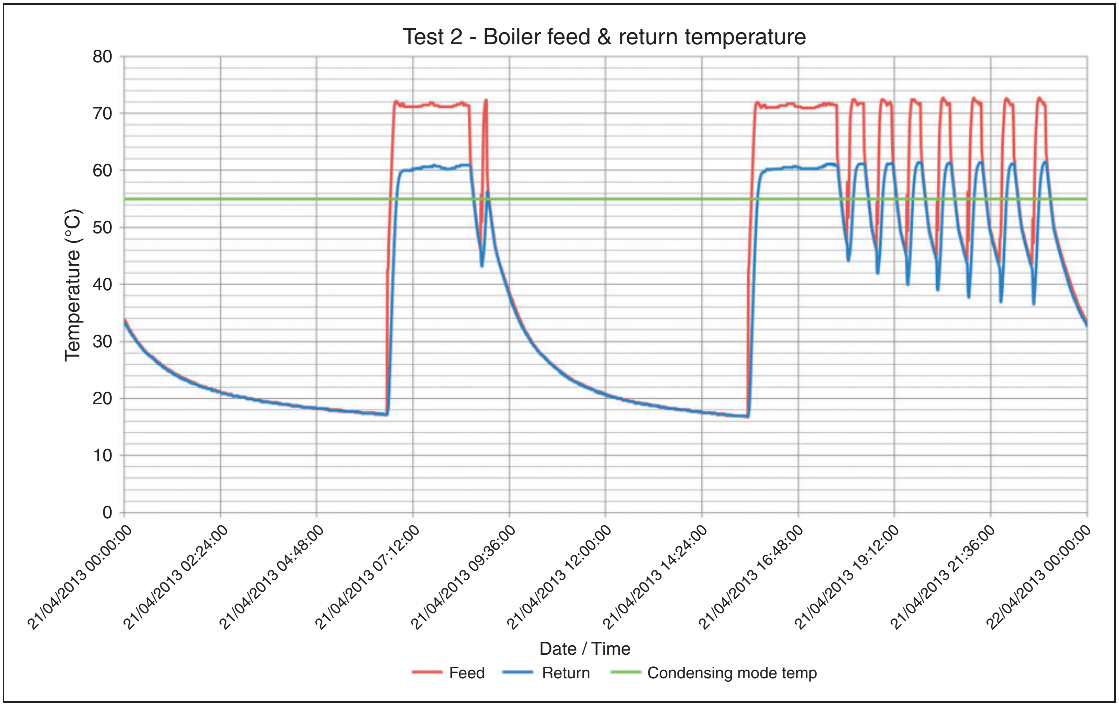

Figure 8. Test 2 flow and return data.

Table 3. Temperatures during Test 2.

	Bathroom	Bedroom 1	Bedroom 2	Hall	Kitchen	Living room
Room temperatures between 6:30 and 9:00 at geometric centre						
Average temp °C	25.44	24.47	24.44	25.44	22.63	20.29
Max temp °C	27.4	27.2	26.8	26.9	25.3	22.7
Min temp °C	19.1	18.4	19	22.3	16.3	14.3
Room temperatures between 15:30 and 23:00 at geometric centre						
Average temp °C	27.15	25.83	25.84	26.29	24.20	21.43
Max temp °C	29.3	27.6	27.7	27.9	26	23
Min temp °C	18.7	17.9	18.5	21.7	16	14

The increased degree of control makes an impact on the flow and return temperatures (Figure 8) as would be expected.

Table 3 shows that during Test 2 the set point was exceeded in all of the rooms apart from the living room when both average temperatures and maximum temperatures were taken, during both morning and evening heating periods.

In Test 3, the building was under full control and it was expected that the set point would be effectively maintained. This, however, was not the case. The set point was still exceeded,

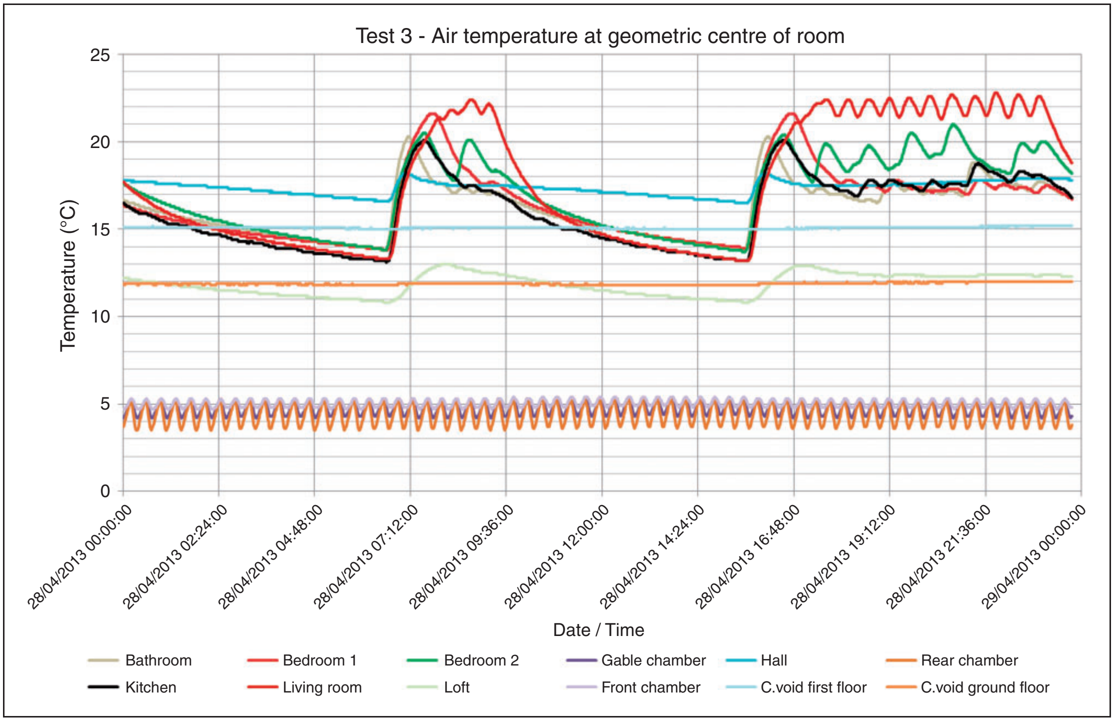

Figure 9. Room and chamber temperatures Test 3.

albeit by much smaller margins and for shorter durations (Figure 9).

Again, the increased degree of control makes an even greater impact on the flow and return temperatures (Figure 10) in Test 3.

The rooms that did exceed the set point did so for a shorter period of time than in the previous tests, as seen in the maximum room temperatures (Table 4), and can be seen to maintain the set point when the room temperatures are averaged over the period of heating.

During the experiments it was found that the TRV was difficult to set to maintain constant temperatures. The TRVs varied widely in set points from room to room despite all being set up to meet the required 18°C set point. It was also found that the valves were unpredictable in terms of how they reacted to the set points. Some would run at the set point for a short period and then lose accuracy, while others would consistently run accurately. Some valves were changed to rule out faults, but the same issues persisted. Bedroom 2 provides an example of the unpredictable nature of these devices, the temperature reached 21°C rather than the 18°C set point. This proved to be a problem in the experiment, but it was felt that this resulted in an overestimation of energy usage rather than an underestimate. It was also found that the living room did not reach its set point during the morning heating period.

Energy consumption and boiler condensing

The overall energy consumption during each of the tests is shown in Table 5. Due to the significant in control in Test 3 compared to Test 1 and 2, it is clear that in this scenario less energy was used. While the removal of occupant factors does mean that results may not directly be comparable with occupied properties, a unique aspect of this research is the capacity to quantify the level of improvement between the three scenarios. Table 4 shows combine gas and electricity

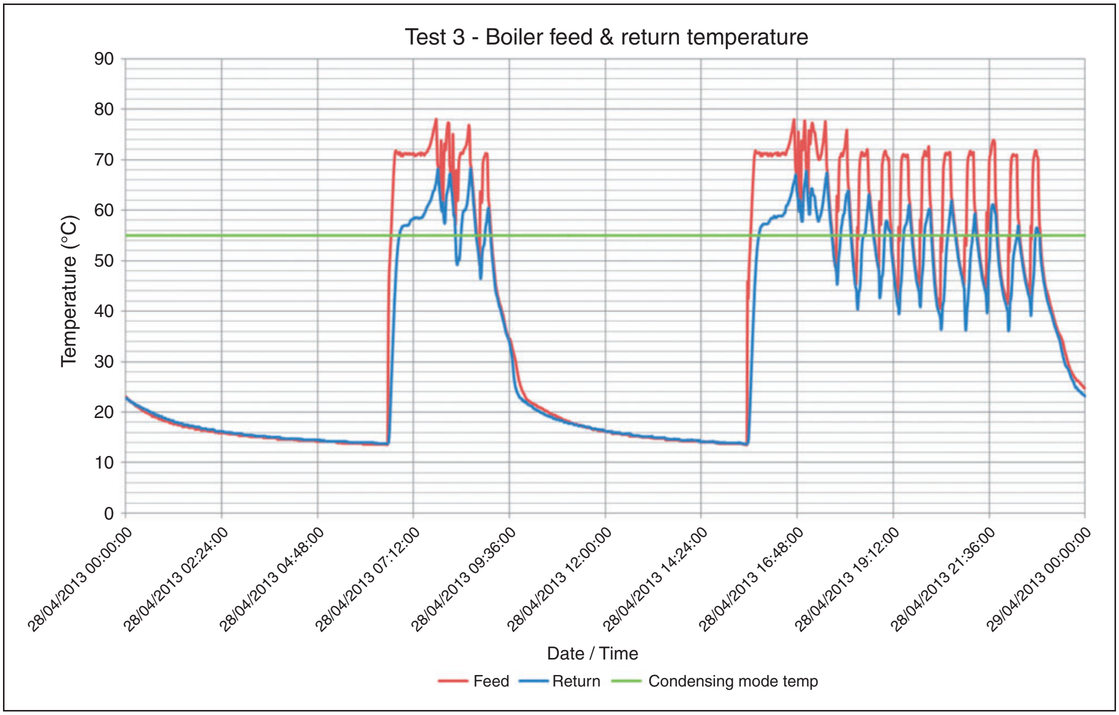

Figure 10. Test 3 flow and return data.

Table 4. Temperatures during Test 3.

	Bathroom	Bedroom 1	Bedroom 2	Hall	Kitchen	Living room
Room temperatures between 6:30 and 9:00 at geometric centre						
Average temp °C	17.69	18.82	18.59	17.58	17.75	19.54
Max temp °C	20.3	21.6	20.5	18.2	20.1	22.4
Min temp °C	13.8	13.8	13.8	16.6	13.1	13.3
Room temperatures between 15:30 and 23:00 at geometric centre						
Average temp °C	17.47	17.88	19.03	17.63	17.76	21.22
Max temp °C	20.3	21.6	21	18.2	20.1	22.8
Min temp °C	13.8	13.9	13.7	16.5	13.2	13.2

consumption. Gas consumption has a measurement error of ±1%, while electricity has a measurement error of ±2%.

In terms of gas consumption, highlighted in Table 5, it is clear that although the introduction of a thermostat in Test 2 did make some improvements resulting in a 12% reduction in consumption, the major savings are gained with the introduction of the TRVs in Tests 3, which resulted in a 42% reduction in overall gas consumption.

When gas consumption is combined with the electricity used to control the system, the savings in terms of total energy consumed, costs and carbon emissions are approximately 40% for Test 3 compared to Test 1 (Table 5). The savings

Table 5. Gas and electricity consumption during the tests.

	Gas used				Electricity used			Totals		
Tests	m^3	kWh*[1]	£*[2]	$kgCO_2$*[3]	kWh	£*[2]	$kgCO_2$*[3]	kWh	£*[2]	$kgCO_2$*[3]
1	10.72	121.8	£5.20	22.558	0.83	£0.11	0.431907	122.63	£5.31	22.99047
2	9.42	107.4	£4.57	19.824	0.75	£0.10	0.390277	107.79	£4.67	20.21514
3	6.28	71.36	£3.05	13.601	0.74	£0.09	0.385073	72.1	£3.15	13.60165

*[1] Calculated using http://www.energylinx.co.uk/gas_meter_conversion_meters.html with default settings (Correction Factor = 1.02264, Calorific Value = 40.0).

*[2] Based on British gas clear and simple cash/card payment (4.274p per kWh gas, 12.797p per kWh electric) not including standing charge (24.439 p per day gas and 15.979 p per day electric) – Prices taken on 07/05/2013 from http://www.britishgas.co.uk/products-and-services/gas-and-electricity/our-tariffs/clear-and-simple-rates.html.

*[3] Calculated using DECC:Climate Change Agreements Interim Guidance (Version 1.1), GP 3.5 Conversion Factors & Procedures, 28/09/2012. Recovered on 10/10/2012 from http://www.decc.gov.uk/assets/decc/11/cutting-emissions/cca/6112-cca-interim-guidance-gp3-5.pdf

resulting from Test 3 can be attributed to the system achieving the desired set points without wasting additional energy that results from exceeding the set point. In terms of boiler efficiency, these tests also highlight the fact that a boiler running with little or no control rarely engages the condensing mode, which is effectively only active during the heat up cycle of the heating schedule, as shown in Figure 4. This represents 11% in the morning period and 4% in the afternoon period for Test 1, as shown in Table 6. This is considerably lower than observed in Test 2 and 3.

It can be seen from Table 6 that, under the conditions of Test 3, the boiler is in condensing mode for 28% of the time in the morning period, and 54% of the time during the evening cycle.

Table 6. Condensing mode %.

Boiler heat return	6:30–9:00	15:30–23:00
Test 1		
ON period	02:29:58	07:29:50
% under 55°C	11.33%	3.78%
Test 2		
ON period	02:29:46	07:30:06
% under 55°C	24.00%	44.67%
Test 3		
ON period	02:29:57	07:29:18
% under 55°C	28.00%	53.67%

Conclusions

This study set out to question whether controls work effectively in a whole house test under fixed weather conditions, with standard installation. As stated previously, the impact of interventions by occupants is not directly addressed in this study. However, the resulting data suggest that even the basic set of controls suggested under UK building regulations may have a significant impact on the energy used in the heating of the building, as well as the potential comfort of the occupant, when compared with a no control scenario. It should be noted that the intervention of occupants in response to elevated temperatures has a major potential to influence the savings figures. Occupants may respond by engaging with their controls or opening windows in response to a wide range of comfort needs – this is difficult to predict. This, however, is not the direct purpose of the study, but the influence of these factors should be recognised when considering the results. We should also recognise that the issue of control would play out differently in house with different insulation levels, which presents an opportunity for potential further work.

It is apparent that the introduction of heating controls improves the control of temperatures within the property. Here, we have quantified the level of that saving within a free running house without occupants and external weather variations. Savings of 40% in terms of energy, CO_2 and costs have been achieved in this experiment, and this area of research warrants further investigation, particularly in terms of introducing more dynamic variables such as internal door opening, occupant interventions and other factors that would quite probably reduce these savings figures.

This study is not designed to address the savings of controls regimes in field-based occupied properties, meaning the savings figures cannot at this stage be directly compared given the experimental design. The control of variables such as door shutting and the removal of the occupants means that the savings described here are higher than may be found in homes. The work represents an exercise in isolating the variables in a way that would not be possible in the field. The extent of data collection undertaken in the house would be untenable across a statistically reliable sample in the field, as well as introducing a high number of dynamic variables making analysis difficult, which explains the lack of field work in this area. However, the main outcome of the study is to allow us to consider a range of heating system controls against this benchmark study. The tests conducted here used a set of mid-range *dumb* controls, but could be compared against more complex and/or expensive devices.

Further work will be undertaken to investigate different control arrangements and this work represents a real opportunity to explore the impacts on energy efficiency of alternative control approaches, such as weather compensation and intelligent controls. In addition, the future collection of comfort data, such as radiant temperature and air velocity, will allow a clearer understanding of the occupant experience under various controls regimes.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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A Study into the Effect of Curtains and Blinds as Energy Savings Measure, Under Controlled Conditions

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Submitted (Reviewed 1st Time and awaiting feedback) to Energy Efficiency
(20th June 2016)

Energy Efficiency

The thermal performance of window coverings in a whole house test facility with single-glazed sash windows

--Manuscript Draft--

Manuscript Number:	ENEF-D-15-00284R1
Full Title:	The thermal performance of window coverings in a whole house test facility with single-glazed sash windows
Article Type:	Original Research
Keywords:	curtains; blinds; domestic energy; windows; Retrofit; Salford Energy House
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Abstract:	The residential sector is responsible for 29% of the total energy consumption of the UK, with 62% of this energy being used for space heating. Heat loss through the fabric of building elements is a crucial factor in the energy-efficiency of homes and a wide number of studies have looked at physical interventions to improve the energy-efficiency of existing buildings, commonly called retrofit. This research considers the impact of window coverings on reducing heat loss from homes, a measure that is not commonly considered an energy-efficiency intervention. Although the amount of glazing varies widely between homes, all windows are a significant factor contributing to heat loss. While physical changes such as double and triple glazing can improve the energy performance of buildings, the impact of curtains and blinds is not well characterised. Previous research into window coverings has been undertaken using laboratory tests, such as hotbox and small climatic chamber environments. This study presents the impact of window coverings on heat loss within a unique whole house test facility. This allows for a better replication of a real heating system and the effects that it has on localised heat transfer. This gives a more detailed picture of in situ performance, similar to that which may be found in the field.
Response to Reviewers:	see attachment

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Monday, 20 June 2016

Dear Sir/Madam,

We have completed the proposed changes to the paper, as well as generally improving the grammar and wording. I have included a table of the referee's comments and our responses to them below.

Referee's comment	Response
R1 – Comment about the format of the paper	The manuscript has been amended to include the features mentioned in this comment, such as adding discussion and conclusion sections.
R1 – It was not clear from the paper whether the research is challenging the assumptions made in the SAP model or not	The text has been amended to state that the research is not challenging the assumptions made in the SAP model, but to create a controlled test leading to more accurate values for use in models.
R1 - Swedish case studies	Reference to the Swedish work has been removed as the authors recognise that this did not benefit the paper.
R1 - Graphs and tables	The graphs have been improved and Table 1 has been replaced with a bar chart.
R1 - What has already been researched and what new knowledge has been added	This is now contained in the discussions and conclusions
R1 - Window coverings	Additional details added to the paper regarding the window coverings.
R1 - Limitations/boundaries of the research	These are more clearly set out in the paper, for example the assumed values taken from the SAP model to allow for comparisons to be made with SAP
R1 - Discussion and conclusions	Greater depth in the discussion and conclusions sections.
R2 - The use of curtains result in very little energy or cost savings	Following comments from other reviewers we have removed the financial and energy savings section, however we did feel that is a significant removal from the paper.
R2 - Heat flux transducers mounted on the glass	We have used these sensors and the methodology used by others in the field who have deemed this adequate and accurate.
R2 - Radiation conditions	We can only assume given the limited measurements that were taken during this the radiative conditions were the same, as the same conditions were maintained in the inside of the building and in the chamber.
R2 – Photographs	The photographs have been improved.

R2 – Secondary glazing	The manuscript has been amended to include secondary glazing and the research of Smith et al (2012).
R2 – Tables	The tables have been improved, although we still feel it is appropriate to use R- and U-values when necessary.
R2 - Paper title	The title has been amended to include single-glazed sash windows.
R2 – ASHRAE research	Additional research from ASHRAE has been included in the paper.
R3 – Furniture	The manuscript has been amended to highlight that the Salford Energy House is fully furnished (as a domestic dwelling) and this can influence air movement and heat transfer.
R3 – Table 4	Table 4 has been amended to address the concerns regarding the R- and U-values.
R3 – Comfort Study	A comfort study is a potential future project in the Salford Energy House and this is now mentioned in the paper.
R4 – Table 4	Table 4 has been amended to address the concerns regarding the R- and U-values.
R4 - Graphs of heat flux and temperatures	Graphs of heat flux and measured temperatures have been provided to aid understanding of the findings.
R4 - U-values measured in test 2	The U-values measured during test 2 have been removed and heat loss only is investigated, due to difference in temperatures measured in the centre of the room not being representative of the temperature close to the window.
R4 – Comparison with Woods et al. (2009)	Comparisons are included between the research findings and the work of Woods et al. (2009).
R4 - Energy and financial savings and the use a degree day model	Savings figures and references to degree days have been removed from the paper.
R4 - Conclusion	The conclusion has been amended to more comprehensively expand on the findings of the research.
R4 – Terminology	The terminology has been corrected to comply with ISO9869.
R4 – Figures and tables	The figures and tables have been amended to improve clarity and aid understanding.
R4 - Table 4	Table 4 has been amended to correct U-value calculation errors.
R4 – Cultural aspects	This reference to cultural aspects of curtain use has been removed from the paper.
R4 – Comparison with Woods et al.	Comparison of the findings with Woods et al has been added to the paper.
R4 - Horizontal or vertical temperature stratification	This was not addressed due to the nature of the being a comparative type of test. Wo do appreciate that this would have been a worthwhile addition to the setup though.

R4 – Temperature measurement	Section 2.4 has been amended to clarify the concern about the location of the temperature measurement with respect to proximity to the heat emitters in test 1.
R4 - Uncertainty of the heat flux logger	This is not included in Bakers work, and we also consider this to be a negligible value in the order of 1%
R4 - Uncertainty calculation method	This is described in more detail in the revised paper.
R4 - Degree days	References and use of degree days have been removed from the paper.

We hope this clarifies the issues highlighted in the paper, which we found extremely helpful and felt greatly improved the paper. Where we have not included the changes we have written a justification.

Yours sincerely,

Richard Fitton

School of the Built Environment

The thermal performance of window coverings in a whole house test facility with single-glazed sash windows

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Abstract

The residential sector is responsible for 29% of the total energy consumption of the UK, with 62% of this energy being used for space heating. Heat loss through the fabric of building elements is a crucial factor in the energy-efficiency of homes and a wide number of studies have looked at physical interventions to improve the energy-efficiency of existing buildings, commonly called retrofit. This research considers the impact of window coverings on reducing heat loss from homes, a measure that is not commonly considered an energy-efficiency intervention.

Although the amount of glazing varies widely between homes, all windows are a significant factor contributing to heat loss. While physical changes such as double and triple glazing can improve the energy performance of buildings, the impact of curtains and blinds is not well characterised. Previous research into window coverings has been undertaken using laboratory tests, such as hotbox and small climatic chamber environments.

This study presents the impact of window coverings on heat loss within a unique whole house test facility. This allows for a better replication of a real heating system and the effects that it has on localised heat transfer. This gives a more detailed picture of in situ performance, similar to that which may be found in the field.

Keywords:
curtains, blinds, domestic energy, windows, retrofit, Salford Energy House

1. Introduction

The domestic housing stock is responsible for 29% of total energy consumption in the UK. A substantial amount of this energy, approximately 62%, is used for space heating (Palmer & Cooper 2013). Reducing heat loss through the fabric of the building through physical interventions is commonly called retrofit (Kelly 2009; Swan et al. 2013). Here we considered the impact of curtains and blinds on the energy efficiency on a property, not generally considered an energy efficiency intervention by retrofit researchers and professionals.

This paper presents an investigation into the impact of window coverings, such as curtains and blinds, on the energy efficiency of a domestic property. While previous studies have been undertaken to examine the performance of individual window coverings, this study was carried out in a whole house environmental test facility. This allowed for the consideration of a wider number of factors, such as the impact of localised heating within a controlled environment. This study explored the differences in performance with a heterogeneous distribution of heat throughout the property, as would commonly be found in the field, and to determine the influence of window coverings in comparison to homogenous distribution of heat as is assumed in laboratory tests and many models.

The UK's standard legislative methods of energy modelling the performance of homes, the Standard Assessment Procedure (SAP) and Reduced Data Standard Assessment Procedure (RdSAP) (BRE 2014) make reference to the reduction in heat transfer that curtains and blinds offer, providing an adjustment to U-values where window coverings are applied. However it is not clear whether these values are based on modelled or experimental data. This study aims to quantify, under controlled conditions, the actual energy savings that can be a made using curtains and blinds. The purpose therefore of this research is not to challenge these values, but to attempt to create a controlled test that will hopefully lead to more accurate values for modellers to use in the future.

Two tests were undertaken to investigate the differences in heat distribution within a property and the potential impact of window coverings with two different heating systems. The first test was carried out using electrical resistance heating, and during the second gas central heating was used. The first test was used to establish base U-value (thermal transmittance) and R-value (thermal resistance) measures to allow direct comparison with SAP predictions and previous studies. The second test, using gas central heating, was undertaken to establish actual heat loss through the windows being subject to issues that may be common to UK centrally heated houses, such as emitter placement and different heating set points. Both experiments were carried using constant external and internal temperatures at a test house facility within an environmentally controlled chamber to ensure reliable results without variables that might be found in the field such as wind and rain effects or solar gain. These results allowed for more accurate simulation of energy consumption in domestic buildings and greater confidence in the values describing the benefits offered by curtains.

1.1 Fabric Losses through Building Elements

When considering buildings from a comfort perspective as the occupant experiences them (F. Nicol et al. 2012), buildings are designed to protect people within them from extremes of heat, cold or wider boundary conditions such as wind and rain. This means that there is an interrelationship between the boundary conditions, the building fabric, any environmental controls systems, such as heating and cooling, and the occupant (Hens 2012). Within this study we consider losses through fabric, specifically glazing, which are generally conductive and radiative losses.

Conductive and radiative losses can be either measured (ISO 1994) or modelled (British Standards Institution 2007). These losses are represented by U-values for thermal transmittance and R-values for thermal resistance. The R-value is the reciprocal of the U-value. The use of U-values is the standard method of comparing heat loss across different building elements. Figure1 presents the comparative difference between elements in the current version of the UK Building Regulations (DCLG 2013) and the maximum U-value for each element. Even in new build properties it is apparent that windows are a significant cause of heat loss.

Figure 1 Limiting U-values of domestic building elements in UK Building Regulations (DCLG 2013)

In the UK most homes have external windows. In comparison with the rest of a building, windows are a major path for heat loss of all types (convective, radiative and conductive). They are also a major pathway for solar radiation gain into the structure. This topic will not be covered in this study.

Heat loss from windows has remained fairly consistent at around 20% of total heat loss from dwellings over the period 1970-2010 (Palmer and Cooper 2013). During this period, total heat loss from UK dwellings and heat loss from windows have both reduced by almost a third (DECC 2013). These reductions are due to improvements in the building envelope and specifically for windows are due to double-glazing and improved frame constructions. Figure 2 shows that despite these improvements, the heat loss from windows is a significant contributor of one fifth of total heat loss from UK dwellings.

Figure 2 Total Dwelling Heat Loss and Heat Loss from Windows 1970 – 2008 (DECC 2013)

1.2 Use of Curtains

There is little published literature with regards to the use of curtains in UK homes. This suggests a gap in knowledge of how curtains are used and the implications and opportunities for energy savings.

1.3 Previous Studies of Window Covering Thermal Performance

There are alternatives to replacing single-glazing with double-glazed units, such as installing secondary glazing. These methods are specifically designed to provide greater protection from the elements and reduce heat transfer through windows. Secondary glazing ranges from thin films that are stretched or shrunk across windows to framed glass units. Although the R-value of secondary glazed windows can be improved by 130-290% compared to single glazing (Smith et al. 2012), these units can be expensive, difficult to install and can restrict the use of the windows.

Unlike secondary glazing, curtains and blinds are very widely used in homes and very little is known about the energy-saving benefits. A number of laboratory-based studies have been carried out to assess the thermal performance of individual window coverings. Baker (2008) identified that energy savings can be achieved with the use of curtains and other window covering systems, ranging from 41-62% while Garber-Slaght and Craven (2012) suggested savings of 24-38% were achievable. Table 1 presents a summary of heat transfer reductions suggested by these previous studies as well as the methods used.

Table 1 Comparison of results from previous studies

As shown in Table 1, there was a range of results for similar coverings. For example, Lunde and Lindley (1988) established a saving of 3.8-9.5% for curtains, while Baker (2008) suggested a 38% reduction in heat transfer. These discrepancies could be explained by variations between test set ups and choice of materials, although this is difficult to establish directly from the literature.

Feather (1980) concluded that substantial savings can be made by using different types of curtain. However, the driving factor was not the actual curtain weight or type, although this was important, but how well the blind was fixed at the perimeter. This fixing creates a layer of stationary air that adds to the insulative effect of the window covering. The way in which a curtain is fitted to the window will affect the amount of heat transferred, with greater levels of airtightness providing better results. The effect of this layer of air is dependent on its width, with a wider air gap providing an increased R-value of the window and thus a decrease in the U-value (Garber-Slaght and Craven 2012; K. Nicol 1986; Lunde and Lindley 1988; Ruyssevelt & Littler 1984).

Creating a layer of stationary air is difficult to achieve in practice due to most window coverings, such as curtains and blinds, not being sealed directly to the frame. Table 2 shows the difference in U-values between sealed edge curtains and those with a loose edge. This illustrates an improved U-value of around 19% with a sealed edged curtain rather than a loose edged curtain on a single glazed window.

Table 2 Comparison between loose fitting curtains and sealed edge curtains (Fang 2001)

In addition to the differences identified between fixed and loose window coverings, the type of window covering can have a significant effect of heat loss from windows and the location in which the coverings are installed. For example, Wood et al. (2009) found that kitchen and bathroom blinds resulted in savings of 12% and 29%.

Woodson et al (1986) investigated the thermal resistance of multi-layered window treatments and tested 48 experimental treatments with respect to the four variables of stitching pattern, face fabric, batting material and number of batting layers. The most significant factor was found to be the stitching pattern holding the layers together, with the least number of perforations in the window treatment performing significantly better than those patterns with more stitches.

Table 3 sets out the R-values of internal blinds and curtains given in CIBSE Guide A (2015) Table 3.27 based on data from Wood et al. (2009). From these values the thermal transmittance (U-values) of windows with curtains or blinds was calculated using the formula:

$$U_{wb}' = [(1/U_w)+R_{bi}]^{-1} \qquad \textbf{Equation 1}$$

Where U_{wb}' is the thermal transmittance of the window corrected for an internal blind or curtain (W/m^2K), U_w is the thermal transmittance of the window (W/m^2K) and R_{bi} is the thermal resistance of the internal blind or curtain (m^2K/W). (Formula 3.37 from CIBSE Guide A 2015).

The conversion to U-values has been undertaken to allow direct comparison with previous findings. From these, the impact of glazing and fabric window coverings can be observed. This provides a useful baseline for the Energy House study and identifies the impact of a wide range of window coverings in terms of their thermal resistance.

Table 3 R- and U-values for Window Coverings given in CIBSE Guide A (2015) based on Wood et al. (2009)

Previous research has been carried out under controlled conditions in environmental chambers or in heat flow meter/hot box settings. While this provides a degree of accuracy, the actual energy savings cannot be compared to field based scenarios as the dynamic of central heating systems and varying room layouts is omitted, with the focus being on the performance of the individual element rather than the element within context. Other trials carried out in the field lack the degree of control and accuracy that the chamber scenarios posses. It is for this reason that a full-scale test facility was chosen to carry out a series of tests on window coverings. This facility provides the accuracy of an environmental chamber but also has a heating system, set point and dynamic variability of a real world scenario.

2. Methodology

The research within the Salford Energy House comprised two elements. The first range of tests mimic the steady-state work carried out in environmental chambers and hot boxes, such as Wood et al (2009). The second aspect of the research is to replicate a *real world* whole house test environment, which takes into consideration issues such as emitter locations and airflow within rooms. This presents a more realistic representation of the effect of window coverings in situ, as chamber or hot-box tests do not account for the differences between experimental laboratory tests and a whole house context.

2.1 Salford Energy House Test Facility

The tests were conducted at the University of Salford's Energy House. The Energy House is a full scale replica of a typical 1910 terraced property from the UK that has been through reasonable modifications, such as heating upgrades. At the time of the validation exercise the building was uninsulated throughout, with the exception of 100mm insulation at ceiling joist level. The windows in the property are single glazed sliding sash type windows reconstructed to meet the airtightness and thermal transmittance characteristics of the dwelling (Ji et al. 2014).

The Salford Energy House is fully furnished throughout as an occupied two bedroom dwelling. Although this may influence air movement and heat transfer, it does more closely resemble real homes.

2.2 Experimental Design – Test 1

Test 1 consisted of a steady state analysis of heat transfer across the windows using an elevated and constant temperature provided by electrical resistance heaters in the centre of each occupied room. This provided a steady testing environment to calculate changes in thermal transmittance (U value) across the centre of the glazing panel. The internal set point for all areas was 25°C and the chamber temperature was 5°C, with a variance of +/-0.5°C. This allows a Δt of 20°C to be achieved. The temperatures were kept constant throughout the test, which lasted 72 hours in line with the requirements of ISO9869 (ISO 1994). This approach can be seen to replicate hot-box or environmental chamber testing, where heat is spread evenly across the element.

2.3 Experimental Design - Test 2

In Test 2 the central heating system in the house was used to heat the building. This helped build a picture of the actual heat loss through the window pane under standard heating conditions, taking into account the placement of radiators under windows and the increase in heat flow that this can lead to compared to a steady state electrical heating test, as conducted under Test 1.

The gas central heating was used under the following conditions. The Energy House environmental chamber was set at 5°C, with a variance of +/- 0.5°C. This figure is chosen as a UK average winter time temperature (given as 4.9°C for the UK in the month of February (BRE 2012)). The setpoints within the house i.e. the internal thermostat settings, were set to 21°C in the Living Room and between 18-19°C in all other areas as identified in SAP. Each room operated on its own heating control, using either a wall thermostat in the living and a thermostatic radiator valve in all other rooms, a common pattern for many UK homes (DCLG 2015). The internal doors remained closed for the duration of the test to remove the complexity of warm air moving from room to room. It is important to note that some radiators are placed under windows, as is standard for a dwelling of this age and design, and some are placed on external walls. Emitter locations in relation to the window are identified in Table 4.

Table 4 Experimental Matrix setting out window covering type and position in relation to radiator

2.4 Instrumentation for U-value Measurement

The purpose of this experiment was to measure heat transfer across the window pane with various window coverings, allowing a U-value to be calculated. This was achieved by using heat flux apparatus that complies with the standards laid down in ISO9869 (ISO 1994).

The system comprised heat flux transducers (HFT) and temperature sensors. One HFT was fixed to the centre of the pane for each window in the house. Air temperature sensors were fixed at the centre of each room, and adjacent to the window in the chamber. The HFT were Hukseflux HPF-01. The air temperature sensors used were Papouch TH2E Semiconductor based network-attached sensors.

Although ISO9869 does not specify an exact location of temperature measurement, during these experiments the ambient temperature was measured in the centre of the room. Heaters were placed far enough away from the sensors so as to not directly affect the readings and spot measurements were taken before testing began to ensure the air temperature was more or less homogeneous.

Placing the heaters closer to the window would affect the delta T, but the test was a comparison between open and closed curtains only and all test conditions remained exactly the same for both cases.

2.5 Accuracy and Uncertainty

Three variables were measured during this experiment (one of each for each window):

- Hukseflux HFP01 Heat Flux in Watts (Q) Accurate to within 5% (Hukseflux 2000)
- Internal Air (C) Accurate to within 0.4°C (Papouch 2013)
- External Air (C) Accurate to within 0.4°C(Papouch 2013)

Attempts have previously been made to define a standardised error/uncertainty figure with respect to thermal transmission. The international standard for measuring thermal transmission in building elements defines this to be between +/-14-28% of the thermal transmittance (U-value) (ISO 1994). Baker (2009) favours a statistical error analysis in his paper on a similar series of tests, this gives an uncertainty for the U value of ±6.3% under these test conditions. Therefore it will be this figure rather than the ISO figure that will be used due to the suitability to environmental chamber experiments. For field trials this is less appropriate and the ISO figure should be used. For heat transfer through the element the standard figure from the manufacturer is ±5% (Hukseflux 2000). This figure was used for the heat loss and is applicable to both field and chamber.

As described by Baker (2013), each measured parameter has associated uncertainties and in order to determine the effect these have on the final U-value, the following equation was used:

$$Err\ C = \sqrt{(U - U_{errQ})^2 + (U - U_{errTi})^2(U - U_{errTe})^2 + (sd)^2}$$

Equation 2

Where Err C is the overall uncertainty of the U-value estimate and U_{errQ}, U_{errTi} and U_{errTe} are the U-values calculated by applying the errors due to the measured values for heat flux, internal temperature and external temperature.

2.6 Calculation method

The experiments were conducted under steady state conditions, and although there were slight variances in temperature due to the gas central heating, the electrical system provided a more homogenous temperature within the property. Therefore a steady state calculation method was used. This method outputs the average heat flux over the complete testing session; this is deemed to be satisfactory due to the stable testing environments, both internally and chamber wide. The 24-hour monitoring period, which was used to calculate average heat flux, was started once the building had reached steady state.

2.7 Experimental matrix

The experiment comprised a whole house solution to window covering. Due to the lack of research with regards to window covering options, an assumed window covering choice was made for each room.

3. Results

3.1 Test 1 (Electrical heating in centre of room)

The first part of the experiment concentrated on gathering a baseline U value for the windows in a covered and uncovered situation, using electrical heating. The values, as laid out in Table 5, achieved were within measurement limits of expected values, as identified in SAP. These figures are subject to an experimental uncertainty of ±6.2%

The exception to this was the living room window, where the U-value appears to be higher than the remainder of the property. Previous work in the Energy House indicates that this may be attributed to the airflow in this part of the chamber being higher, as the bay protrudes into the airflow of the chamber environment whereas the other windows are recessed into the wall

Table 5 Electrical Heating Measured U-values

The differences between measured and modelled values are not significant and vary between positive and negative differences; the mean of these figures gives an overall difference of just 0.07 W/m^{2}K. It is not possible to say definitively whether the SAP model over or underestimates the savings offered by window coverings, due to the low number of measures and cases within the study. However, when the results are separated into curtains and blinds, it appears that there may be a significant underestimation in SAP on the potential energy savings from the use of blinds. When blinds are considered in isolation, SAP calculates a higher U-value by an average of 0.05 W/m^{2}K, and curtains generally a lower U-value on average of 0.07 W/m^{2}K. These figures are all within the boundaries of the measurement error, and whilst potentially indicative of an issue, are not conclusive. As can be seen in Figure 3, the HFT is significantly improved when the blind is used in the kitchen and the curtains are drawn in bedroom 1.

Figure 3. Graphs of heat flux and measured temperatures in the kitchen and bedroom 1, with and without window coverings when electric heating is used.

3.2 Test 2 (Building heated by wet central heating system)

The second test measured the heat transfer through the window in a typical home, using a standard gas wet central heating system. This allowed a greater concentration of heat to flow through the window depending on the location of the heat source in the room. It more closely reflects the actual heat loss that might be found in a normal domestic dwelling, where radiators are often placed below windows.

Figure 4. Graphs of heat flux and measured temperatures in the kitchen and bedroom 1 with and without window coverings when using gas central heating.

As can be seen from Figure 4, when using a gas central heating system there is greater fluctuation in measured temperatures. It is important to note that the two drops in HFT show the effect of closing the curtains and blinds at the beginning of the test and data from this period was not used for analysis.

Table 6 Gas Central Heating Measured HFT

Table 6 shows the measured HFT during the second test. Whilst the figures in tables 5 and 6 may seem relatively straightforward, the base line heat loss and the reductions in terms of energy transfer are significantly different across the array of windows. This is due to a number of variables affecting each window in each room.

The variables include the air temperature of the room, whilst the chamber maintains a standard 5°C the room temperatures have been set at 21°C in the living room and 18-19°C in all other areas. This will lead to a greater amount of heat flux through the living room. The distance from the heat source to the window also appears to have an impact, with some rooms having the radiator located directly underneath the window (living room and bathroom) and which have the highest heat loss rate when uncovered whereas other rooms (bedroom 1 and bedroom 2) have the lowest heat flux across the window, as the radiator is placed across the room from the window. The contradiction to this point is the kitchen, which has a relatively high heat loss but the radiator is located some way across the room. However the combination boiler is placed directly next to this window and will generate a higher rate of heat flux through the adjacent window.

The focus of the research was firstly to establish U-values for windows and their coverings. The second issue was to identify the differences in these values between homogenous heat distribution, as assumed by many steady state models such as SAP, and heterogeneous heat distribution as is more commonly found in buildings in situ.

The U-values under electrical heating, i.e. homogenous heat distribution throughout the property, compared closely with both previous studies and the assumptions within SAP. As seen in Table 7, the R-values are comparable with the assumed R-values of SAP, taking into consideration measurement error.

Table 7 Comparison between SAP and measured R-values in Test 1

When the resulting U-values from the electric heating test are compared with those presented in Table from CIBSE Guide A (2015) and Woods et al. (2009), it can be seen that there were differences. Some of these differences may be accredited to differences in the exact types of window coverings specified by Guide A, for instance, although the curtains in the Salford Energy House are lined they may not be considered to be *heavy* curtains. As can be seen from Table 8, the differences between actual and expected U-values were greatest in the rooms that had curtains rather than blinds.

Table 8 Comparison between expected and actual U-values in Test 1

Air spaces are a significant contributing factor to the overall U-value of the window when considering savings made by curtains (Fang 2001; Wood et al. 2009). This research confirms the standard method of calculating a U-value where curtains are concerned, which stipulates that a standard air layer should be used to make the calculation. This research found that this was not required in curtains that did not make any seal to the window reveal. For steady state heating when using curtains the effect on the U-value of the window is the only addition of an extra layer of resistance provided by the curtain.

4. Discussion

A significant conclusion from this work is that steady state homogenous air temperature models may not accurately reflect the potential savings that can be achieved with window coverings. It is also clear that in *real world* situations where radiators are placed at different locations in each room, the opportunity to make energy savings regardless of covering type are at the locations with the greatest proximity to emitters, either directly underneath or adjacent to the windows. This has implications for steady state models such as SAP where savings are generated using an average mean room temperature.

Further to energy efficiency, thermal comfort is clearly a significant issue in domestic dwellings (Lunde and Lindley 1988). Curtains can affect the rate of convection around a room and prevent some air infiltration and exfiltration, in particular when used with *leaky* windows such as the sliding sash windows at the Energy House. More research is needed on how the curtains in a room can affect the thermal comfort levels in a room, and how this may be improved.

Another important factor to consider is that single glazing also poses a significant risk to surface condensation in buildings with high humidity levels due to the high conductivity levels and the consequential low surface temperatures. The addition of an extra layer of resistance to the internal face of the window element will have the effect of lowering the surface temperature considerably during the heating season; this could increase the risk of condensation in these areas. Models such as WUFI can be used to predict and help mitigate these situations (May and Sanders 2014).

5. Conclusions

This study set out to establish the impact of window covering son a single glazed sash window within a whole house context under controlled conditions. The data from Test 1, which was under homogenous electrically heated conditions suggest a broad agreement with other studies carried out under controlled conditions. Test 2, however, indicates that much higher rates of heat loss occur when the heating emitter is adjacent to the window, as is common in UK domestic heating systems. This means that steady state models such as SAP may not accurately represent the actual heat loss through the window element, whereas more 3D dynamic simulation modelling may address this issue by providing a greater level of accuracy. The convective nature of central heating systems means that placing heating emitters under windows improves the convective flow of heat through a room, this will lead to greater heat loss through covered window elements. However, this does have implications for their performance and how they are represented in models. Potentially, this could be used to identify the greater heat losses of these windows when replacement windows are being installed.

This work is the first stage of a series of studies that will be carried out on window coverings by the Salford Energy House team. This study provides baseline data and methodological approaches for further work with regards to airtightness improvements offered by window coverings through the reduction of drafts, thermal comfort issues based operative temperature readings, dynamic modelling of energy and commensurate costs savings of window coverings and heat up and cool down times of rooms with and without window coverings. Additionally, these are baseline steady state tests. It is felt that undertaking more dynamic testing and modelling could provide a more detailed insight into longer term data for energy savings for this type on intervention.

Appendix A (Photographs of Room Layouts)

Figure 5 Living room with lined curtains and radiator directly beneath window

Figure 6 Kitchen with roller blind and radiator not in close proximity to window

Figure 7 Bedroom 2 with lined curtains and radiator not in close proximity to window

Figure 8 Bedroom 1 with lined curtains and radiator on opposite wall

Figure 9 Bathroom with roller blind and radiator directly beneath window

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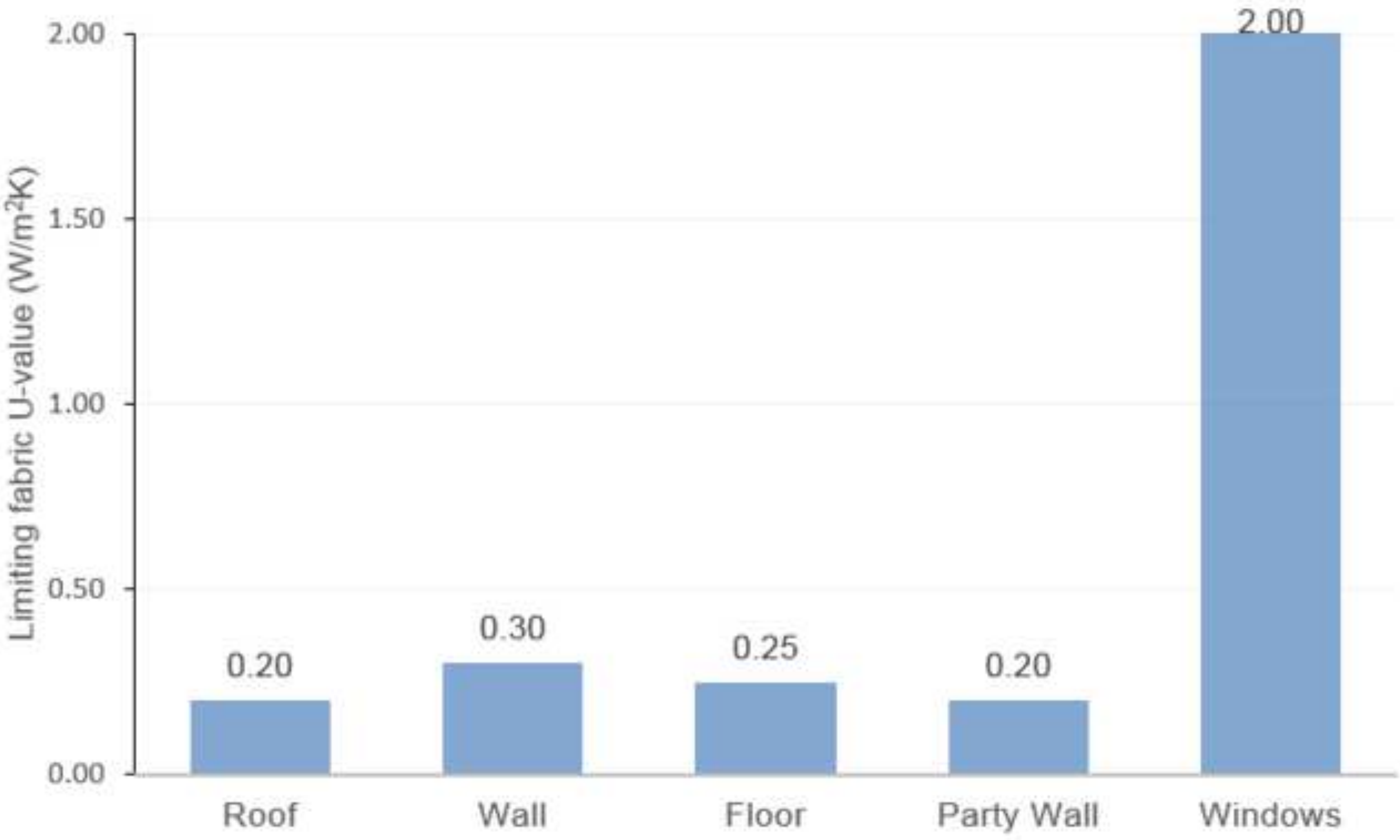
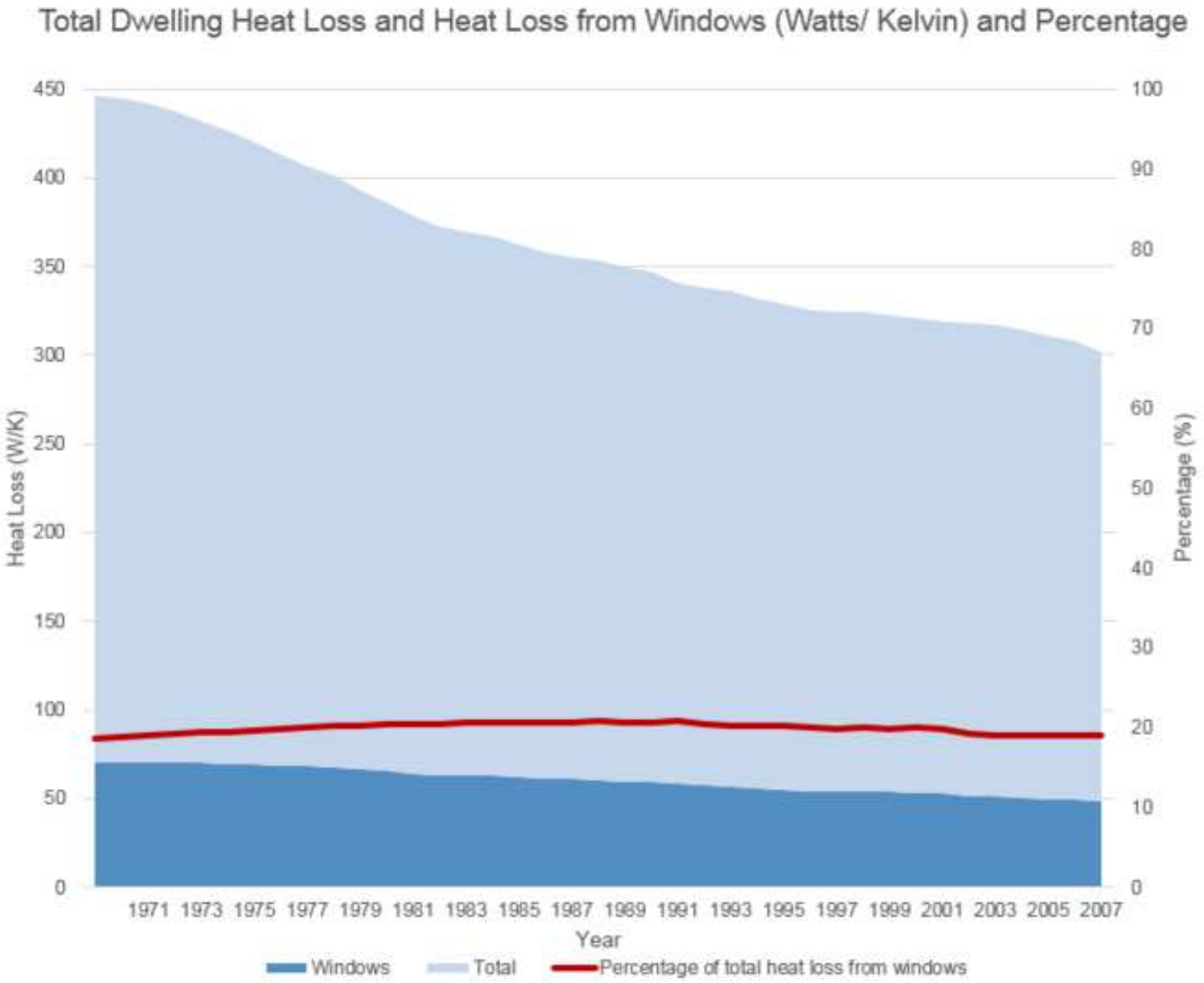
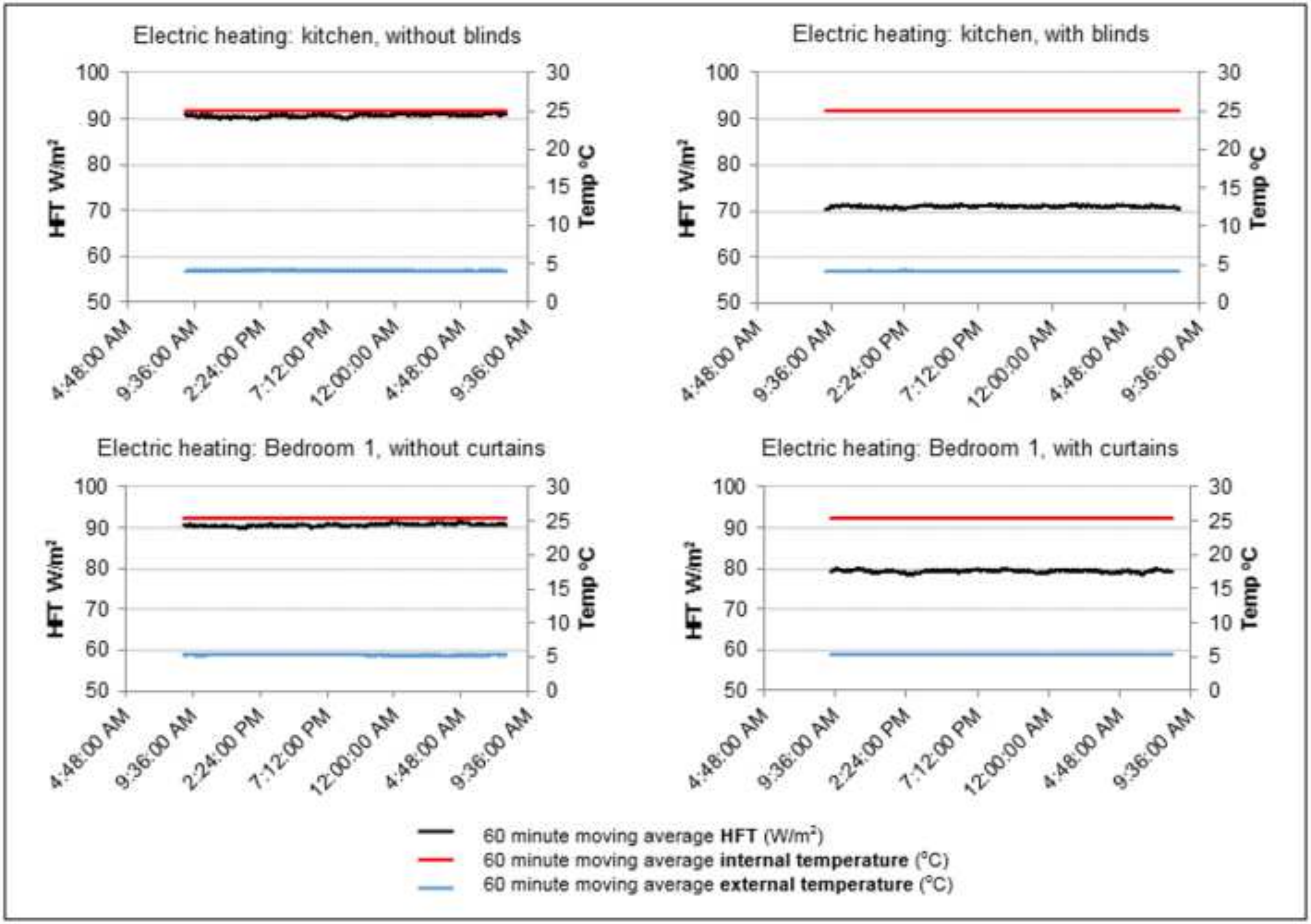

Limiting fabric U-value (W/m2K)
2.00
1.50
1.00
0.50
0.00
0.20
0.30
0.25
0.20
2.00
Roof
Wall
Floor
Party Wall
Windows


Total Dwelling Heat Loss and Heat Loss from Windows (Watts/ Kelvin) and Percentage
Heat Loss (W/K)
450
400
350
300
250
200
150
100
50
0
Percentage (%)
100
90
80
70
60
50
40
30
20
10
0
1971 1973 1975 1977 1979 1981 1983 1985 1987 1989 1991 1993 1995 1997 1999 2001 2003 2005 2007
Year
Windows
Total
Percentage of total heat loss from windows


Electric heating: kitchen, without blinds
Electric heating: kitchen, with blinds
Electric heating: Bedroom 1, without curtains
Electric heating: Bedroom 1, with curtains
HFT W/m²
Temp °C
100
90
80
70
60
50
30
25
20
15
10
5
0
4:48:00 AM
9:36:00 AM
2:24:00 PM
7:12:00 PM
12:00:00 AM
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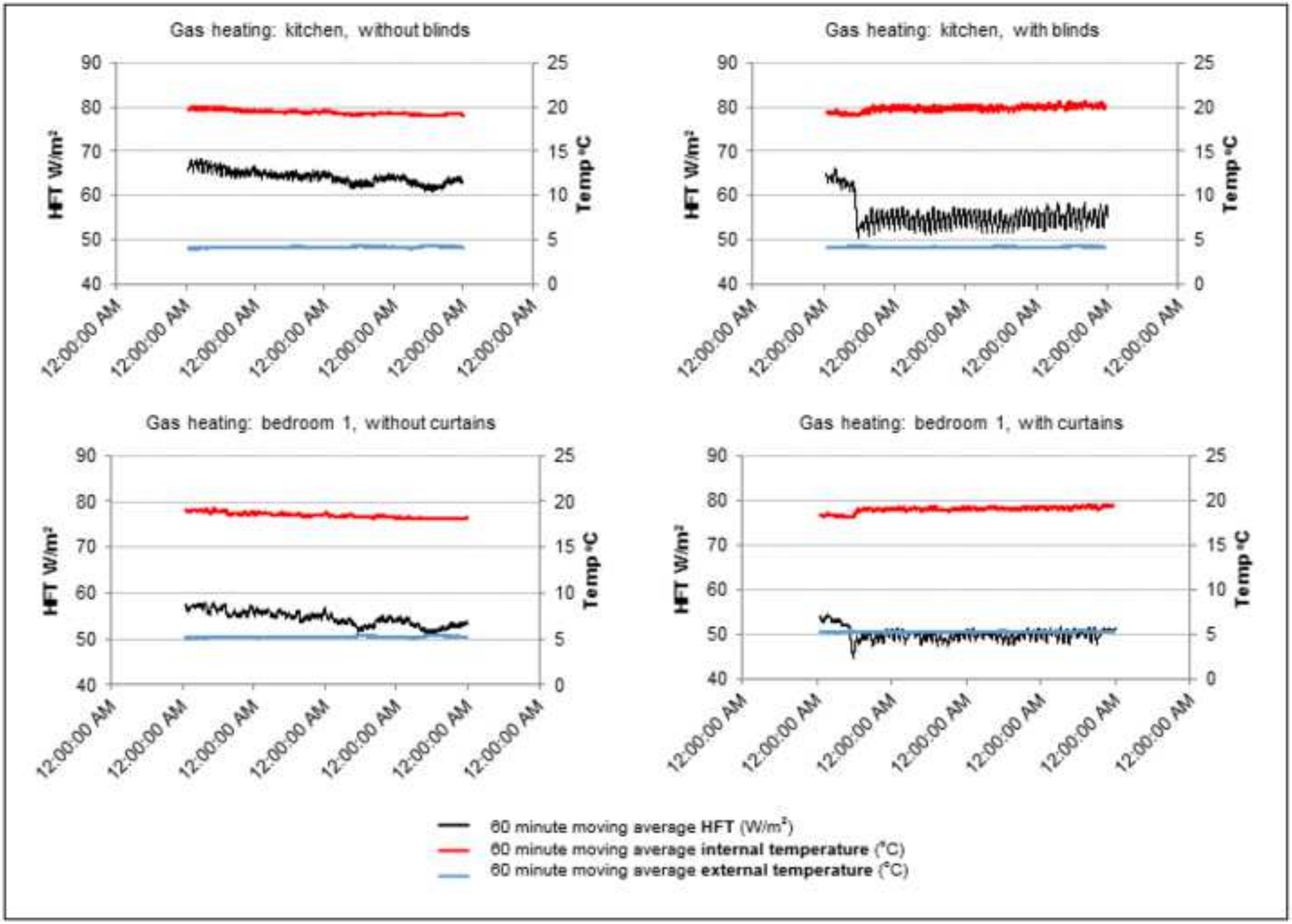
60 minute moving average HFT (W/m²)
60 minute moving average internal temperature (°C)
60 minute moving average external temperature (°C)


Gas heating: kitchen, without blinds
Gas heating: kitchen, with blinds
Gas heating: bedroom 1, without curtains
Gas heating: bedroom 1, with curtains
HFT W/m²
Temp °C
90
80
70
60
50
40
25
20
15
10
5
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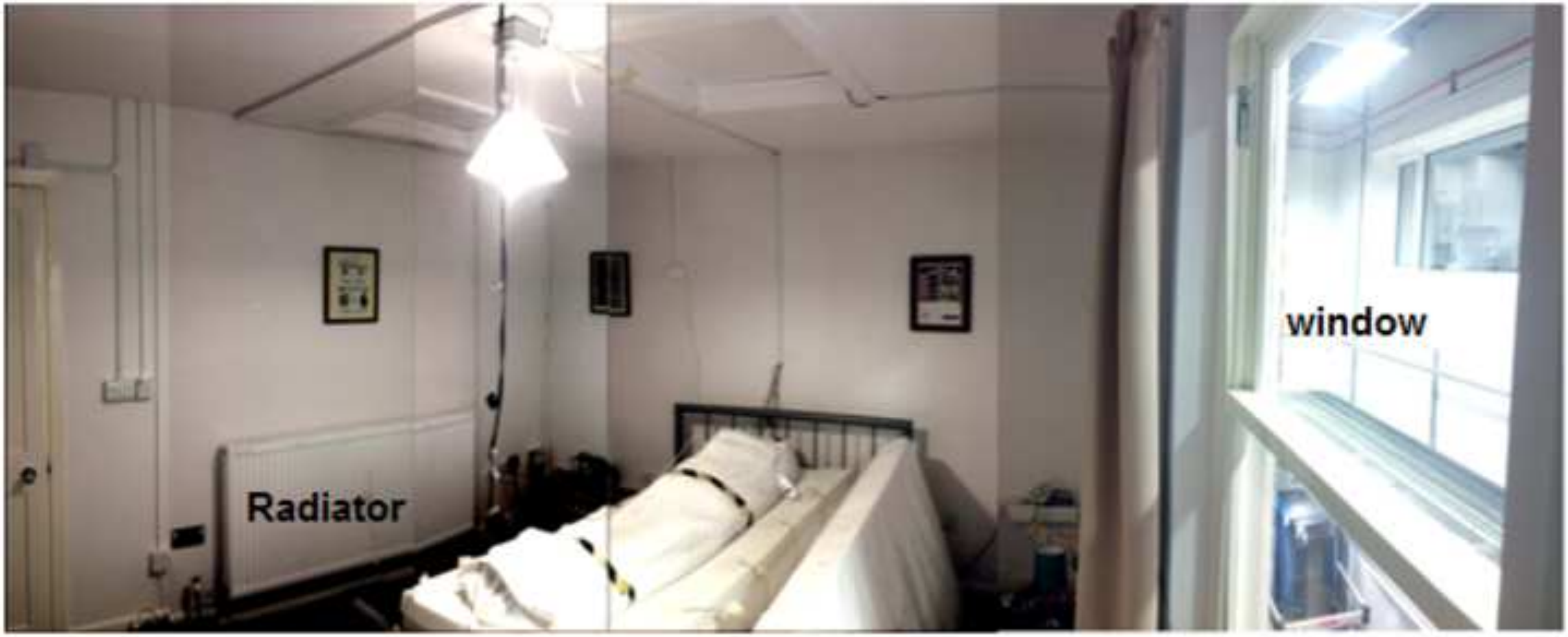
12:00:00 AM
60 minute moving average HFT (W/m²)
60 minute moving average internal temperature (°C)
60 minute moving average external temperature (°C)


Fire exit


Radiator
window

Table

Authors	**Window Covering**	**% Reduction in Heat Transfer**	**Method**
(Lunde & Lindley 1988)	Various curtain materials	3.8-9.5%	Hotbox Environment (controlled)
	Roller Blinds	6.3-38%	
(Garber-Slaght and Craven 2012)	Insulated blinds	15%	In Situ Testing (uncontrolled winter conditions)
	Curtains	38%	
(Baker 2008)	Heavy curtains	39%	Hotbox Environment (controlled)
	Plain Roller Blind	37%	
	Insulating Blind	68%	

Table

Window Type	**U-value (W/m^{2}K)**		**Percentage Difference**
	Sealed Edge Curtain	Loose Edge Curtain	
Single Glazed	3.66	4.44	19.26%
Double Glazed	2.16	2.58	17.72%

Table

Description	Thermal resistance (R-value) of covering layer (m^2K/W)	Thermal transmittance (U-value) of covering layer (W/m^2K)	Thermal transmittance (U-value) of window with curtains or blinds (W/m^2K)
Single Glazing Only	0.19	-	5.16
Roller blind	0.14	7.14	3.03
Heavy curtains	0.16	6.25	2.86
Secondary glazing	0.18	5.55	2.70
Honeycomb insulated blind	0.24	4.17	2.33
Roller blind with low emissivity film on outside face	0.3	3.33	2.04
Low emissivity secondary glazing	0.32	3.13	1.96
Well-fitting shutters	0.33	3.03	1.92
Low emissivity secondary glazing and shutters	0.39	2.56	1.72

Room	**Window Covering**	**Window Covering Material**	**Position of Window in Relation to Radiator**	**In-use Window Covering Detail**
Living Room	Lined Curtain	Cotton lining, synthetic face material	Above radiator	Curtains tucked behind radiator
Kitchen	Roller Blind	Polyester	Not adjacent to radiator	Bottom of blind rests on windowsill
Bedroom 1	Lined Curtain	Cotton lining, synthetic face material	Not adjacent to radiator	Curtains drape 25cm below windowsill
Bedroom 2	Lined Curtain	Cotton lining, synthetic face material	Not adjacent to radiator	Curtains drape 15cm below windowsill
Bathroom	Roller Blind	Polyester	Above radiator	Bottom of blind rests on windowsill

Table

	Living Room	**Kitchen Blind**	**Bedroom 1**	**Bedroom 2**	**Bathroom Blind**
Without coverings U-value average over 24 hours (W/m^{2}K)	**5.10**	**4.32**	**4.50**	**4.45**	**4.43**
Overall uncertainty of U-value (W/m^{2}K)	0.29	0.25	0.26	0.26	0.25
Error (%)	5.77	5.74	5.76	5.73	5.74
With coverings average U-value over 24 hours (W/m^{2}K)	**4.13**	**3.40**	**3.93**	**3.96**	**3.49**
Overall uncertainty of U-value (W/m^{2}K)	0.24	0.19	0.23	0.23	0.20
Error (%)	5.76	5.74	5.76	5.73	5.74
Savings (W/m^{2}K)	**0.97**	**0.93**	**0.57**	**0.49**	**0.93**
Savings (%)	**23.42**	**27.33**	**14.46**	**12.37**	**26.71**

Table

	Living Room	**Kitchen Blind**	**Bedroom 1**	**Bedroom 2**	**Bathroom Blind**
Without coverings average HFT over 24 hours (W/m^2)	96.42	62.91	52.81	62.01	63.11
With coverings average HFT over 24 hours (W/m^2)	69.66	55.15	50.20	55.65	44.72
Savings (W/m^2)	26.76	7.76	2.61	6.36	18.39
Savings (%)	27.75	12.34	4.94	10.26	29.14

Table

	Living Room	**Kitchen**	**Bedroom 1**	**Bedroom 2**	**Bathroom Blind**
R-value without curtains average over 24 hr (m^2K/W)	0.20±0.01	0.23±0.01	0.22±0.01	0.22±0.01	0.23±0.01
R-value with curtains average over 24 hr (m^2K/W)	0.24±0.01	0.29±0.02	0.25±0.02	0.25±0.02	0.29±0.02
Measured Delta R-value (m^2K/W)	**0.05**±0.003	**0.06**±0.004	**0.03**±0.002	**0.03**±0.002	**0.06**±0.004
Predicted R-values with coverings according to SAP 2012 (m^2K/W)	0.28	0.33	0.29	0.29	0.33
Difference between SAP and measured R-value	0.01	0.02	-0.01	-0.01	0.02

Table

	Living Room	**Kitchen Blind**	**Bedroom 1**	**Bedroom 2**	**Bathroom Blind**
Without coverings U-value average over 24 hours (W/m^{2}K)	**5.10**	**4.32**	**4.50**	**4.45**	**4.43**
Comparison with expected U-value (from Table 3, 5.16W/m^{2}K for single glazing only) Difference	-0.06	-0.84	-0.66	-0.71	-0.73
With coverings average U-value over 24 hours (W/m^{2}K)	**4.13**	**3.40**	**3.93**	**3.96**	**3.49**
Comparison with expected U-values (from Table 3, 2.86W/m^{2}K for heavy curtains and 3.03W/m^{2}K for roller blinds) Difference	+1.27	+0.37	+1.07	+1.10	+0.46

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Research paper

The variability of UK domestic energy assessments

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ABSTRACT

The 2008 Climate Change Act has committed the UK to reduce carbon emissions by 80 per cent in 2050 from 1990 levels. Key to achieving this is a focus on reducing carbon emissions in residential property, where more than a quarter of the nation's carbon dioxide is emitted. The assessment of dwellings is an essential part of this process and this paper investigates the role of the assessor and the various energy models as applied in the UK. Within this context, the authors consider the building energy modelling system that is in place for reporting carbon reductions, with a focus on the role of assessors. In doing this, the authors will simulate errors in data collection and input, and analyse their ramifications for building performance and the incentive systems in the UK. The paper closes by considering how the problem may be *further investigated to better understand the linkages between policy, knowledge and performance analysis in UK domestic properties.*

Keywords: energy efficiency, residential, SAP, RdSAP, DEA

INTRODUCTION

Issues of climate change have brought the issue of energy efficiency of domestic properties to the top of the international policy agenda. The European Union has implemented policies, such as the Energy Performance of Buildings Directive,[1] which have related performance targets that have cascaded through to individual member states. In the UK, where more than a quarter of total carbon emissions are from residential buildings,[2] there is an obvious need to tackle this sector if the 2008 Climate Change Act's binding target of reducing carbon emissions by 80 per cent in 2050 from a 1990 baseline is to be achieved. The UK's residential building stock is much older than stock in many developed countries. Approximately 40 per cent of buildings were constructed prior to 1944.[3] Furthermore, it is estimated that over 75 per cent of buildings in use today will still be standing in 2050.[4]

Increasing the energy efficiency of the nation's existing building stock may, therefore, be considered an essential part of reducing the energy consumption of the domestic building stock).[5] A central part of this process is a robust system for the calculation of emissions from both new and existing residential buildings. The European Performance of Buildings Directive (EPBD) requires each member state to have a National Calculation Methodology (NCM) in place to assess the energy use and carbon dioxide emissions of the nation's housing stock. Furthermore, there is a requirement to have a plan in place to reduce the emissions of both new build and existing homes. This paper considers the schemes that have been put in place to address energy consumption in the domestic sector's existing stock, identified as the 'retrofit' agenda.[6] It considers the role of the modelling tools that are available to assessors and the implications of the role of assumptions and data collection errors in assessing the performance of the existing stock. It also considers some of the implications for the decision-making in terms of identified improvements and performance.

PREVIOUS ENERGY SAVING SCHEMES

There have been a wide range of policies that impact domestic energy consumption reaching back to the first oil crises in the 1970s).[7] However, this paper will look at more recent policy, which is directly focused on the existing domestic building stock, covering the Green Deal, ECO and its most recent predecessors CERT and CESP. It should be noted that there are a number of other policies that had a direct impact on the energy efficiency of the housing stock, such as Decent Homes for social housing),[8] which affected 1.4 million homes,[9] and Warm Front,[10] which led to more than 2.3 million domestic property upgrades[11] However, these schemes were not directly underpinned by performance data of energy or carbon savings during the decision-making process, and are therefore outside the scope of this study.

The most recent incarnation of the Government's energy efficiency schemes is the Energy Company Obligation (ECO)[12] It is worthwhile to look briefly at the last supplier obligations schemes that the Government delivered, supported by the Office of Gas and Electricity Markets (Ofgem), a UK Government department and an independent National Regulatory Authority. It is the latest in a series of supplier obligation schemes that have underpinned much of the UK's energy policy in the sector.[13]

These supplier obligations were the Carbon Emissions Reduction Target (CERT from April 2008), and the Community Energy Saving Programme (CESP from April 2009), both of which expired in December 2012.[14] For CESP, the UK Department of Energy and Climate Change (DECC) set an overall carbon emissions reduction target of 19.25 million tonnes of carbon dioxide (Mt CO_2). This was to be met by requiring gas and electricity suppliers and electricity generators to deliver energy saving measures to domestic consumers in specific low-income areas. This obligation was placed on all licensed gas and electricity suppliers that had at least 50,000 domestic customers and all licensed electricity generators that had generated on average 10 TWh/yr or more over a specified three-year period.

CESP was designed to promote a 'whole house' approach, treating the property as a whole system by considering the interrelationship of improvements[15] and to treat as many properties as possible in defined geographical areas that were selected using the Indices of Multiple Deprivation (IMD) in England, Scotland and Wales. In England, the lowest 10 per cent of areas and in Scotland and Wales, the lowest 15 per cent of areas qualified. Consequently, CESP contributed to the Government's Fuel Poverty Strategy of the time.[16] Energy companies achieved 16.31 Mt CO_2 of the 19.25 Mt CO_2 target, or approximately 85% of target.[14]

For CERT, gas and electricity suppliers that generated power above a certain pre-designated level (of 10 TWh/yr or more over a three-year period), had to achieve targets for reducing carbon emissions within domestic properties.[17] For this scheme, the targets were much higher: an overall target of 293 Mt CO_2 was to be achieved. This was broken down into subsections, with 40 per cent of this to be within a 'priority group' (people over 70 and on certain qualifying benefits), 16.2 million tonnes of carbon dioxide savings designated to those on qualifying benefits (sometimes referred to as the 'Affordable Warmth' group, together with the over 70s above), and 73.4 million tonnes of CO_2 designated to professionally installed insulation measures. A total saving of 296.9 Mt CO_2 was made by the energy companies, achieved against the overall target of 293 Mt CO_2.[14]

The carbon saved under this scheme was done saved in a different way to the current ECO scheme, without measuring savings for each individual property. 'Deemed' carbon saving scores were applied to properties,[18] where measures were installed. For example, a three-bedroom, semi-detached house of either 'small', 'medium' or 'large' size, having loft insulation applied, might be deemed to save 8, 10, or 12 tonnes of carbon respectively, and the utility company would report it as such. This raised a number of issues, as the deemed scores incentivised installers to aim for more straightforward measures,[18] such as cavity wall insulation to regularly shaped semi-detached and detached houses in suburban areas, as opposed to hard-to-access, hard-to-treat cavity walls in inner-city areas).[19] Similarly, flats and older, solid-walled terraced houses in inner city areas were also overlooked, also being considered difficult in comparison with those post-war suburban areas. The deemed scores took no account of geography throughout the UK,[18] meaning carbon saved from a three-bedroom, semi-detached house in the warmer South, for example, would result in the same nominal saving as an identical property with the same measure applied in a colder area in the North.

Rates for each deemed tonne of carbon were agreed between the utility company and installer, and would vary, mainly dependent on the progress made toward targets. This was a commercially led process, with only CERT and CESP *outputs* being carefully prescribed, and so further led to the easier measures being taken first. In this respect, cheaper measures would be targeted by installers, meaning a high level of cavity and loft insulation measures were taken up under these schemes at the expense of more expensive and technically complex/skilled measures such as internal/external wall insulation, heating upgrades or glazing.

These varying rates, dependent upon progress toward targets, presented difficulties for installing companies as the process led to large peaks and troughs in volumes of measures installed.[18] This meant large numbers of redundancies or rapid and poorly planned recruitment drives depending on demand. This potentially created issues for installation standards, with Ofgem reporting a 14 per cent failure rate in installation standards of technically monitored jobs throughout the scheme.

Reflecting on the previous schemes (CERT and CESP), it would seem that further progress at similar rates would be more costly and time-consuming to achieve, as the opportunities to install more straightforward measures, in easy-to-access properties, diminish, leaving technically complex, higher skilled and more expensive carbon gains left, such as hard-to-treat cavity walls, internal and external wall insulation measures, and heating upgrades/fuel switches, presenting potential difficulties for both policy-makers and the installation industry.

THE ENERGY COMPANY OBLIGATION

The Energy Company Obligation (ECO), started in January 2013, is the most recent incarnation of the supplier obligation, a major part of the Government's plan to reduce carbon emissions in the UK. The framework is broadly similar to that of the CERT and CESP schemes. The ECO scheme places three separate obligations on energy suppliers: the Carbon Emissions Reduction Obligation (CERO), the Carbon Saving Communities Obligation (CSCO) and the Home Heating Cost Reduction Obligation (HHCRO)[20] Each of these are met by installing measures that reduce carbon emissions, or energy bills in the case of 'Affordable Warmth' in the domestic residential sector. In the same way as CERT and CESP, the targets imposed on the energy companies are a reflection of their share of the market, and they are expected to meet these obligations by promoting and subsidising the measures.

Initially, the ECO scheme was set to run alongside the Green Deal, a scheme set aside from energy company obligations that was intended to increase uptake of energy efficient measures by providing a novel financing mechanism, in which the cost of installed measures were financed through a charge attached to a property's electricity meter.[21] As part of the Green Deal, a framework of quality assurance, advice and accreditation has been implemented through the PAS 2030[22] and the National Occupational Standards[23] with the aim of providing reassurance to prospective customers as regards quality and robustness of energy advice and installation. The initial concept was that more expensive Green Deal measures could be installed with the help of 'top-up' ECO funding, so that a notional 'golden rule' could be maintained, whereby repayments must not exceed the amount saved in efficiencies on household energy bills, even with the installation of more expensive measures such as solid-wall insulation or glazing. However, reductions in the level of ECO, and the relative failure of the Green Deal, has led to the Green Deal's withdrawal. From a policy perspective, the UK domestic energy efficiency position is under review, with the UK commissioning a report from Sir Peter Bonfield. At time of writing, this review had just commenced.

ECO's carbon targets are 27.8 Mt CO_2 over the initial period from January 2013 to March 2015.[12] These targets were initially apportioned as a 20.9 Mt CO_2 target under CERO, and 6.8 Mt CO_2 under CSCO, of which at least 15 per cent, or 1 Mt CO_2 must be delivered to rural households — the 'rural safeguard', thus ensuring that these more difficult-to-access areas are not wholly ignored, as was seen under CERT and CESP schemes. However, CERO targets were revised downwards from 20.9 Mt CO_2 to 14.0 Mt CO_2, after talks between energy companies and the Government seemed to end in agreement that the costs to achieve the initial target would be more expensive than initially anticipated. The HHCRO targets are independent of the carbon-saving targets, quantified as fuel cost savings, and a total reduction of lifetime notional space and water heating costs were set at £4.2 bn by March 2015. Ofgem's January 2015 compliance update points to reasonable progress toward these figures.[24]

Understanding this policy framework leads us to consider the models that underpin the metrics and assessment methods for upgrading properties. The Green Deal Assessment and the data models, which underpin measures approved by Ofgem and DECC, are largely driven by the BRE Domestic Energy Model (BREDEM) 'family' of energy models, which identify the performance of a property based on a range of characteristics of the dwelling.[25] While RdSAP particularly comes in for some criticism in terms of its accuracy, the models remain the regulatory standard that underpins domestic energy policy.[26]

ENERGY MODELLING

The current methods of assessing energy use within a dwelling are the Standard Assessment Procedure (SAP) and the Reduced Data version (RdSAP). SAP was developed by the Building Research Establishment (BRE) for the Department of the Environment in 1992, as a standardised tool to help deliver its energy efficiency policies. The SAP methodology is based on the BRE Domestic Energy Model (BREDEM), which provides a framework for calculating the energy consumption of dwellings. BREDEM was developed in the early part of the 1980s, as a single zone building physics model with averaged weather conditions over seasons[27] In 1986 this was further developed into a two-zone model (allowing for two internal temperature set points) with degree-day calculations used as a more accurate input of external conditions.[28] The development of the BREDEM tool is still ongoing, with the latest update being issued in 2012. However, many of the calculations and assumptions in BREDEM have been brought into RdSAP and SAP methodologies.

In 1994, SAP was cited in Part L of the Building Regulations as a means of assessing the energy efficiency of newly constructed dwellings. This involved a detailed audit of a property using architects plans, specifications for heating systems and materials. Reduced Data SAP (RdSAP), a non-intrusive inspection, was introduced in 2005, as a lower-cost method of assessing the energy performance of existing dwellings, with software-driven models providing assumed values for elements that are not always accessible after construction, such as floor depth, wall insulation type, and width of cavities. SAP and RdSAP, as well as BREDEM, are now the only tools used by Government to underpin the delivery of a number of key energy and environmental policy initiatives, such as Building Regulations and Energy Performance Certificates[29] SAP works by assessing how much energy a dwelling will consume when delivering a defined level of comfort and service provision. The assessment is based on standardised assumptions for occupancy and behaviour. This enables a like-for-like comparison of dwelling performance. Related factors, such as fuel costs and emissions of carbon dioxide (CO_2), can be determined from the assessment.

The resultant Energy Performance Certificate (EPC), created using SAP and RdSAP, presents the householder with an overview of dwelling energy efficiency, including dwelling fabric and anticipated energy use, generating a SAP and Energy Impact (EI) score. The EPC created using SAP, and those created using RdSAP, are presented in the same way. SAP quantifies a dwelling's performance in terms of: energy use per unit floor area, a fuel-cost-based energy efficiency rating (the SAP rating) and emissions of CO_2 (the Environmental Impact rating). These indicators of performance are based on estimates of annual energy consumption for the provision of space heating, domestic hot water, lighting and ventilation. Other SAP outputs include estimates of appliance energy use, the potential for overheating in summer and the resultant cooling load. Despite popular belief, SAP and RdSAP do not estimate building energy efficiency *per se* but instead attempt to estimate the cost-effectiveness of energy efficiency measures.

The use of RdSAP and SAP, within the ECO and Green Deal, began with the inception of these schemes in January 2013, some time after the creation of SAP and its subsequent acknowledgement by Government as the preferred tool for measuring dwelling energy performance. Its use under ECO as a carbon calculating tool may be considered a new use for SAP, and not one for which it was originally intended. This is in contrast to the preceding CERT and CESP schemes, as discussed earlier, where 'deemed' carbon scores were used.

The methodology is open to uncertainty issues,[30] particularly around the impact of the occupant,[31] and this led to the introduction of an occupancy assessment element for the Green Deal and in use factors to address issues associated with the performance gap).[32] However, the use of the EPC, underpinned, by RdSAP, has been seen to have a marked impact on the decision making of home owners engaging in retrofit,[33] showing the impact of the EPC process and output in decision-making. This makes the quality of data and the understanding of the role of assumptions important, not only at a national policy level, but also at the level of the consumer.

DOMESTIC ENERGY ASSESSORS (DEA), ACCREDITING BODIES AND AUDITS OF EPCS

The Domestic Energy Assessor is the competent individual responsible for the reporting of EPCs. The assessor must have undertaken training, passed a qualification, and become a member of an accrediting body recognised by the UK's Department for Communities and Local Government (DCLG). The qualification can be completed by a person with no previous experience of building assessment in five days at a cost of around £1,800 (2,400 Euro).[34]

The UK Department of Communities and Local Government details the role of the accrediting bodies (or 'schemes') and the role and responsibilities of the DEA.[35] In summary it states that

> The (D)EA shall act in a professional manner, as defined by the National Occupational Standards for Domestic Energy Assessors (p.32) and 'An (D)EA shall not undertake an EPC if the nature of the property is such that the (D)EA lacks the competence or knowledge to produce an accurate EPC for that property.' (p. 32)

DEAs should also undertake CPD, such as updating themselves on new software models. Accrediting bodies have a minimum requirement to check at least one EPC per quarter year (where a minimum of one EPC has been produced) and 1 per cent of an individual member's EPCs over a year. Depending on the number of EPCs produced by a DEA, the checks should be randomly selected by the accrediting body, which also has the option of 'targeting' further checks on an individual DEA where results from random checks seem to highlight a problem. However, the checks are based on photographic evidence and site notes rather than a physical visit, meaning that data could superficially appear to be correct, but in fact be incorrect, an issue identified by Kelly et al.[36] Work by the Zero Carbon Hub looked at variance of SAP as applied in new build housing and identified a wide variance between practitioners in terms of the difference between as built and as reported.[37] Given that full SAP assessors are generally trained to a higher standard, this does mean consideration should be made to the role of the RdSAP EPC model and its role in issues of performance gap.

RDSAP AND CARBON CALCULATING: SIMULATION OF VARIATIONS

This section of the paper considers how small variations in the data input might lead to changes in the reported values of a property's performance. This exercise should be considered theoretical, as detailed research into exact errors in RdSAP assessments and their frequency has not currently been undertaken. Two positions have been taken: the first is to identify the impact of common errors based on the experience of the authors in the field and the second considers the potential for the system to be 'gamed' to claim greater than possible carbon savings — a problem that is currently anecdotal within the industry, but worthy of consideration.

Developing a control property

A 'control property' has been identified to provide a benchmark, based on a common property type. This is a simple property: a 1950s semi-detached house, of traditional cavity construction, measuring 7.0 × 7.2 m = 50.4 m per floor, 101 m^2 overall, with no cavity insulation, 50 mm loft insulation, gas central heating from a modern, condensing combination boiler complete with make, model and model 'qualifier', which gives an accurate assessment of a boiler's efficiency which is sometimes not available, an important issue discussed later (see Figure 1). It has double-glazing, no secondary heating and no renewable energy sources or other outlier characteristics.

This paper will present the two key indicators on an EPC — the SAP score and the Environmental Impact score (EI), as well as annual carbon emissions from each drafted Energy Performance Certificate (EPC) to indicate the impact of errors or changes. The purpose of having a control property is to evaluate changes when measures are applied, precisely the way they would be if they were to be submitted as a claim for carbon funding

Figure 1: Gas boiler with 'qualifier'

under ECO. The control property's key attributes after inputting the data into a SAP model (software driven) are presented as follows:

- SAP D65
- EI D60
- 4.3 tonnes of CO_2 emitted per annum.

For the purpose of this investigation, the aim is to use a relatively simple illustrative model: loft insulation and cavity wall insulation measures are arguably the most simple and effective retrofit applications.[38] The resulting impact on the control property when the measures were applied are shown in Table 1.

We will now consider the differences that may be applied using the two identified approaches. The first is to consider human error, based on experience of common issues in practice and the second to address the potential influencing of the system for financial advantage.

Control property variations: Human error

Gathering site data through a survey of a property for an EPC can be challenging: physical restrictions can impede access to certain areas of a property, which can have an impact on the accuracy of measurements taken, as well as reducing visibility to some important areas. Simple issues such as poor weather conditions[39] or an overly attentive/inquisitive householder can contribute to rushed or inaccurate measuring and recording of data. The EPC inspection process is non-intrusive and a householder's furniture and possessions should not be moved. All this gives scope for human error. Even small errors can have a significant impact on the quality of the data, and hence the calculations that are driven by these inputs.

To exemplify this the control property was re-submitted with two key areas altered:

- a 5 per cent margin of error has been applied to the original measurement of the floor area and ceiling height (now 7.35 × 7.56 m = 55.57 m floor area, 2.52 m ceiling height, 22.26 m heat loss perimeter);
- an assumption has been made that the boiler model qualifier is obscured on this occasion, so the precise boiler model cannot be selected from the RdSAP software (see Figure 1). Instead, a generic 'condensing combination boiler' is selected under RdSAP's 'main heating code' to account for dwelling heating.

All other data inputs are identical to the original Control Property. The 'human error' EPC is shown in Table 2.

We can see that two relatively simple errors can make a significant difference to the performance of the individual improvements. A 20 per cent improvement in performance is gained for loft insulation and 21 per cent improvement in the impact of cavity wall in terms of carbon savings.

Control property variations: Maximising ECO

It is possible that DEAs may be incentivised to claim additional carbon savings for each prop-

Table 1: Control property, with insulation measures applied

Control property (Benchmark)	*Control property with loft insulation (300mm):*	*Control property with cavity wall insulation:*
SAP D65 EI D60 Carbon count 4.3 tonnes of CO_2	SAP D67 EI D63 Carbon count 4.0 tonnes CO_2	SAP C72 EI C69 Carbon count 3.3 tonnes CO_2

Table 2: Human error EPC

Human error EPC	*Human error EPC with loft insulation (300mm):*	*Human error EPC with cavity wall insulation:*
SAP D63 EI D56 5.1 tonnes CO_2	SAP D65 EI D58 4.8 tonnes CO_2	SAP C70 EI C66 4.0 tonnes CO_2

erty they assess under the ECO scheme — given that the more carbon claimed, the greater the financial return. Evidence of this can be considered anecdotal, however, if we consider that audits are based on photographic evidence and site notes adjustments might easily be made. To illustrate this, the human error EPC has been given two further amendments.

First, when inspecting a loft, it can be difficult to measure the depth of insulation very accurately. The difference between 50mm and 25 mm of quilt, especially when it may be decades old, compressed in places by items of storage, and affected by condensation or damp, can be very difficult to assess. It might be possible for even the most scrupulous DEA to record a 25 mm depth of insulation over a 50 mm depth, or a 75 mm depth over a 100 mm depth, and to provide seemingly robust photographic evidence in support of this. Indeed, there may well be a considerable range of depths available to record just from either side of the loft hatch — but this data makes a significant difference to the EPC outputs. Figure 2 illustrates this issue.

To reflect this, the next simulated error has been to reduce the loft insulation depth from the 50 mm recorded in the control property EPC and human error EPC, to 25 mm.

A second issue that may be used to influence the results is the fact that some householders may own small, portable heaters for localised heating or drying clothes, potentially in the belief that using just the one heater saves them money over using the central heating system (see Figure 3).

For the DEA, this represents a way to increase the carbon saving that the EPC will record when the insulation measure is applied. This is because the more inefficient the property is to begin with, the greater the carbon saving when the measure is applied. The electric 'panel or convector' heater is now recorded under secondary heating irrespective of frequency of use. The results of the EPC are shown in Table 3.

Figure 2: Examples of measuring insulation depth

Here we can see that the changes are even greater than for human error. Here the difference between the control property and the ECO maximising example are 30 per cent for loft insulation and 36 per cent for cavity wall insulation.

Complexity and assumptions for U-values

The model shown identifies how the outcomes of an EPC, based on relatively small errors or decision-making, can vary significantly. Another dimension that can add to inaccurate carbon counting, is the ability to combine SAP with RdSAP. For example, Wall U-values, a measure of the thermal conductivity of a building's elements, are assumed in RdSAP, with defaults applied based on the age and type of property selected earlier in the data set.

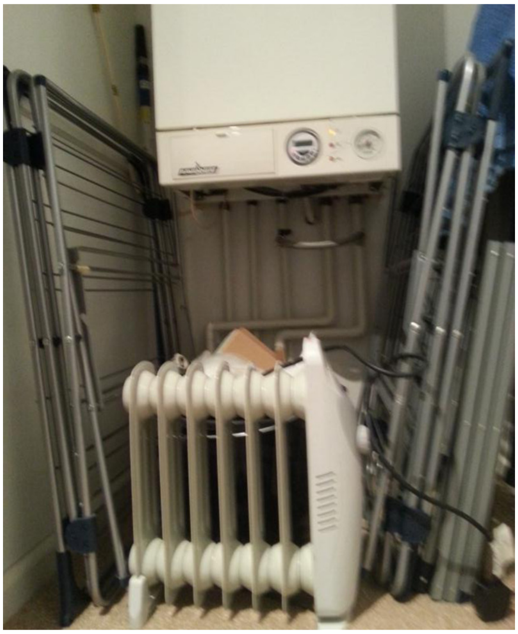


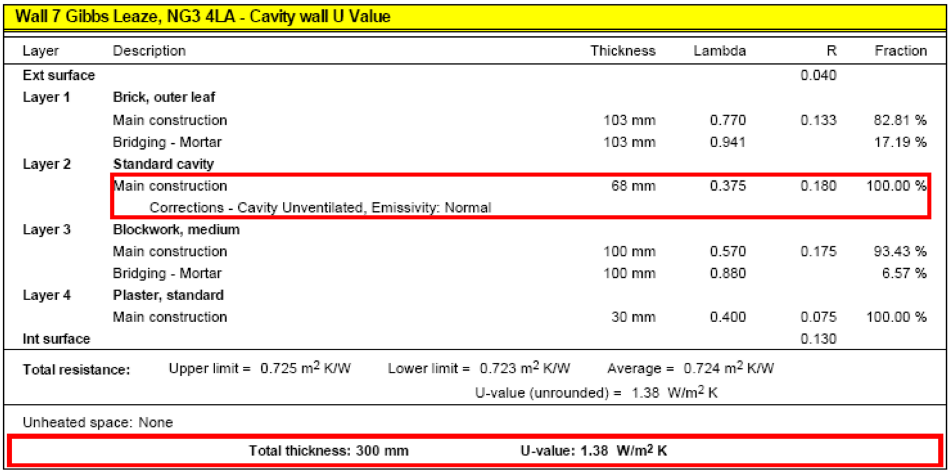
Figure 3: Electric convector heater stored in cupboard. Note also the boiler is older and does not have a qualifier available as per Figure 1

The DEA is able to record the constituent parts of the wall, independently of RdSAP. For example, brickwork 100 mm, cavity 60 mm, blockwork 100 mm, plasterboard with 20 mm adhesive 'dabs', with a plaster skim of 3 mm. In theory this would give a more accurate representation of the dwelling, however, DEAs are not necessarily trained in intrusive survey inspection, both having been previously identified as significant factors resulting in inaccurate surveys generally,[40] nor are they necessarily equipped with the understanding that is needed to provide an accurate description of the building materials identified. Hence, there is scope for inaccurate data to be turned into defined U-values by DEAs, often generating far greater carbon gains. Figures 4 and 5 show two contrasting U-values, but one relatively simple mistake (shown in red) increases the U-value for the same property — in Figure 5 the DEA has mistakenly identified sub-floor ventilation air bricks as cavity vents, increasing the U-value from 1.38 W/m^2K to 1.98 W/m^2K, leading to a 30 per cent decrease in performance of the element.

The difference between these two values is relatively high, and yet the error has been created by a simple mistake. There are other similar errors that can be made during this process — there are a wide number of types of concrete block, many with varied thermal

Table 3: ECO maximising EPC

ECO maximising EPC	*ECO maximising EPC with loft insulation (300mm):*	*ECO maximising EPC with cavity wall insulation:*
SAP D56 EI D51 5.7 tonnes CO_2	SAP D60 EI D55 5.2 tonnes CO_2	SAP C64 EI C64 4.5 tonnes CO_2



Wall 7 Gibbs Leaze, NG3 4LA - Cavity wall U Value

Layer	Description	Thickness	Lambda	R	Fraction
Ext surface				0.040	
Layer 1	**Brick, outer leaf**				
	Main construction	103 mm	0.770	0.133	82.81 %
	Bridging - Mortar	103 mm	0.941		17.19 %
Layer 2	**Standard cavity**				
	Main construction	68 mm	0.375	0.180	100.00 %
	Corrections - Cavity Unventilated, Emissivity: Normal				
Layer 3	**Blockwork, medium**				
	Main construction	100 mm	0.570	0.175	93.43 %
	Bridging - Mortar	100 mm	0.880		6.57 %
Layer 4	**Plaster, standard**				
	Main construction	30 mm	0.400	0.075	100.00 %
Int surface				0.130	

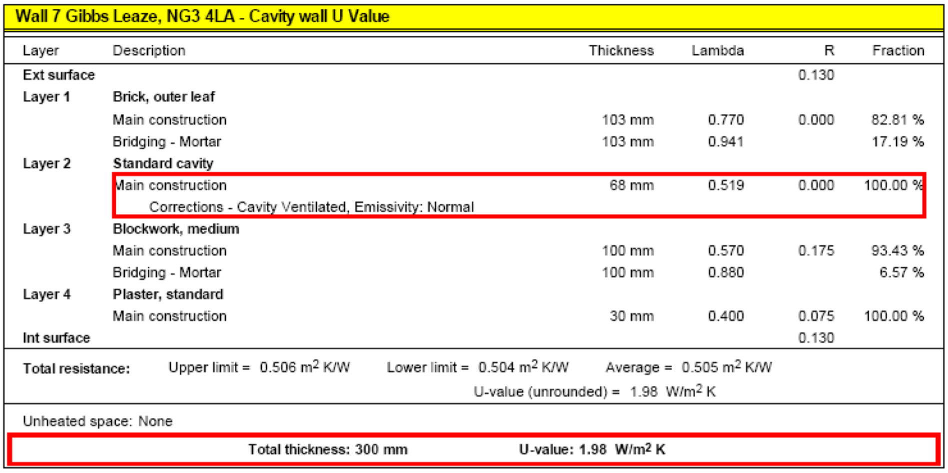
Total resistance: Upper limit = 0.725 m^2 K/W Lower limit = 0.723 m^2 K/W Average = 0.724 m^2 K/W

U-value (unrounded) = 1.38 W/m^2 K

Unheated space: None

Total thickness: 300 mm **U-value: 1.38 W/m^2 K**

Figure 4: U-value 1 — 1.38 W/m^{2}K
(Source: W-Y-P Gledhill, March 2015)



Wall 7 Gibbs Leaze, NG3 4LA - Cavity wall U Value

Layer	Description	Thickness	Lambda	R	Fraction
Ext surface				0.130	
Layer 1	**Brick, outer leaf**				
	Main construction	103 mm	0.770	0.000	82.81 %
	Bridging - Mortar	103 mm	0.941		17.19 %
Layer 2	**Standard cavity**				
	Main construction	68 mm	0.519	0.000	100.00 %
	Corrections - Cavity Ventilated, Emissivity: Normal				
Layer 3	**Blockwork, medium**				
	Main construction	100 mm	0.570	0.175	93.43 %
	Bridging - Mortar	100 mm	0.880		6.57 %
Layer 4	**Plaster, standard**				
	Main construction	30 mm	0.400	0.075	100.00 %
Int surface				0.130	

Total resistance: Upper limit = 0.506 m^2 K/W Lower limit = 0.504 m^2 K/W Average = 0.505 m^2 K/W

U-value (unrounded) = 1.98 W/m^2 K

Unheated space: None

Total thickness: 300 mm **U-value: 1.98 W/m^2 K**

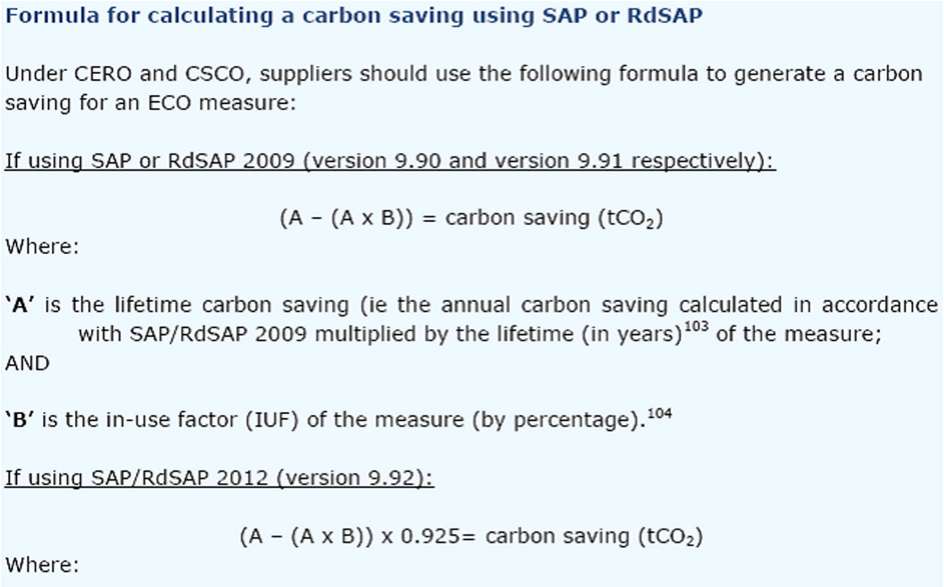
Figure 5: U-value 2 — 1.98 W/m^{2}K
(Source: W-Y-P Gledhill, March 2015)

mass, but superficially these blocks may appear the same, leading to errors of performance calculation.

CARBON CALCULATING

When we consider the errors of the assessment process, intentional or otherwise, we must also consider the implications for carbon savings as may be addressed under the ECO. The process of calculating carbon is identified in Ofgem's ECO Guidance for Suppliers.[24] The relevant extract is shown below in Figure 6.

Using the data from the previous models (Tables 1, 2 and 3) we can compare and contrast those carbon scores identified earlier, using the calculation method for ECO scoring, as outlined above, and then analyse the potential impact that those variations in carbon income could have on the ECO scheme overall. The 'In Use Factor' (IUF) is subtracted from the overall carbon calculated over the lifetime of the insulation measure. The IUF is employed to account for inefficiencies such as loss of effectiveness over the lifetime of the system, or discrepancies during



Formula for calculating a carbon saving using SAP or RdSAP

Under CERO and CSCO, suppliers should use the following formula to generate a carbon saving for an ECO measure:

If using SAP or RdSAP 2009 (version 9.90 and version 9.91 respectively):

$$(A - (A \times B)) = \text{carbon saving } (tCO_2)$$

Where:

'A' is the lifetime carbon saving (ie the annual carbon saving calculated in accordance with SAP/RdSAP 2009 multiplied by the lifetime (in years)[103] of the measure;

AND

'B' is the in-use factor (IUF) of the measure (by percentage).[104]

If using SAP/RdSAP 2012 (version 9.92):

$$(A - (A \times B)) \times 0.925 = \text{carbon saving } (tCO_2)$$

Where:

Figure 6: Carbon calculation[24]

Table 4: In Use Factor and lifecycles[14]

Measure	*In Use Factor (%)*	*Lifecycle (years)*
Cavity wall insulation	35	42
Loft insulation	35	42

installation that detract from the overall effectiveness of the installed system. IUFs vary for each measure, as do their anticipated lifecycles.[32] For loft and cavity insulation the lifecycle is 42 years in both cases, as is the IUF, which is 35 per cent (see Table 4).

Carbon calculations for the control, human error and ECO maximising EPCs

Applying loft insulation to the control property EPC saved 0.3 tonnes of carbon annually. To covert this into a carbon claim under ECO we will apply the methodology above to give an overall saving of 8.19 tCO_2. Applying the same method to cavity wall insulation applied to the control property gives a saving of 27.3 tCO_2. Table 5 shows the difference in savings when compared to the human error and ECO maximising models.

Table 5: Human error and carbon catcher EPCs summary

Human error EPC	*Carbon catcher EPC*
Loft insulation $0.3 \times 42 = 12.6/65\%$ $= 8.19$	Loft insulation $0.5 \times 42 = 21/65\%$ $= 13.65$
Cavity wall insulation $1.1 \times 42 = 46.2/65\%$ $= 30.03$	Cavity wall insulation $1.2 \times 42 = 50.4/65\%$ $= 32.76$

So while the consequence of the simulated human error on this occasion did not make any difference to the loft insulation carbon claim, as the difference was not large enough, the carbon claimed when installing cavity wall insulation has increased by 3 tonnes, or approximately 10 per cent.

In the ECO maximising model, loft insulation has resulted in an extra 5.46 tonnes of lifetime carbon under ECO over the control property EPC, and cavity wall insulation has led to an extra 5.46 tonnes of notional savings. The ECO maximising model EPC allows for a combined extra 11 tonnes of carbon under ECO therefore.

At its peak in February 2013, carbon was trading at £120 per tonne[41] At these levels this represents a potential increase to an installing company's bottom line, as the costs to install each measure remain largely unaltered. Additionally, this will have made greater inroads into the utility company's obligation in terms of carbon saved: the ECO maximising EPC produces a carbon saving of 20 per cent more than the saving of 27.3 tonnes recorded by the control property EPC, and the loft insulation identified over 65 per cent more carbon than that of the control property EPC.

CONCLUSIONS

While no system for modelling building performance and carbon emissions will be without faults, this hypothetical study identifies issues for practice that deserve to have more attention drawn to them. RdSAP and SAP could be described as blunt instruments for the purpose of carbon calculation as they were never designed with this purpose in mind. However, the practice of applying SAP and RdSAP is important and needs to be better understood. There are areas where the DEA may see and record things differently, and this provides scope for variability of outcomes. This is complicated further when they are potentially given unintentional incentives to achieve a particular outcome. The point where genuine human error or lack of understanding of the increasingly complex 'conventions', the rules relating to data collection and input, become errors for the purpose of extra financial gain is difficult to identify, but the indicative models show the potential for this type of behaviour.

The discrepancies analysed look only in one direction: toward increased carbon returns. However, it is likely that errors could be made that lead to underreporting of savings — again a more detailed understanding of the process within a controlled research context would be helpful to better understand the issues. This would further widen the overall scope of potential carbon outcomes for any one property. The lack of availability of some data inputted to RdSAP tends to point the software model towards a default position of worst-case scenario, making under scoring more pronounced than over scoring.

The area is one that merits further investigation. A research project will be undertaken, commissioning a number of actual EPCs undertaken by qualified DEAs, on the same property, in order to compare and contrast them, followed by interviews with each DEA to understand the decisions made on site and the subsequent data entry, providing a link to an understanding of the practice decisions not directly addressed within the Zero Carbon Hub SAP study.[37] Once more is understood on both aspects, solutions can be proposed, which may be related to three main factors — first, the policy framework and consideration of the incentives of the energy assessment system; secondly the knowledge, skills and understanding of the assessor in the data collection process, and finally the analytical frameworks that are applied. This initial research should be considered a framing of the potential issues within the assessment process, explicating some of the concerns highlighted by practitioners and framing them for future research. The role of the assessor is a major one when considering the developing performance gap agenda in energy and buildings research.

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Assessing overheating of the UK existing dwellings – A case study of replica Victorian end terrace house

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ABSTRACT

This paper aims to investigate the likely thermal performance of a unique pre-1919 Victorian case study property by using both current and future projected weather data after a deep retrofit. The property is a re-construction within an environmental chamber using reclaimed materials designed to test housing retrofit solutions. Climate projections for Manchester from both UKCIP02 and UKCP09 programmes were used to assess the likely overheating in summer for this 'Hard to Treat' property judging by both single and adaptive comfort criteria from CIBSE Guide A and BS EN 15251. In the bedroom, where occupants have less ability to adapt, overheating could occur as early as 2020s; while in the living room, using the annually adaptive approach, overheating may not happen until 2080s. For high expectation occupants, however, short term overheating (weekly or monthly) can occur much earlier. The research highlights the discrepancies in predicting overheating using the two UK climate impact programmes; the inconsistencies of risk evaluation using different comfort criteria; and the differences between risk and severity of potential overheating.

1. Introduction

With more and more emerging scientific evidence few now would doubt that tackling the impacts from climate change is one of the greatest challenges facing mankind. A better and sustainable world for future generations will very much depend on how we respond to this challenge now and how to mitigate the likely severe consequences associated with greenhouse gas emissions. Research has shown that by 2035 the concentration of greenhouse gases in the atmosphere may be doubled from the pre-industrial level [1]. This could potentially lead to a global average temperature to rise over 2 °C and in the long run, with a 50% chance the rise could exceed 5 °C. In the UK, the projected average temperature elevation ranges from 1 °C to 6 °C depending on the specific region and the assumed emission scenarios [2]. Reducing carbon emissions and the associated energy consumptions is among the top priorities of the UK government. The Climate Change Act [3], the world first legally binding emission reduction framework was introduced in 2008. It established an ambitious target of reducing the nation's greenhouse gases emissions to at least 80% below 1990 levels by 2050. The overall shared responsibility of carbon emissions from UK domestic homes (emissions associated with space heating, hot water, lighting and appliances) accounts for almost 30% of the total national emissions, of which about two-thirds is for space heating [4]. Improving the energy efficiency of the housing sector is one of the key objectives in order to meet the UK's national emission target, in particular, for the existing stocks.

The English House Condition Survey conducted in 2006 reported that about 82% of the current stock was already built before the 1980s [5]. The total domestic housing stock in the UK is around 26 million, and with the current rebuild rate, it is estimated that approximately 70%–80% of these stocks will remain until 2050 [6]. In particular, typical solid wall construction was used for houses built during the late 18th and early 19th centuries, and these houses account for approximately 30% of the total stock and are regarded as 'Hard to Treat' (HTT) homes [7]. By meeting various government initiatives and much tightened building regulations, new built houses are able to bring energy consumptions down considerably, and the 'zero carbon home' standard 'code for sustainable homes' will become mandatory in 2016 [8,9]. Therefore the new built houses should not present much problem before 2050 for meeting the national target. It is the existing stocks which bear the greatest risk of failing if they are not refurbished to advanced, low carbon standards.

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In recent years, insulating the building fabric has become a common practice among designers and service engineers for reducing heating demands. This is a sensible approach because space heating consumes majority of energy used in homes. Meeting the latest regulations on building fabric may have been another important drive on this, particularly for new built housing. However, one aspect that has been of increasing concern to professionals is the potential summer overheating in homes. With the increased level of insulation and air tightness of dwellings, alongside with the potentially elevated temperature in the future, building adaptation issues, particularly on overheating in summer, need to be addressed in association with those energy efficient measures. The Green Deal [10] and the Energy Company Obligations [11] (ECO, replacement of CERT – Carbon Emission Reduction target) are both focused on delivering insulation measures. These could potentially exacerbate the issue further.

Assessing potential overheating in homes in the UK with future climate change in mind has been subject of much research after the future weather data were made available. Hacker et al. (2008) investigated the effects of thermal mass on overheating mitigation for a semi-detached house located in south-east of England given the research evidence that overheating will happen after year 2050s [12]. Future projected weather years used in the research was from the 'morphing' method of Belcher et al. (2005) [13] after the UKCIP02 programme [14] (with medium–high emission scenario) and the overheating criteria used are from CIBSE Guide A [15] for bedrooms and living rooms. Research on the adaptation of dwellings in heat waves from Porritt et al. (2011) used the same projected weather data and the overheating criteria, and their case study Terraced properties were also located in south-east of England (Weather data base station is London Heathrow) [16]. A number of interventions, applied both individually and in combinations, were investigated to demonstrate their capability of reducing the number 'degree hours' (*ref*: Section 3.3) over the CIBSE overheating threshold temperature. For the purpose of assessing the effects of these proposed interventions on the indoor temperatures the 'degree hours' definition serves the purpose, however, it may not be used to judge overheating as the CIBSE criterion assesses the dry resultant temperature. McLeod et al. (2013) investigated the overheating risks of Passivhaus dwellings in the UK with a changing climate by focusing on the role of design factors such as glazing ratios and external shading devices [17]. One of the key findings of the research states that "unless there is a move towards whole life design optimisation based on minimising future overheating risks, active cooling systems may become a de-facto requirement in urban Passivhaus and low energy dwellings in the UK within the next 30–40 years". A recent survey study of summertime temperatures in English homes reported that the incidence of warm bedrooms is already of concern, in particular, for new homes and retrofitting existing with better insulation standards [18]. The research of Peacock et al. (2010) also highlighted that potential overheating in homes will happen in the south of the UK by comparing two geographical locations – London and Edinburgh, they stated cooling in bedrooms may be needed for approximately a third of a year judging by a single threshold temperature of 23.9 °C [19]. Oikonomou et al. (2012) and Mavrogianni et al. (2012) included the urban heat island effects in the analysis of potential overheating risks of London dwellings using future projected weather data after UKCP09 programme [20,21]. It is believed that the built form and individual dwelling characteristics are the more important determinants of high indoor temperatures than the urban location of the dwellings. A recent comprehensive study from Gupta & Gregg (2012) on domestic homes adaptations in future climate scenarios also used the probabilistic climate change data from UKCP09, and with the high emission 90 percentile probability projections (defined as 'unlikely to be higher than'), overheating in homes in Oxford area needs to be addressed in the near future and a number of mitigation measures including user-controlled shading, surface albedo of building fabric and exposure of thermal mass, were proposed [22]. These existing studies focused on the south of the UK (primarily in London area), using CIBSE single temperature overheating criterion and future weather projections after either UKCIP02 or UKCP09 programmes.

The research reported herein, however, aims to assess a property in Manchester by using future weather projections from both UKCIP02 and UKCP09 programmes to examine their consistency on overheating predictions. Both single and adaptive overheating criteria (*ref*: Section 3.3) will be used to carry out the risk based analysis. This aims to reveal that different judgements on overheating in homes may result from using different weather projections as well as different assessment criteria. The dynamic model has been developed using the Salford Energy House (*ref*: Section 2) as a reference which is a typical solid wall construction, as was used for houses built during the late 19th and early 20th centuries, and is regarded as a HTT property. The purpose of using the Salford Energy House is that it is a property that is constantly monitored in considerable detail and is located within an environmental chamber. This allows the model to be verified under specific conditions using some of the available measurements.

2. The energy house and its model

The Salford Energy House (EH hereafter) is a replica of a pre-1919's Victorian type, end-terrace house, located within an environmentally controlled chamber at the University of Salford (Fig. 1). The EH was constructed using reclaimed materials and traditional methods of the time, such as lime mortar, lath and plaster ceilings. This "Victorian" archetype forms a large proportion of HTT properties. They tend to have high air infiltration, lack insulation, and their energy efficiency is low when compared with new built housing.

The EH model is a 3D numerical model constructed in IES VE [23]. IES VE is a well-established thermal simulation tool for analysing the dynamic responses of a building based on the hourly input of weather data. Fig. 1(a) and (b) shows the plan view of the house, a typical two-bedroom house with a dining kitchen and a living room. A conditioning void replicates an adjacent environment to simulate a neighbouring dwelling to the end-terrace house. An axonometric view of the EH model is shown in Fig. 1(c). The EH is built on a concrete base, with vents provided for the raised timber ground floor (Fig. 1(d)). The fireplace is not in use due to the restriction of the testing environment within the laboratory. Retrofit modelling exercises were conducted earlier for this EH model to examine the effectiveness of various interventions [24].

The construction materials used for the EH are reclaimed materials in order to make the testing dwelling as close the pre-1919 Victorian terrace house as possible. Table 1 shows the details of the construction for the EH.

3. Methodology

3.1. Verification of the EH model

The EH provides an opportunity to replicate the model conditions with those within the EH. The environmental chamber of the EH is able to maintain a steady thermal environment for testing purposes. Two tests were carried out with the chamber temperature, which replicates a steady external environment, maintained at 5 °C (the recorded temperature at various locations shows an oscillation for the EH within ±1.5 K).

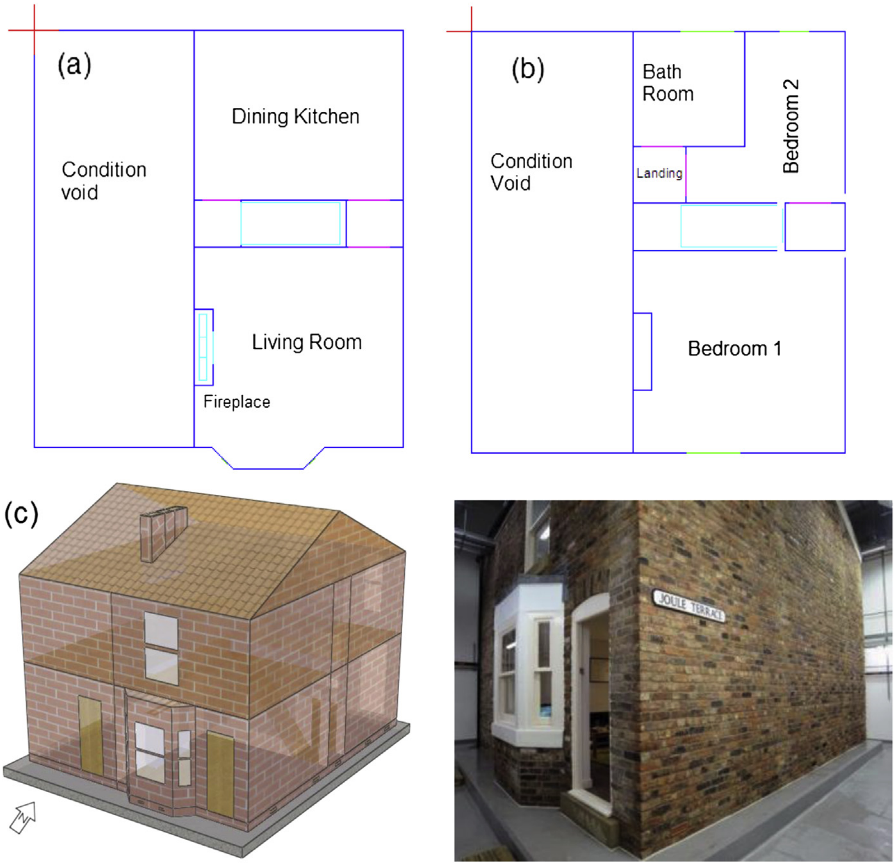

Fig. 1. The EH model (a) ground floor plan, (b) first floor plan, (c) 3D model view, and (d) the EH in the lab.

The first test was a constant heating scenario, heating to 20 °C for all spaces with radiators, and the second test was intermittent heating, with heating from 6:30am to 9am, and from 3:30pm to 11pm. Before these tests, the chamber and the EH were running other tests for a number of days using the same conditions. This ensures the mass of the EH has been fully conditioned. The living room temperature was controlled by a standard thermostat, while all the other rooms were controlled by thermostatic radiator valves (TRV). The measured power of heat emitters and heating set points for different rooms in the EH are shown in Table 2. The heating controls are standard domestic controls and therefore less accurate than the measurement equipment within the house, this led to differences between the measured average temperatures and the heating set points. In the constant heating scenarios, the measured average temperatures are used as the heating set points for the IES model in order to examine the heating demands; for intermittent heating, the original heating set points were used in the IES model, focusing on the verification of the heat dissipation through fabric and infiltration.

The measured natural gas consumption for three days constant heating is 25.26 m^3, 285.7 KW h equivalent [25]. The total heating demands for all the spaces with heating elements from IES calculation is 273.6 KW h. The difference is primarily due to the heating system efficiency as the figure from IES is a net demand.

For the intermittent heating test, the EH modelling results showed a similar dynamic thermal response as the measured data from the experiments (Fig. 2). The thermostatic controlled living room (Lounge) has a slower temperature increase rate than the IES model predicted once heating is started at 6:30am and 3:30pm, and a slower temperature drop rate at 9am and 11pm when heating stops. The comparisons between measurements and IES model for both bedrooms show the similar slow responses during active heating and passive cooling. In IES model, the heating system and its controls are 'ideal', i.e. once the air temperature gets to the set point, it will stay there, while in reality, there is over and under-shooting due to the physical

Table 1
Construction details of the EH.

Parts	Construction details	U-values (W/m^2K)
External walls	Terrace house: 225 mm brickwork + internal plastering;	2.05
	Condition void: 225 mm brickwork + 45 mm EPS Slab[a]	0.55
Partition walls	Internal – 13 mm plastering + 115 mm brickwork + 13 mm plastering	1.97
	Connection to Condition void – Plastering + 225 mm brickwork	1.59
Ceiling/ floor	First floor: Synthetic Carpet + timber flooring + Cavity + Plaster	1.39
	First ceiling: Timber board + Glass-Fibre Quilt (100 mm) + Cavity + Plaster	0.34
Roof	Stone chipping + Felt/Bitumen Layers + Slate Tiles	6.05
Ground Floor	Synthetic Carpet + timber flooring + Cavity + Cast Concrete (dense)	1.53
Glazing	6 mm Pilkington single glazing	5.56

[a] In the modelling, a thin plastering layer was added to the polyurethane board to avoid numerical instability.

Table 2
Heat emitter power and heating set points.

Rooms	Set point (measured average) °C	Emitter power (Watts)
Living Room	21 (19.1)	1632
Kitchen & Dinning	21 (19.2)	1284
Stairs	21 (21)	388
Landing	21 (21)	553
Bedroom 1	21 (20.7)	1498 + 3004
Bedroom 2	21 (18.1)	1489
Bath Room	22 (18.9)	1325

control elements of thermostatic control (Lounge) and the TRVs (Bedrooms). The 'slowness' of the EH during active heating and passive cooling compared to the IES model may be explained by two key aspects. One would be the thermal mass difference. In the IES model, construction mass is included but nothing else; while the EH is fully furnished (Sofa, rugs, beddings, appliances, etc.); everything inside has a thermal mass that impacts heating and cooling. The other would be the residual heat from the radiators after heating system stops. In IES model, once heating is stopped there will be no heating output immediately; while in the EH, the radiators will still emit residual heat to the internal environment until equilibrium, this may sometimes take up to half an hour.

Validation of building dynamic thermal modelling tools such as IES using a real live case is difficult and often unrealistic due to the over simplification of the inputs and the environmental data. Model calibration was often done by using the simple standardised benchmark cases described by ASHRAE 140 [26], for example, the calibration report from IES VE [27]. The exercise using the EH allowed a quick verification under strictly controlled conditions. Overall, the model predications are consistent with the physical measurements, and this offers confidence for using the model to do further studies when the EH is 'relocated' virtually to the Manchester standard environment.

3.2. Modelling assumptions

After the retrofitting modelling exercises on the EH model [24], the following measures were given to the EH base model (*ref.* Section 2) in order to assess potential overheating of this type of HTT property after a deep retrofit: standard double glazing, 0.5 ach air infiltration rate, 200 mm insulation for loft, ground floor and walls (externally). The resultant U values are 0.18, 0.12 and 0.12 W/m^{2}K respectively. This level of insulation is similar to what a Passivhaus standard requires [28], and this fabric first approach is gaining momentum in the EU countries including the UK, consistent with the various UK government initiatives aiming to improve building thermal efficiency such as the Green Deal.

When examining overheating risk, Bedroom 1 and the Living Room (Fig. 1) are the main concern. The typical heating months were excluded with the modelling being carried out from May to September inclusive. A simple occupancy profile for two working adults, the same as in Ref. [24], is used (as shown in Table 3). No incidental heat gains other than occupants were included in the Bedroom 1. In the Living Room, gains from lighting and other entertainment equipment gain were assumed 15W/m^2 when occupied. Openable windows (assume only half of the windows are openable) of the two rooms were governed by both internal and external dry bulb temperatures using a ramp function, i.e. when the internal temperature is from 20 °C to 24 °C, the windows are regulated from closed to fully open (linear control), and in the mean while the external temperature needs to be over 15 °C and less than the internal temperature. During the night windows could only open 2.5% of the full glazing area for security caution or potential noise issue. Other times when the house is occupied, windows could open as much as 10% of the full glazing area (this corresponds to 0.16 m^2 for the Bedroom 1 and 0.19 m^2 for the Living Room) providing the temperature preferences are met. All the internal doors are set to half open during simulation.

3.3. Comfort criteria

In the UK, winter temperature within dwellings can be regulated by the heating system and achieving comfort temperature is unlikely to be a problem from a technical perspective. The CIBSE Guide A [15] recommended summer comfort temperature range for dwellings is 23 °C–25 °C for living and bedrooms. This recommendation is not always practical without air-conditioning, which the majority of UK homes do not have. When considering the

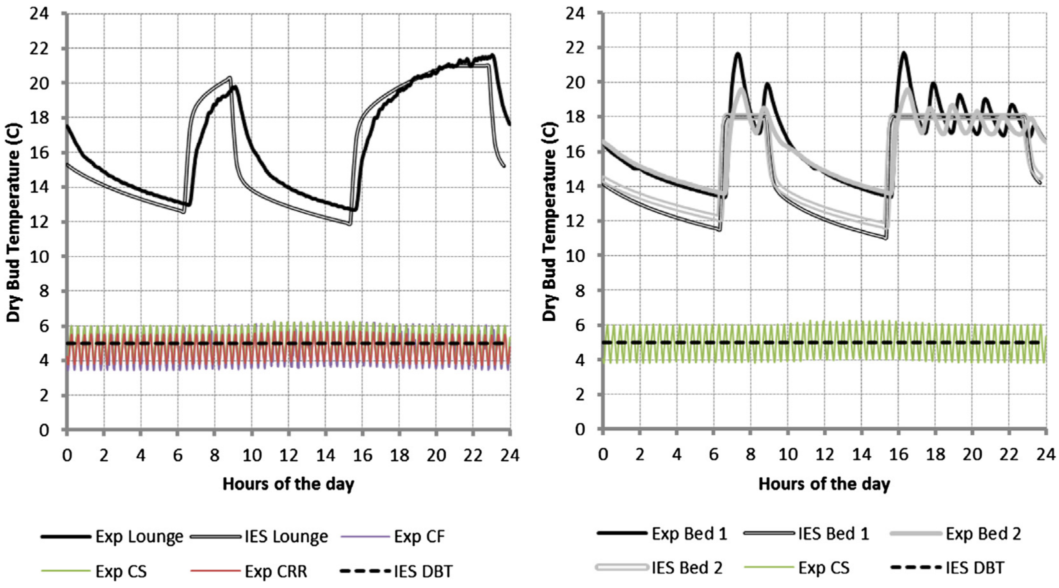

Fig. 2. Measured and predicted temperature for the lounge and two Bedrooms of the EH and IES modelling.

Table 3
Occupancy profile used.

Room occupied	Monday to friday (Times of the day)	Saturday & sunday (Times of the day)
Living Room	7pm–11pm	9am–10am; 12noon–1pm; 7pm–11pm
Kitchen & Dinning	7am–8am & 6pm–7pm	8am–9am; 1pm–2pm; 6pm–7pm
Bedroom 1	11pm–7am	11pm–8am

Note: the remaining time of the day, i.e. from 8am to 6pm, the house is not occupied.

overheating risk, the Guide A defines benchmark temperature that should not be exceeded as a percentage of the annual occupied period. For dwellings, the overheating criterion is 'less than 1% of occupied hours over comfort temperature 26 °C (bedrooms) and 28 °C (living areas). The advantage of this criterion is that it is straightforward to make the judgement, however, the downside is that it does not indicate the severity of the overheating, for example, one hour at 28.1 °C is equivalent to 33 °C when counting the number of hours over 28 °C. An alternative counting method, degree hour (K·h) is a good indicator of the severity of warmth. Degree hour (K·h) or degree days (K·day) are often used to assess external conditions in order to estimate cooling/heating loads, for example, 28.1 °C will be counted as 0.1 K·h while 33C is 5 K·h when using 28 °C as a base temperature [29]. The K·h counting method used in this work is not to judge overheating, but to indicate the severity of indoor warmth. Both methods will be used in this work to reflect the risk and the severity of potential overheating. It is worth noting that the comfort temperature here was previously referred as the Dry Result Temperature (DRT) in CIBSE Guide A (before 2006 edition), which is a combination of air temperature and mean radiant temperature. For consistency with other international standards such as ANSI/ASHRAE, BS EN, the Guide A is now using 'Operative Temperature (OT)' to replace the DRT.

The above single figure temperature criterion was developed using the heat-exchange method, which needs information such as clothing and the metabolic rate in order to calculate the required temperature for comfort. An alternative method, the adaptive approach, which has been developed from extensive field studies [30], assumes the indoor acceptable thermal conditions are related to the outdoor environment. This method, as discussed in CIBSE Guide A, argues that "*people in daily life are active in relation to their environment, given time and opportunity, they can make themselves comfortable by adjusting their clothing, activities and their thermal environment*". The comfort temperature is therefore defined as a band (rather than a single threshold temperature) for free running buildings (i.e. dwellings that are neither heated nor cooled), its upper and lower limits are:

$$\theta_{\mathrm{com}} = 0.33\theta_{\mathrm{rm}} + 20.8 \;\; ; \;\; \theta_{\mathrm{com}} = 0.33\theta_{\mathrm{rm}} + 16.8 \qquad (1)$$

where, θ_{com} is the indoor comfort temperature (operative temperature) and θ_{rm} is an exponentially weighted running mean (RM) of the daily mean (θ_{ed}) outdoor air temperature. θ_{rm} is defined as $\theta_{\mathrm{rm}} = (1-\alpha)(\theta_{\mathrm{ed-1}}+\alpha\theta_{\mathrm{ed-2}}+\alpha^2\theta_{\mathrm{ed-3}\ldots})$, which can be simplified as:

$$\theta_{\mathrm{rm}} = (1-\alpha)\theta_{\mathrm{ed-1}} + \alpha\theta_{\mathrm{rm-1}} \qquad (2)$$

where θ_{rm} is running mean temperature for today, $\theta_{\mathrm{ed-1}}$ is daily mean external temperature for the previous day, $\theta_{\mathrm{rm-1}}$ is running mean temperature for previous day, and α is a constant between 0 and 1. θ_{rm} is decreasingly affected by any particular daily mean temperature as time passes, the rate at which the effect of any particular daily mean temperature dies away depending on α. The larger the value of α, the more important the effects of the past temperature. The recommended value for α is 0.8 [31].

The adaptive approach is also discussed in the standard BS EN 15251 [31]. Three Categories were defined with Category I the same as Eq. (1). Categories II and III widen the comfortable temperature range by 2 and 4 °C (i.e. increasing 1 °C or 2 °C to the upper limit and decreasing 1 °C or 2 °C to the lower limit, as shown by the parallel shifting in Fig. 3). Category I is the most stringent criteria when there are "*High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons*", Category II is for "*Normal level of expectation and should be used for new buildings and renovations*", and Category III is for "*An acceptable, moderate level of expectation and may be used for existing buildings*" as described in BS EN 15251. This gives a more holistic view of the comfort temperature criteria when looking at adaptation issues, in particular, when considering the potential elevated temperature in the future. The adaptive method is often used for assessing commercial buildings which have more field studies to back up its theory and practice. As noted in both BS EN 15251 and the CIBSE Guide A, people tend to adapt relatively better in their homes than in offices on the assumption that '*one is relatively free to adjust metabolism and the amount of clothing worn dependant on outside weather conditions and indoor temperatures*'. Therefore, the comfort temperature bands proposed in these standards can be applied to dwellings. However, care must be given to bedrooms since sleep quality can be greatly affected when the Operative Temperature is over 26 °C. Both standards also suggest that the use of quiet ceiling fans can offset the comfort temperature to a certain extent, i.e. an airflow speed at 0.6 m/s can make one feel about 2 °C cooler, potentially minimising overheating risk.

3.4. Standard current and future weather files

The typical weather condition in the UK is represented by the Test Reference Year (TRY) weather data, combining hourly data for 12 typical months, selected from approximately 20 years data sets previously, i.e. from year 1983 to 2004. TRYs are often used to assess the likely energy consumption of buildings. The Design Summer Year (DSY) weather data is a selection of an actual hot summer year from the previous 20 years data sets, i.e. the third warmest based on the dry bulb temperature (DBT) during April to September, to represent a hot but not the extreme year. DSYs are used to assess overheating risks, as suggested by the CIBSE Guides. The CIBSE Guide J [32] publishes these TRY and DSY weather data periodically for 14 sites within the UK and the current weather data of Manchester used in this work is from the 2005 release.

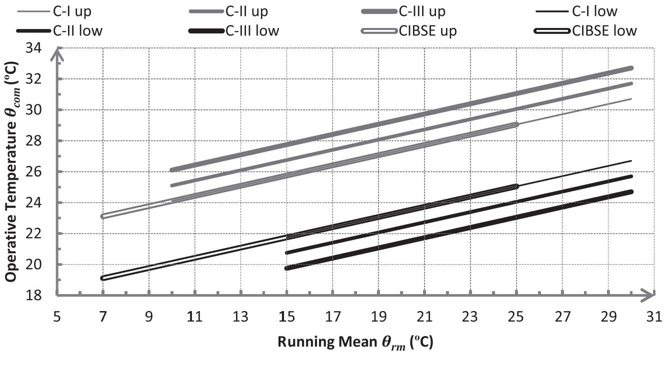

Fig. 3. CIBSE Guide A [15] and BSEN15251 [31] comfort temperature boundaries for free running buildings (Eq. (1) with parallel shifting).

Future probabilistic weather data from UKCP09 weather generator [33] will be used in this work to assess potential overheating issues for the EH after the proposed retrofit. These weather files were made on the assumption of the medium high emission scenario from the IPCC Special Report on Emissions Scenarios (a1b, used in UKCP09 [2]), and they are now freely available after the EPSRC funded project ‘The use of probabilistic climate data to future-proof design decisions in the buildings sector’. In the UKCP09 probabilistic weather projections, five different CDF (cumulative distribution function) percentiles are used to reflect the probabilistic nature of the potential climate changes. These are defined as unlikely to be less than (10%) or greater than (90%), everything between 33% and 66% is generally considered being equally likely, defined as the ‘likely band’, with 50% as the centre estimate (but not the most likely). Multiple simulations are therefore needed to evaluate the full range possibilities for future projected climate conditions. In this work the future weather years of 2030, 2050, and 2080 generated by the weather generator, are used to assess the likely performance of the EH after a deep retrofit.

For the purposes of verification, the future projected weather data based on the UKCIP02 [14] using the morphing method of Belcher et al. [13] were also tested in this work. The morphing method, described in CIBSE TM36 [34], also used the medium high emission scenario. Using the morphing method, the future weather files of TRYs and DSYs for year 2020, 2050 and 2080 were produced and released by CIBSE in 2002. It is worth noting that the CIBSE 2005 release was based on the recorded data sets from years ‘1983 to 2004’ while the 2002 release was on the basis of the recorded data sets from years ‘1961 to 1994’. This can lead to inconsistency when comparing the modelling results of TRYs/DSYs 2005 and the future projected weather TRYs and DSYs produced after both UKCIP02 and UKCP09 programmes, as they both used the same base line ‘1960s–1990s’to produce future weather files.

Fig. 4 shows the temperatures annually from the UKCP09 projected weather file, Manchester, year 2050, TRY with 50 CDF percentile. The daily mean temperature smoothens out the daily fluctuations and the running mean temperature is directly correlated with the daily mean, which follows its pattern but is less spiky. With reference to Eq. (2), as the time passes, the running mean was less influenced by the daily mean. Only the immediate few daily means are primarily governing the value of the running mean. The Category I upper limit (BS EN 15251) was also plotted on the graph. The upper limit falls within a typical range of the running mean temperature: $10\,^{\circ}\mathrm{C} < \theta_{\mathrm{rm}} < 30\,^{\circ}\mathrm{C}$. Within this range, there are field studies to back up this approach. When the running mean temperature is below the 10 °C threshold, overheating is unlikely to be a concern for free running buildings, so the limits were capped at 24.1 °C whenever the running mean is lower than 10 °C using Eq. (1). The CIBSE adaptive approach upper limit does not set a specific range but the presented data range is from 7 °C to 25 °C (ref: Fig. 3). The CIBSE running mean temperature range is adequate to evaluate overheating for the current climate condition. When the future projected weather data are used, the BS EN 15251 range will be able to cover the potential temperature extremes.

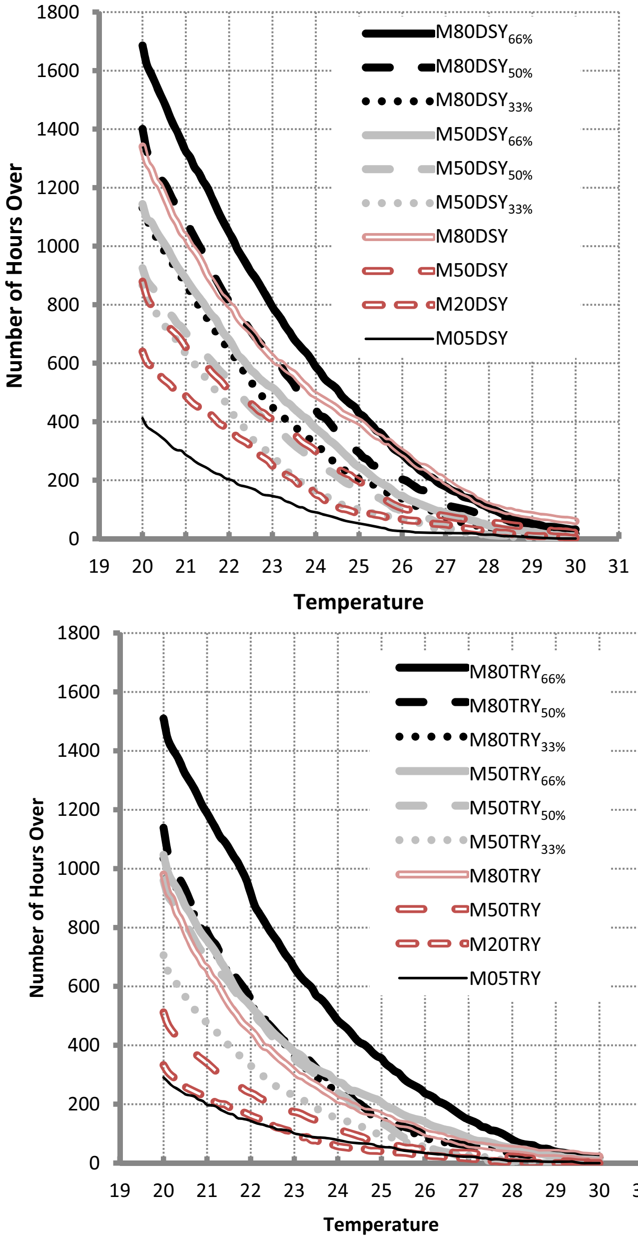

Fig. 5. Number of hours over degrees for current (2005) and future project weather years of Manchester (after UKCIP02 [14] and UKCP09 [2] programmes).

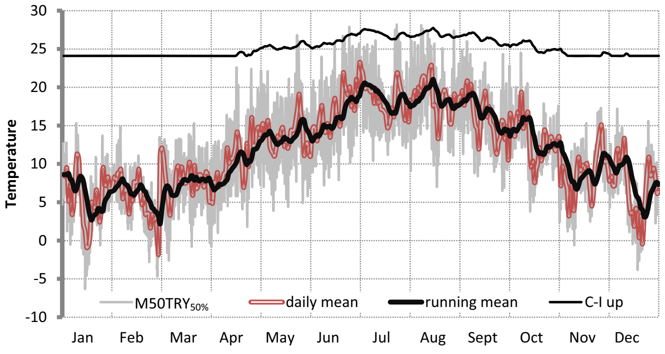

Fig. 4. A typical future weather year’s dry bulb temperature, its daily mean, running mean (Eq. (2)) and its BS EN 15251 [31] Category I upper comfort temperature limit (Eq. (1)).

Fig. 5 examines the number of hours over a temperature for the Manchester weather files which this work is going to use. This comparison looks at the severity of the possible temperature increase by examining the current typical weather conditions (year 2005) and the future projected weather conditions focusing on the dry bulb temperature. The future weather years of TRYs and DSYs include the weather files generated after UKCP09 (WG 2050 & 2080) and the morphed weather files after UKCIP02 (2020, 2050 & 2080). Broadly speaking, both methods are consistent in demonstrating the potential temperature increase in the future. Due to the probabilistic nature of the UKCP09 projections, a single CDF percentile is not representative. For example, in the TRYs on the left, the 66 percentile of 2080 weather files is much hotter than the morphed weather files after UKCIP02. However, the 50 and 33 percentile of 2080 weather file is much closer to the UKCIP02 prediction. For 2050 TRYs, the prediction of temperature from UKCP09 is generally higher than the morphed weather after UKCIP02. It is worth noting that the Manchester 2005TRY shown here is very similar to the morphed UKCIP02 future weather projections of year 2020. This is due to the base line temperature explained earlier. For the DSYs, predictions from the morphed weather files of UKCIP02 fall within the 'likely band' of the predictions from UKCP09. Due to the probabilistic nature of the predictions, the 'likely band' of the UKCP09 predictions is used for this work rather than a single CDF percentile.

4. Results and discussion

Energy efficiency is often the main concern when refurbishing existing housing stock. Looking at the potential temperature elevation in the future positively, if external climate temperatures rise as anticipated, the annual heating demands could decrease. Fig. 6 shows the level of reduced heating demand due to potential climate change. By year 2050 when the UK is required to meet its legally binding 80% carbon reduction target against 1990 level, without doing any other interventions, 18% of the heating demand may be reduced. Considering the housing sector contributes 30% end energy use and about two-third of which is for space heating [4], this does add a marginal (about 4%) contribution to achieve the overall emission reduction target.

Fig. 7 shows the Living Room operative temperatures from May to September against the comfort temperature boundaries defined by CIBSE Guide A and BSEN15251 for free running buildings. With the current climate condition (m05dsy), almost no operative temperatures exceed the CIBSE upper limit, so currently with a deep retrofit to the EH, there is unlikely to be any overheating concern. When using the morphed future projected weather year DSYs after UKCIP02, the running mean temperature upper range is extended and the operative temperatures start exceeding the CIBSE upper limit by year 2020 (m20dsy) but still within the BSEN15251 Category II upper limit. In the year of 2050 (m50dsy), the operative temperatures start exceeding the BSEN15251 Category II upper limit, and by 2080 (m80dsy), more operative temperatures are moving towards the upper ranges, and some are even exceeding the BSEN15251 Category III upper limit. It is worth to note that, by 2080, the maximum running mean temperature is 25.2 °C, which slightly exceeds the CIBSE comfort boundary limit (25 °C), but is well within the BSEN15251 boundary (maximum RM is 30 °C). There are operative temperatures spreading towards the lower comfort boundaries, with more for the current climate, and less in the future due to elevated external temperatures. The house was modelled to be free running without active heating (May to September inclusive), and the focus of the modelling here was to examine overheating. Issues related to low operative temperatures are not discussed.

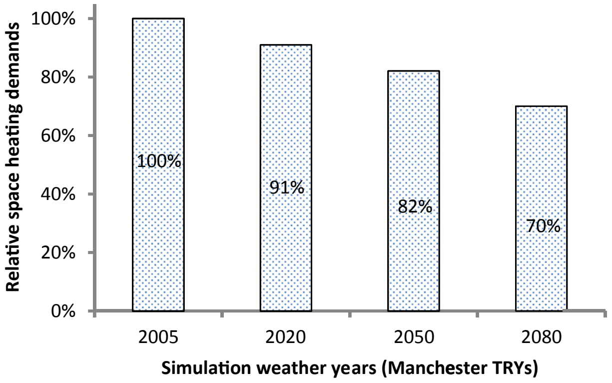

Fig. 6. The predictions of the EH model space heating demands, using Manchester TRY 2005, and the morphed future TRYs of 2020, 2050 & 2080 after UKCIP02 [14].

Table 4 is a summary of predicted Operative Temperatures for both the Bedroom and the Living Room using current and future projected DSY weather files. The dark shaded row is for the current climate, the light shaded rows are for the weather files after UKCP09, and the rest (clear) rows are for the morphed weather files after UKCIP02. Using the single comfort criteria of CIBSE Guide A, less than 1% of occupied hours over, there is no overheating concern for both rooms using the current DSY weather condition. By 2020 (m20dsy), the Bedroom shows some signs of overheating (4.7% of occupied hours over 26 °C) while in the Living Room the number of hours over 28 °C is only 0.3%. By 2050 (m50dsy), both rooms are overheated (10% and 4.3%), and in the subsequent years, the severity of overheating is increased as indicated by both the number of hours over threshold temperatures and the accumulated degree hours (K·h). When comparing the Bedroom comfort temperatures predicted by using weather files of 'm50dsy' and 'm50dsy$_{66\%}$', the number of hours over 26 °C is similar (122 & 110, corresponding percentages are 10.0% and 9.0%), while their degree hours (K·h) show a larger difference (175.9 and 110.9). This indicates that the predicted overheating using 'm50dsy' is more intense than it looks by just comparing the 'number of hours over'. Similarly, by examining rows of 'm80dsy$_{33\%}$ and m80dsy$_{50\%}$', high 'degree hours' (K·h) are against a small 'number of hours over'. In essence (although the differences shown here are small) it shows that the Bedroom is overheated more for 'm80dsy$_{50\%}$' weather, but you may use more energy for 'm80dsy$_{33\%}$' weather if cooling is invoked to maintain the Bedroom temperature below 26 °C. Therefore the degree hours (K·h) are an important indicator to illustrate the severity of overheating. It is not a criterion used to judge overheating, but useful to add alongside to assist understanding.

Using the adaptive approach, CIBSE Guide A does not provide a criterion, i.e. the percentage deviation over its upper limit, to judge overheating; while BS EN 15251 does provide a recommendation, i.e. allowed 3%–5% occupied hours over the upper limits of an individual category in question. The percentage is applied daily, weekly, monthly and annually. For the Living Room in Table 4, if '5% deviation over' is used for months from May to September simulated here, overheating does not occur until 2080 for the living room (m80dsy). This is on the assumption of two working adults and the house is renovated, which Category II applies (normal level of expectation and should be used for new buildings and renovations).

From the predicted indoor conditions, there is a clear difference between the projected DSYs after the two programmes although the expectation would be that these clear rows with morphed future DSYs after the UKCIP02 would fall within the relevant light shaded rows of future DSYs generated from the Weather Generator after UKCP09, i.e. for years of 2050 and 2080. This is clearly not the case shown in Table 4, indoor Operative Temperatures for both rooms are higher for 'm20dsy' than that of 10 years later 'm30dsy$_{33\%,\ 50\%\ \&\ 66\%}$'. The same is true for the years of 2050 and 2080. When examining these weather files particularly for the future years of 2050 and 2080 in Fig. 5, broadly speaking, the morphed weather files do seem to fall within the likely range of those weather files generated by the weather generator for the

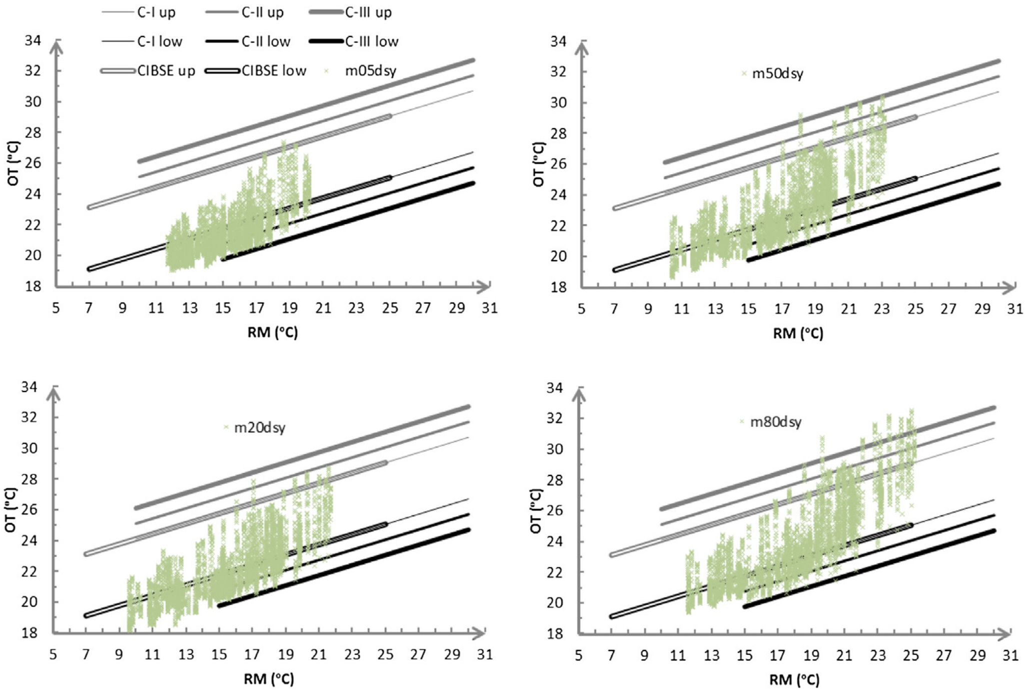

Fig. 7. Living Room operative temperature plots for Manchester DSY weather years of 2005 (m05dsy), 2020 (m20dsy), 2050 (m50dsy) and 2080 (m80dsy).

same future years. However, at the higher temperatures, i.e. 26 °C, 27 °C and above, the 'number of hours over' shows a different story with the morphed weather years showing higher numbers (see Fig. 8). Although the differences look small in numbers this will have a great impact on the indoor Operative Temperatures at the upper range (i.e. when OT is over 26 °C) when overheating is examined. This is an interesting observation as the risk based analysis of overheating in dwellings was often based on one of the two future weather projections (ref: Section 1). It naturally raises questions, i.e. which 'projections' should be used when assessing overheating risks in the future? There is unlikely a clear answer on this as there is no research evidence to show one is better than the other. Discussing the robustness of the two sets of the future weather projections after UKCIP02 and UKCP09 programmes is outside the scope of this research. However, it is advisable to assess overheating risks of dwellings using both projections to identify the worst case scenarios.

The future years TRYs are also modelled and a similar table is generated but removed those rows with no likely overheating concern using both single and adaptive criteria. Table 5 shows, in 'typical' weather conditions in contrast to the DSYs which represent hot weather extremes, what the indoor comfort temperature performs. There are overheating concerns using the single criterion up to year 2050, while using the adaptive criteria, overheating is

Table 4
Summary of the predicted Operative Temperatures in the Bedroom 1 and the Living Room using DSYs.

	Bedroom 1					Living room										
	24/7		Occupied			24/7		Occupied								
	>26[b]	%[c]	>26	%	K·h[d]	>28	%	>28	%	K·h	Cat I[e]	%	Cat II[e]	%
m05dsy[a]	18	0.5%	0	0.0%	0.0	0	0.0%	0	0.0%	0.0	1	0.1%	0	0.0%
m20dsy	213	5.8%	58	**4.7%**	40.5	15	0.4%	2	0.3%	0.4	19	2.7%	3	0.4%
m30dsy33%	0	0.0%	0	0.0%	0.0	0	0.0%	0	0.0%	0.0	1	0.1%	0	0.0%
m30dsy50%	43	1.2%	3	0.2%	0.4	0	0.0%	0	0.0%	0.0	1	0.1%	0	0.0%
m30dsy66%	58	1.6%	6	0.5%	0.9	0	0.0%	0	0.0%	0.0	4	0.6%	0	0.0%
m50dsy	490	13.3%	122	**10.0%**	175.9	109	3.0%	30	**4.3%**	28.1	33	4.7%	17	2.4%
m50dsy33%	42	1.1%	0	0.0%	0.0	0	0.0%	0	0.0%	0.0	2	0.3%	0	0.0%
m50dsy50%	175	4.8%	29	**2.4%**	10.8	20	0.5%	3	0.4%	0.4	11	1.6%	0	0.0%
m50dsy66%	370	10.1%	110	**9.0%**	110.9	67	1.8%	22	**3.1%**	11.3	27	3.9%	4	0.6%
m80dsy	1188	32.4%	374	**30.6%**	685.2	360	9.8%	87	**12.4%**	129.5	105	**15%**	41	**5.9%**
m80dsy33%	363	9.9%	73	**6.0%**	74.4	68	1.9%	19	**2.7%**	22.7	28	4.0%	8	1.1%
m80dsy50%	383	10.4%	85	**6.9%**	61.1	69	1.9%	18	**2.6%**	11.8	31	4.4%	3	0.4%
m80dsy66%	730	19.9%	205	**16.7%**	193.8	132	3.6%	44	**6.3%**	25.6	54	**7.7%**	8	1.1%

[a] 'm50dsy' is the morphed Manchester Design Summer Year weather of 2050, the added subscripts 33%, 50% and 66% are the CDF percentile to represent the likely further year weather conditions after UKCP09.

[b] '>26' means number of hours the Operative Temperature is over 26 °C, same for '>28'.

[c] '%' is the percentage of number of hours over (i.e. over 26 °C, 28 °C and Category I and II upper boundaries) the total hours (simulated total hours from May to September is 3672 h, the Living Room occupied hours are 700, and the Bedroom 1 occupied hours are 1224); the bold '%' numbers are exceeding their relevant threshold percentages, i.e. 1% for CIBSE Guide A single criterion, 3%–5% for BS EN 15251 criterion.

[d] K·h is the accumulated degree hour over 26 °C (Bedroom 1) or 28 °C (Living Room), refer Section 3.3.

[e] Cat I and Cat II are number of hours over the CIBSE Guide A and BS EN 15251 Category I and II's upper limits (defined in Section 3.3).

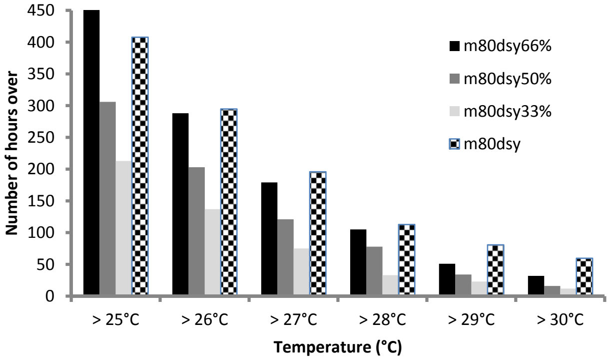

Fig. 8. Number of hours over temperatures for DSY, year 2080: comparison between the morphed weather and the weather files generated by the weather generator.

unlikely to happen under 'normal' future conditions in the Living room.

In Tables 4 and 5, the adaptive criteria are not used for the Bedroom due to its more stringent requirement on comfort temperature. As discussed in CIBSE Guide A, sleep may be impaired when the OT is above 24 °C, and little further adaptation is possible when the OT is above 27 °C without using other assisting means such as ceiling fans. Therefore it is appropriate to use the more stringent single criterion to judge overheating concern for the Bedroom, and as shown in Table 5, overheating become a 'likely' concern in 2050 for 'm50try$_{66\%}$', by 2080 this may become a definite concern.

The adaptive criteria used here is to evaluate from May to September by counting the number of hours over the comfortable temperature limits, i.e. the upper boundaries for categories I and II. If putting the contexts into an annual evaluation, the 'percentage over' on Tables 4 and 5 will be halved (assuming overheating is unlikely to happen for the rest of the months). When using the yearly criteria, it does not show, when exactly the overheating happens and how severe it is. Table 6 gives an example year of 'm50dsy' when examining overheating at weekly level. In the Living room there are 'number of hours over' Cat I upper limit during one consecutive 7 days (20–26 Aug). This indicates that these 7 days (it does not matter whether they are in the same week or not), if using the weekly adaptive criteria (3% or 5%) from BS EN 15251, they are seriously overheated. Evaluating the same criteria at daily level, all the dates when the number of hours over Cat I upper limit is not zero during occupancy are overheated. The standard does not offer recommendations on these potential short-term overheating. It is down to the home owner's preference whether they want to use air-conditioning or not. Alternatively, the mitigation measures discussed in Refs. [16,17,22] may help prevent the short-term overheating from happening.

Unlike the single temperature criterion, the Category upper limit changes reflecting the adaptive nature of the method (ref. Fig. 4). For example, 'Cat I upper' in Table 6, the bold numbers are over the 28 °C of the CIBSE Guide A single threshold temperature criterion. Hotter conditions will result in more over 28 °C category upper limiting temperatures which will make the adaptive approach less sensitive to judge overheating; for less hot conditions, this approach gets more stringent compared with the single figure temperature criterion. In Table 6, the Daily Mean, Running Mean (RM, ref Section 3.3), dry bulb temperature (DBT) Daily Max and the Operative Temperature (OT) Daily Max are listed for reference.

5. Conclusions

This paper presents dynamic thermal simulations on the replica of a typical pre-1919 Victorian end terrace house. The model verification exercise done in this work for the EH is useful to provide confidence in a dynamic thermal simulation tool such as IESVE. For the constant and intermittent heating scenarios, predictions from the EH model agreed well in principle with the measurements. In practice model validation has been rarely possible due to the fact that weather and occupancy behaviour are difficult to replicate.

Overheating risk would occur when putting the EH in the future projected Manchester climate conditions after a "deep" retrofit, judging by both single comfort temperature criteria and the adaptive approach. With the given scenario, the living room will not be overheated until 2050 using the single temperature criterion; while using the adaptive method, the overheating risk becomes a concern until 2080 for high expectation occupants but not for the normal expectation occupants defined in BS EN 15251. This conclusion on the judgement of the adaptive approach is drawn upon the evaluation of May to September, or yearly on the assumptions of no overheating for the rest of months. When examining overheating at daily, weekly or monthly level using the adaptive approach the argument changes: there are weeks or even

Table 5
Summary of the predicted Operative Temperatures in the Bedroom 1 and the Living Room using TRYs.

	Bedroom 1					Living room								
	24/7		Occupied			24/7		Occupied						
	>26[b]	%[c]	>26	%	K·h[d]	>28	%	>28	%	K·h	Cat I[e]	%	Cat II[e]	%
m50try[a]	29	0.8%	0	0.0%	0	0	0.0%	0	0.0%	0	10	1.4%	0	0.0%
m50try33%	52	1.4%	8	0.7%	2.21	3	0.1%	0	0.0%	0	9	1.3%	0	0.0%
m50try50%	104	2.8%	9	0.7%	1.65	4	0.1%	0	0.0%	0	8	1.1%	0	0.0%
m50try66%	233	6.2%	70	5.7%	48.61	52	1.4%	17	2.4%	8.34	31	4.4%	8	1.1%
m80try	275	7.3%	72	5.9%	41.65	27	0.7%	9	1.3%	3.92	25	3.6%	5	0.7%
m80try33%	179	4.8%	51	4.2%	28.94	33	0.9%	7	1.0%	2.8	16	2.3%	2	0.3%
m80try50%	197	5.2%	49	4.0%	31.53	21	0.6%	7	1.0%	4.14	11	1.6%	2	0.3%
m80try66%	526	14.0%	99	8.1%	42.16	40	1.1%	12	1.7%	4.37	28	4.0%	0	0.0%

[a] 'm50try' is the morphed Manchester Test reference Year weather of 2050, the added subscripts 33%, 50% and 66% are the CDF percentile to represent the likely further year weather conditions after UKCP09.

[b] >26' means number of hours the Operative Temperature is over 26 °C, same for '>28'.

[c] '%' is the percentage of number of hours over (i.e. over 26C, 28C and Category I and II upper boundaries) the total hours (simulated total hours from May to September is 3672 h, the Living Room occupied hours are 700, and the Bedroom 1 occupied hours are 1224); the bold '%' numbers are exceeding their relevant threshold percentages, i.e. 1% for CIBSE Guide A single criterion, 3%–5% for BS EN 15251 criterion.

[d] K·h is the accumulated degree hour over 26 °C (Bedroom 1) or 28 °C (Living Room), refer Section 3.3.

[e] Cat I and Cat II are number of hours over the CIBSE Guide A and BS EN 15251 Category I and II's upper limits (defined in Section 3.3).

Table 6
Examine overheating at weekly and daily level for the living room by using m50dsy as an example year.

Dates	m50dsy Living room										
	°C						Number of hours over				
	Daily mean	Running mean	Cat I upper	Cat II upper	DBT[b] D.Max	OT[c] D.Max	May to Sept	Occ[a]	May to Sept	Occ[a]	Occ[a]
							Cat I	Cat I	Cat II	Cat II	>28 °C
08-Jul	22.4	17.1	26.4	27.4	29.5	27.4	8	**3**	0	0	0
09-Jul	25.5	18.1	26.8	27.8	32.3	29.2	12	**4**	11	4	4
25-Jul	19.5	19.3	27.2	28.2	25.5	27.3	2	0	0	0	0
26-Jul	19.6	19.3	27.2	28.2	26.1	27.4	2	0	0	0	0
30-Jul	21.8	19.3	27.2	28.2	28.6	27.5	2	**2**	0	0	0
11-Aug	19.0	18.0	26.7	27.7	23.6	26.7	1	0	0	0	0
20-Aug	23.8	20.2	27.5	28.5	30.6	28.7	11	4	5	2	3
21-Aug	24.8	20.9	27.7	28.7	30.4	29.7	12	5	9	3	4
22-Aug	25.4	21.7	28.0	29.0	32.4	30.0	13	5	9	3	5
23-Aug	24.5	22.4	**28.2**	29.2	30.0	29.7	13	4	8	2	4
24-Aug	24.3	22.8	**28.3**	29.3	30.4	29.6	12	4	7	3	4
25-Aug	22.5	23.1	**28.4**	29.4	26.0	29.0	8	0	0	0	2
26-Aug	21.9	23.0	**28.4**	29.4	28.4	30.4	10	2	5	0	2
28-Aug	21.0	22.5	**28.2**	29.2	25.5	28.2	1	0	0	0	0
29-Aug	20.0	22.2	**28.1**	29.1	24.6	28.7	3	0	0	0	0
30-Aug	19.1	21.7	28.0	29.0	22.5	28.7	4	0	0	0	0
31-Aug	20.9	21.2	27.8	28.8	25.8	28.2	3	0	0	0	0
01-Sep	21.9	21.1	27.8	28.8	24.4	28.7	5	0	0	0	0

[a] Occ - means 'occupied hours', the number of occupied hours over category upper limits or 28 °C.
[b] DBT D.Max – Daily Maximum Dry Bulb Temperature.
[c] OT D.Max – Daily Maximum Operative Temperature.

individual months, before 2050, overheating exists using the 3%–5% number of hours over the category upper limits. Whether the short periods of overheating during a year would lead to the use of air-conditioning is a question which the standards used in this work did not provide recommendations.

For the bedrooms, overheating could occur as early as 2020 using the CIBSE Guide A single temperature criterion (number of hours over 26 °C) and the morphed weather year of 'm20dsy'. For normal or standard weather conditions – the future TRYs, overheating would not happen until 2050. Clearly, overheating in bedrooms is more prone to happen and it needs to be addressed, as people tolerate high temperatures less during sleep and there are fewer opportunities to adapt in terms of clothing, covering sheets, and/or opening windows. This is probably one of reasons why the adaptive approach does not offer any guidance on night time overheating risk assessment. Discussing interventions on avoiding overheating has been well documented and is outside the scope of this research, however, as suggested by both CIBSE Guide A and BS EN 15251, using quiet ceiling fans at night would be a straightforward option to tackle the issue to certain extent.

The future projected weather data used here are the morphed weather files after UKCIP02 and those generated by the Weather Generator after UKCP09. These projections are broadly consistent in terms of temperature elevation in the future years. However, the predicted indoor temperatures are not as consistent, with those morphed projections predicting a greater number of hours over comfort threshold temperatures, i.e. single and adaptive criteria. This observation can raise concerns on which set of projections should be used when evaluating buildings in the future scenarios. There is unlikely a firm answer to this as both projections use assumptions to 'predict the future'. One may argue which set of assumptions are more sensible, but none of these future projections can be validated at this point in time, so both sets of projections should be considered. For future work a sensitivity study on these weather files by examining what parameters, such as, dry bulb temperatures, solar radiation (direct and diffusive), and wind, drive the key differences in predicting the thermal performance of a building in question.

An interesting observation from this research is that both the risk (judging by 'number of hours over' threshold temperature) and the severity (judging by degree hours: K·h) of overheating need to be examined together in order to provide a better understanding of overheating for the spaces investigated. This is potentially very useful when considering interventions to mitigate overheating or choosing the size of conditioning system if necessary.

The modelling exercises done in this work is focused on the EH, a typical Victorian end terrace house, within a well-controlled environment, the standard Manchester climate conditions and their future projections, the methodology used here can be applied to many other building types to assess indoor thermal conditions.

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Adoption of sustainable retrofit in UK social housing

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Abstract

Purpose – The study was designed to assess the knowledge, adoption and perceived effectiveness of sustainable retrofit technologies within the UK social housing sector.
Design/methodology/approach – The study was undertaken using a structured questionnaire that was completed by 130 providers of social housing.
Findings – The study showed that social housing providers were evenly split in their reliance on internal or external information for sustainable retrofit knowledge. In terms of adoption identified that this was strongly driven by government-funded programmes, leading to widespread adoption of low technology solutions. The respondents identified that many leading edge technologies were perceived to be less effective.
Research limitations/implications – The study represents a snap-shot of adoption and effectiveness issues, therefore does not show the trajectory of adoption which should be addressed in a follow-up study.
Practical implications – The social housing sector has been viewed as a market maker for some of the newer technologies. It indicates that some of the newer technologies, such as heat pumps are viewed as less effective than more established technologies.
Social implications – The study has implications for the adoption of technology to address fuel poverty and climate change, as well as informing future policy such as Green Deal.
Originality/value – The study includes 130 responses from the social housing stock and gives a perspective of current views on adoption and effectiveness of retrofit technologies within the social housing sector. This is useful for both other social housing providers and policy makers.

Keywords Sustainable retrofit, Social housing, Technology adoption, Housing, United Kingdom
Paper type Research paper

Introduction

The UK has a legally binding target to reduce carbon emissions in the UK by 80 per cent by the year 2050 (HM Government, 2008). The UK housing sector contributes approximately 27 per cent of these emissions (Department for Energy Climate Change (DECC), 2012a; Palmer and Cooper, 2011) through "derived demand" (Government Office for Science, 2008) activities, such as gas for heating and hot water demand that contribute 15 per cent of the UK's carbon dioxide emissions, with a further 12 per cent through supplied electricity. Domestic carbon emissions will need to be virtually nil by 2050 (Wetherell and Hawkes, 2011), to balance out emissions from other more intractable sectors, such as heavy industry. Upgrading properties through sustainable

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retrofit can reduce energy use and carbon emissions. Modernisation, retrofit and refurbishment are all used within the literature (Hong *et al.*, 2009; Jenkins, 2010; Reeves *et al.*, 2009; Bell and Lowe, 2000; Kelly, 2009) when discussing the upgrade of a property's physical characteristics to improve its environmental performance. Here we will use the term sustainable retrofit. Sustainable retrofit includes upgrades to the fabric or systems of a property that may reduce energy use or generate renewable energy. Sustainable retrofit is adopted to address the three energy policy aims of the UK government; climate change, fuel poverty and energy security (Department for Trade Industry (DTI), 2006, 2007).

Policy and regulatory tools regarding the use of energy by homes initially focused on new build housing, such as the *Code for Sustainable Homes* (CLG, 2006; Lowe and Oreszczyn, 2008) and the *Building Regulations* (ODPM, 2006; Lowe and Oreszczyn, 2008). This focus on new build was challenged; the UK replacement rate for homes was less than 1 per cent per annum even at peak construction levels for the UK housing market. Approximately 70-80 per cent of the buildings currently in the housing supply will be in use in 2050 (Kelly, 2009; Boardman, 2007; Ravetz, 2008), the target date for the UK to have a legislatively driven reduction of 80 per cent in carbon emissions (HM Government, 2008). Many of these existing buildings have poor energy efficiency (Roberts, 2008), so this places the existing stock at the centre of the debate.

A number of studies have considered the technological choices that might be considered to drive carbon savings in the existing stock. Natarjan and Levermore (2007) evaluate a number of retrofit strategies as defined in four models of retrofit, including issues such as demolition. These packages were identified by other studies and the D-Carb model was applied to consider their various carbon emissions impacts. Reeves *et al.* (2010) also model the impact of the adoption of technology with a perspective on carbon emissions against local carbon reduction targets. Both of these papers discuss the technical possibilities of reducing carbon through sustainable retrofit, but Reeves *et al.* in particular recognise the important role of adoption, driven by finance and resident demand, and the complexities this has for reducing carbon emissions in practice.

In 2010, the previous UK government identified the social housing sector as having a market development role for sustainable retrofit (HM Government, 2010a). The coalition government reiterated this in the *Low Carbon Construction Innovation and Growth Report* (HM Government, 2010b). Jenkins (2010) specifically identifies the fuel poor in social housing as a key target group.

There are a number of available sources that give an indication of the trajectory of retrofit adoption currently developed in the UK. The Great Britain's Housing Energy Fact File (Palmer and Cooper, 2011) brings together a range of data sources, chiefly the DECC energy use statistics, the English Housing survey and models of energy performance of homes, to provide a combined model of stock, energy use and improvements to describe the current status of the stock in relation to energy use. The Homes Energy Efficiency Database (HEED) links to data provided for Energy Performance Certificates, as well as government-funded improvement programmes to identify performance of homes and installation of improvements. This has been partially extended by the developing National Energy Efficiency Database, which has linked HEED data to bill data and information about occupants (Department for Energy Climate Change (DECC), 2012c). Both of these resources focus on the stock and the resultant energy savings for a large sample, while this study considers the adoption of technology in the context of the social housing provider.

In the adoption of new technology (Rogers, 1995) there will be different responses to new technologies or approaches in a population. Egmond *et al.* (2006) consider the factors driving adoption within social housing in the Netherlands, identifying the nature of the actors using Rogers adoption curve, which recognises new technology adoption diffuses at different rates through a given population and considers the approaches to accelerate this process. Cooper and Jones (2009) look in more detail at how UK social housing providers address broader sustainability issues, including environmental factors, in their existing stock, particularly around asset management processes undertaken in 2007. This study highlights a wide number of factors including organisational structure, policy, residents and finance that all influence the decision to invest. It also highlights that at the stage of the study, there were few formal processes that fully engaged sustainability into the decision-making process for social landlords. Social landlords also rely on their supply chains to deliver. Osmani and O'Reilly (2009) specifically looked at house builders in relation to zero carbon, but identified issues of cost, knowledge and client demand as key driving factors for adoption, issues reiterated by a follow-up study with architects with specific reference to retrofit (Davies and Osmani, 2011). While these studies focused on new build, they indicate that adoption is driven by wider factors than technical decision making, and are equally applicable in social housing sustainable retrofit.

The Retrofit State of the Nation Survey was designed to provide a perspective of current attitudes to retrofit amongst UK social housing providers, covering issues of strategy, drivers and barriers, technological adoption and perceptions of resident attitudes. Previous studies outline potential technical options and the factors that may influence adoption; here we discuss the technological choices that have been adopted by UK social housing, and their perceived effectiveness in use by the respondents to the survey. The objective of this element of the survey was to consider the sources of information used to determine adoption, the level of engagement with specific technologies and issues of perceived effectiveness.

UK social housing stock and energy efficiency

The UK housing stock is made up of 26.8 million homes (CLG, 2011; Welsh Assembly Government, 2011; Scottish Government, 2012; Northern Ireland Housing Executive, 2012) as shown in Table I. Within England 67 per cent of houses are owner-occupied, 16 per cent are privately rented and 17 per cent are social housing (CLG, 2011). Social housing is defined as, housing that is affordable, provided on a needs driven basis where housing provision is not met by the market (CLG, 2011). There are 4.7 million social homes in the UK, 18 per cent of total stock, including social housing providers and local authorities.

The social housing stock generally performs better against the energy efficiency standards than the housing stock as a whole. Energy efficiency for houses is the UK is measured using the standard assessment procedure (SAP) on a potential scale from 1-120, although practically the upper limit is 100, with a higher score indicating higher

Country	All tenures stock (millions)	Social stock (millions)
England	22.3	3.8
Scotland	2.5	0.6
Wales	1.3	0.2
Northern Ireland	0.7	0.1
UK	26.8	4.7

Table I.
UK All tenures and social stock by country

energy efficiency (Hong *et al.*, 2006). The English Housing Survey identifies the average SAP rating for the housing stock as 53 in all tenures and 60 in the social housing stock, indicating a marginally better performance.

The social housing stock has experienced a number of upgrade programmes that explain this higher performance (Boardman, 2007). The *Decent Homes Programme* included a range of fabric and heating improvements that improved the energy performance of stock (Reeves *et al.*, 2009; Power, 2008). In all, 1.4 million homes have benefited from some kind of Decent Homes intervention (National Audit Office (NAO), 2010). The energy companies deliver two UK Government programmes, the Carbon Emissions Reduction Tariff (CERT) and the Communities Energy Saving Programme (CESP). CERT is a programme focused on the reduction of carbon emissions deploying measures such as loft and cavity wall insulation (Jenkins, 2010). It has a requirement to address vulnerable households; older people, families with children under five, and those on some types of benefit (Druckman and Jackson, 2008), many of whom live in social housing. CESP addresses community-wide projects, taking a whole-house approach to sustainable retrofit (Reeves *et al.*, 2009) in areas of deprivation.

The Energy Company Obligation (ECO) will replace the CERT and CESP programmes in 2012/2013 (Department for Energy Climate Change (DECC), 2011b). ECO has three main components; affordable warmth and carbon saving, which replicate the CERT elements, and the *Carbon Saving Communities Obligation* (Department for Energy Climate Change (DECC), 2012b), replacing the CESP area-based approach. Warm Front, due to end in 2013, is a programme targeted at fuel poverty and health (Critchley *et al.*, 2007; Gilbertson *et al.*, 2006). It includes fabric and heating systems upgrades for vulnerable households. Over 2.3 million upgrades have been undertaken through the Warm Front programme (Warm Front Team, 2011). In addition, the loan-based green deal will also be available to the social housing sector (Guerler, 2012).

While social housing appears to perform better than the general stock, it might be considered that older houses in the private rented sector and owner-occupier sector present better opportunities for the reduction of carbon emissions or energy efficiency through sustainable retrofit. It should be noted that the owner-occupier sector contains many larger properties and individuals on higher incomes, both factors that drive higher energy consumption (Department for Energy Climate Change (DECC), 2011a). It should also be noted that these programmes influence the adoption of specific technologies within the social housing sector.

Methodology

In 2010/2011, the Retrofit for the Future Survey was undertaken in association with Procurement for Housing and Fusion21, social enterprises that provide procurement services to the social housing sector. The data were collected through a web-based questionnaire and the link was sent to 704 social housing providers who were registered with Procurement for Housing There were 130 valid responses, a response rate of 18 per cent. Nineteen responses were rejected for being organisational duplicates, in which case the most complete response was retained.

The survey objectives were developed with three housing professionals with a specific expertise in sustainable retrofit in the social housing sector, this included one supply-chain consultant and two social housing provider asset managers. They identified the main areas of concern, and were supported by the research team, who identified specific issues from the literature. These were converted into a number of questions that were a mixture of multiple choice, Likert Scale responses with some free text responses allowed.

There were 20 questions in total covering the following main areas (Table II).

Here we discuss the knowledge that social housing providers use to make decisions on the adoption of new technologies, the different technologies that have been adopted and their perceived effectiveness.

Respondents

Responses by size of registered provider (RP)

The responses from the sample by size of RP are shown in Table III. Nationally, the smallest 50 per cent of RPs manage less than 1 per cent of the stock, while the largest 18 per cent of RPs manage 90 per cent of the total social housing stock (HCA, 2012). The view was that the RPs with a larger stock would be more engaged with retrofit, having asset management programmes, and therefore these larger organisations were targeted.

Responses by region

The responses by region (Table III) were compared with the *Registered Statistical Return* (HCA, 2012). There are three regions that were over-represented by 20 per cent when compared to national distributions of social housing providers: northeast, east midlands and southwest. London was the only region that was significantly lower than expected (Table IV) nine organisations identified themselves as national, while a

Topic area	Question
Organisational information	Provider type Provider size Region
Strategic perspective	Main sectoral challenges Decent homes progress Strategic plan Adoption timescale Barriers
Assets	Average SAP rating Confidence in asset data
Knowledge	Externally sourced? Sources of information
Technology	Technologies adopted Effectiveness of technology
Resident engagement	Approaches adopted Effectiveness of approaches Drivers for residents to adopt Barriers for residents to adopt

Table II. Overview of the question issues

Number of units under management	% of respondents
< 250 units	5
251-1,000 units	5
1,001-5,000 units	26
5,001-10,000 units	34
10,001-50,000 units	26
> 50,000 units	4

Table III. Percentage of responses by size of registered provider number of regional organisations identified more than one region, particularly those who identified London, east of England and the southeast. Other connected regions, such as southeast and southwest, east midlands and east of England, also lead to multiple selections by regional RPs.

Responses by job role

Respondents were largely from an asset management or managerial background (Table V). 62 per cent of respondents have a technical role in connection with property and asset management, technical or environmental roles. The remainder of the respondents fall into the management/strategy category covering CEOs, directors, procurement, finance and other managerial roles.

Main findings

Sources of information

The respondents were asked to identify the main sources of information used when they were making decisions about what retrofit technology to adopt. The first question was designed to identify perceived organisational capability to make decisions, considering the adoption issues identified by Egmond *et al.* (2006), to indicate the role internal knowledge played in adoption of technologies. Of the 130 respondents, 66 (51 per cent) relied on internal sources, while 64 (49 per cent) relied on external sources. Once the categories with low respondent numbers have been discounted, there appears to be a slight increase of reliance on internal advice as the size of the organisation increases (Table IV). This indicates that larger organisations have the potential to support the technology adoption decision-making process internally when compared to smaller organisations (Table VI).

Table IV.
Responses by region of operation

Region	Number of respondents operating within region
Northwest	32
Northeast	14
Yorkshire and Humber	16
East midlands	15
West midlands	22
Southwest	23
East of England	19
Southeast	28
London	22

Table V.
Percentage of responses by job role

Job role	% of respondents
Asset/property	42
Technical	6
Procurement	7
Environment	14
CEO	5
Finance	2
Other directors	8
Other managers	16

External sources of information. Table VII identifies the external sources of information that the 130 RPs relied on to make decisions with regards to retrofit options. The respondents were allowed to select a maximum of three responses.

The largest source of information is professional networks, particularly other social housing providers (80 responses – 62 per cent). This is potentially driven by two factors; first, the social housing sector is willing to share and publicise new knowledge, and second the sector has had a number of demonstration projects in the retrofit area (Swan *et al.*, 2012). This reiterates the role of communities of practice (Davenport and Prusak, 1998; Wenger, 2000) in generating and sharing trusted knowledge between organisations.

The next largest number was government advisory services (67 responses – 51 per cent), which may operate at either the national level, such as the Energy Saving Trust, or at the regional level, such as Envirolink in the northwest of England. An interesting group of responses is around manufacturers (36 per cent), installers (18 per cent) and consultants (39 per cent) as sources of information. This does not chime with construction innovation generally where product manufacturers and installers were seen as major sources of innovation (CIOB, 2007). However, the study is less specific than this study, relating to construction innovation generally, which can potentially explain the differences.

Technology adoption and effectiveness

Adoption and effectiveness of technology. Table V compares the level of take-up of a specific technology as compared to the average perceived effectiveness for the specific technology. The question did not address the numbers of installations, rather it identified whether or not a RP had installed a particular technology. The respondent was then asked to rate the technology in terms of effectiveness on a Likert Scale of 1-5, with 1 being not effective and 5 being highly effective (Table VIII).

Size of RP	Internal	External
250 or less	2 (33%)	4 (66%)
251-1,000	1 (18%)	5 (82%)
1,001-5,000	14 (41%)	20 (59%)
5,001-10,000	25 (56%)	20 (44%)
10,001-500,000	20 (59%)	14 (41%)
500,001 +	4 (80%)	1 (20%)
Number	66	64

Table VI.
Reliance on internal or external knowledge by social housing provider size

Information source	Number of responses
Procurement bodies	23
Government advisory services	63
Universities	7
Internet	30
Networks	80
Industry reports	37
Consultants	51
Installers	24
Manufacturers	47

Table VII.
External sources of information for retrofit decision making

Table VIII.
Technology take-up and perceived effectiveness

Technology adopted	Number of providers adopting	Mean perceived effectiveness of technology	SD
Loft insulation	123 (94.6%)	4.42	0.75
Cavity wall insulation	119 (91.5%)	4.26	0.94
Thermally efficient doors and windows	90 (69.2%)	3.98	0.86
Draught stripping	83 (63.8%)	3.45	0.99
Solid wall insulation solutions	72 (55.4%)	3.96	1.14
Solar thermal	70 (53.8%)	3.61	1.00
Air source heat pumps	60 (46.2%)	3.30	0.91
Mechanical ventilation/heat recovery	57 (43.8%)	3.09	0.81
Grade A appliances with supplements (e.g. gas-save)	53 (40.8%)	4.00	1.13
Photovoltaics	53 (40.8%)	3.56	0.82
Ground source heat pumps	33 (25.4%)	3.65	1.09
CHP boilers	30 (23.1%)	3.34	1.04
Supply of high-efficiency white goods to residents	19 (14.6%)	3.21	1.18
Biomass boilers	18 (13.8%)	2.11	1.02
Wind turbines	4 (3.1%)	1.00	0

The four most widely adopted technologies are low-technology fabric solutions: loft insulation, cavity wall insulation, doors and windows and draught stripping. These approaches have been driven by a number of programmes such as Warm Front, CESP, CERT and some elements of the *Decent Homes Programme*. The next range of technologies includes, air source heat pumps, mechanical ventilation and heat recovery (MVHR), solar thermal and solid wall insulation, which could be viewed as more technically complex. Combined heat and power, ground source heat pumps, biomass boilers and wind turbines all had significantly lower levels of adoption. There were five responses in the other category. Two of these responses were concerned with behavioural programmes, two were concerned with energy saving light bulbs and one was concerned with PassivHaus retrofit. Energy saving light bulbs had been deliberately excluded from the study as the resident, without landlord intervention, could directly adopt them. PassivHaus was also excluded, as it is a methodology of insulation and associated ventilation technologies, rather than a specific technology in itself. When compared with data available from the GB Energy Fact File (Palmer and Cooper, 2011), we can see it reflects the data from the Retrofit State of the Nation Survey reflects the national trends with respect to fabric improvements. However, data available for microgeneration in the Fact File, such as solar thermal, photovoltaics, wind and ground source heat pumps, is from 2008 and potentially does not reflect the adoption of these technologies in 2010/2011, particularly in the context of the feed in tariff. In addition, the collection of data on solid wall insulations is also highlighted as problematic in the Fact File.

Loft and cavity wall insulation are viewed as the most effective technologies. “A” rated heating systems, solid wall insulation and doors and windows rated are the next group, with many of the renewable and energy-efficient heating systems falling into the lower level of effectiveness. In terms of low effectiveness, two technologies stand out, biomass and wind turbines. Twenty RPs adopted biomass with an average effectiveness rating of 2.11, slightly ineffective. Wind turbines were only adopted by four RPs and deemed as not at all effective. The lack of adoption of wind turbines is probably due to the view that wind is generally ineffective at a small scale and in urban and suburban environments (Encraft, 2009) limiting its applicability to housing. The correlation between adoption rates and perceived effectiveness was 0.65 suggesting a moderate correlation between the variables.

The standard deviations indicate the level of agreement among the sample with regards to the level of effectiveness. Removing the result for wind turbines, that has a very small sample, the standard deviations range from 0.75 for loft insulation to 1.18 for the supply of white goods. What might have been expected is that there would be less agreement with regards to the effectiveness of products where there is more potential uncertainty in their performance driven by installation or in use risks, leading to a wider variance of outcome. Air source heat pumps, for example, have a number of recognised issues around specification and installation that might affect their performance (Energy Saving Trust, 2010), while MVHR has issues around usability (Heaslip, 2012). However, air source heat pumps (0.91) and MVHR (0.81) are both at the lower end of the range of the standard deviations, suggesting marginally more agreement among the respondents with regards to their effectiveness when compared to other technologies.

The high level perspective of what effectiveness is and how it is evaluated used in the survey raises a number of issues. What criteria are the respondents using to assess effectiveness? A number of authors have identified the kinds of carbon savings that might be achieved through the application of different technologies (Jenkins, 2010, Reeves *et al.*, 2010), but given the context of issues such as fuel poverty and resident relationships that are part of the social housing landlords agenda, is this carbon saving perspective view of effectiveness too narrow? The Construction Products Association (2010) identified three potential factors that might potentially colour landlord's views of effectiveness; cost, carbon savings and the level of disruption caused by installation in their study of potential retrofit solutions. The consideration of how residents engage with technologies also might form part of this perception. In addition, how different products work together as different packages of measures has an influence on their performance (Simpson and Banfill, 2012). Heating systems provided without additional fabric improvements may cause performance to be greatly reduced. The Retrofit State of the Nation was designed to give a higher level of the attitudes of the sector concerning a range of issues surrounding sustainable retrofit, but in terms of considering effectiveness, it does not investigate the context in which measures are implemented and the precise definitions that may be used by different respondents. This view may be driven by organisational context (Reeves, 2011), as well the complex inter-relationship between project definition, delivery and in-use factors, all of which have a capacity to influence the potential performance of retrofit solutions. The complexity surround the notion of effectiveness is certainly worth further consideration.

Conclusions

The survey shows some predictable patterns of adoption of retrofit technologies. Low technology, grant-funded options are almost universal, while more complex technologies, particularly those based around new approaches to heating, such as biomass or heat pumps are less widespread. The social housing sector is starting to engage with these newer technologies, although the data does not indicate whether these are commonplace within the RP's stock, or merely demonstrator projects. There is some evidence that larger organisations do perceive themselves to have more knowledge with regards to retrofit, the expertise does seem to extend to smaller organisations. The sector appears to have developed industry networks, which the respondents identified as a key information source.

Considering effectiveness, there is a question as to what social landlords actually know about the performance of retrofits and how they may be defining the term effectiveness. This limitation of the study does highlight the importance of us needing to understand the different definitions and perspectives of what effective solutions might be. There needs to be a better understanding of effectiveness as view not only by technical staff, but also residents. This can only be achieved through effective monitoring and evaluation of retrofit projects to build an evidence base that a social landlord can access. Large-scale monitoring projects such as *FutureFit* (Affinity Sutton, 2011) are not widespread. This needs to change, projects need to be undertaken and the results widely disseminated.

The Retrofit State of the Nation Survey represents as snapshot. There is an argument for undertaking the survey again periodically to see the trajectory of the sector. It is also worth considering in more detail as to whether this adoption pattern can be considered market-making activity that will serve the wider housing stock. Knowledge appears to be being built, but much of this knowledge is being built with the repeat client. While projects that have piloted new technology do build skills and knowledge, how this will translate into a private sector market remains to be seen.

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A UK practitioner view of domestic energy performance measurement

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There is a growing body of evidence concerning the energy efficiency performance of domestic buildings in the UK, driven by policy-based agendas, such as the need for zero carbon dioxide homes by 2016 for new build homes, and the prior Green Deal and energy company obligation for sustainable refurbishment. While there have been a number of studies funded and results presented in this area, little work has been done to understand the drivers, practices and issues of data collection and analysis. There are a number of major building performance evaluation (BPE) studies in the UK, yet behind many of these research projects are practical issues of data loss, experimental error, data analysis variances and resident issues that are common when studies move from the actual to the living lab. In this paper the issues of domestic energy are addressed by leading BPE practitioners in the UK. They identify issues of client demands, technical failure, costs and implementation. This work provides insights of both academic and industry-based practitioners and considers, not only the practicalities of building performance studies, but also issues for these types of studies in the future.

1. Introduction

Research into domestic energy performance of buildings has grown in recent years in response to the policy agenda. There has been a large number of projects as identified by Gupta and Gregg (2012), including the building performance evaluation (BPE) programme (Menezes *et al*., 2012) undertaken for Innovate UK (TSB), as well as other grant funded and private research. The drivers to undertake research vary. Government requires an evidence base (DECC, 2014) to drive and inform policy, while the manufacturing and installation companies need to understand the evidence for the performance of their products and services. There has been a long-standing argument that buildings rarely perform as modelled in the field (Jaffe and Stavins, 1994; ZCH, 2013, 2014). The reasons for this have been widely discussed (Bordass *et al*., 2001; Wingfield, 2011; Wingfield *et al*., 2008; ZCH, 2014). The growth in field testing of domestic properties and products has not been balanced by a wider discussion about the methodological issues of gathering data in the field.

Nine experienced UK domestic practitioners from the Innovate UK domestic BPE panel were interviewed to investigate their perspectives of the methods and practical issues of fieldwork and analysis. What emerged is a pattern of practices that potentially point to a measurement and analysis gap that needs to be addressed to understand better the problems of building performance (Stafford *et al*., 2012).

The introduction of the Climate Change Act 2008 (2008) created a legislative binding target to reduce carbon dioxide (CO_2) emissions by 80% by 2050. In 2010, the UK domestic housing stock accounted for approximately 27% of UK carbon dioxide emissions (Palmer *et al*., 2011). This policy agenda provides a potential driver to understand better the performance of the existing housing stock in terms of its energy use and carbon dioxide emissions. The new build market delivered 109 370 homes in 2013 (DCLG, 2014) and is subject to building regulations, specifically part L of the building regulations that relates to fuel conservation, which has become more stringent in recent years. There is a requirement for zero carbon dioxide homes by 2016. This places pressure on the UK house builders to understand how to achieve these levels of performance (Osmani and O'Reilly, 2009). New build housing has been identified as suffering from a performance gap, the gap between designed and measured performance (ZCH, 2013, 2014). It is perhaps only recently that consideration of the measurement side of the equation has been given more thought. The understanding of a potential measurement gap by the industry, driven by methodological issues of domestic BPE, is of interest to the policy makers, manufacturers, installers, stockholders and end users.

There are approximately 26 million homes in the UK (Swan *et al*., 2013), and of this existing stock 70–80% will remain by 2050 (Ravetz, 2008). In terms of policy ambitions for emissions from the domestic sector, this is the biggest challenge (Kelly, 2009). In the retrofit market, the Green Deal (Dowson *et al*., 2012) has been implemented as part of the Energy Act 2011 (2011). The Green Deal is a loan facility attached to the property that uses potential energy savings to fund improvements to the property, such as insulation, or new heating systems. The Green Deal loan is currently constrained by the golden rule that requires that the savings of energy must be equal to or more than the cost of the loan, leaving the occupant no worse off than if they had not taken out the loan (Guertler, 2012). These savings are modelled using the often criticised reduced data standard assessment procedure (RdSAP) model (Wetherell and Hawkes, 2011). The energy company obligation (ECO) is a form of supplier obligation. There are three types of ECO, all of which deliver a range of retrofit improvements to properties, with many similarities to the Green Deal in terms of eligible measures, which are modelled using RdSAP.

An accurate view of the performance of individual actions and packages of measures both before and post-installation is important. There are policy and financial interests that rely on data provided by the BPE sector; this is an industry that is difficult to identify fully, perhaps due to its broad range of activities that might be determined as BPE.

2. What is BPE?

The growing research into building performance is largely driven by energy consumption and its related outcomes (Gupta and Gregg, 2012), such as ventilation, condensation and issues of building pathology. However, this is a more complex issue than merely measuring the energy consumption of the property; boundary conditions, building fabric and form, systems, controls, and occupant factors, such as comfort, health, economic and psychological factors, all come into play when evaluating not only performance, but underlying factors that drive this performance (Oreszczyn and Lowe, 2010).

Leaman *et al*. (2010) focused mainly on commercial buildings and identified that BPE falls into the category of real world research and this position is equally applicable to domestic properties. This highlights the practical nature of building performance problems identified and determines that BPE should create actionable knowledge. This school of thought builds on the work of Bordass *et al*. (2001) that looked at practical tools for commercial buildings. It identified a wide number of potential outcomes and embedded BPE within a practical research philosophy. Gupta and Gregg (2012) outlined the current research profile of energy and buildings in the domestic sector and identified the sheer complexity and range of research questions that are covered. They also identified how research questions are shaped depending on where the focus of outcome is placed.

While it is not the intention to address the debate of the philosophical structure of building performance energy research, it is clear that there is an important debate to be had about both why and how this research is undertaken in this strategically important area. While BPE generally addresses both domestic and non-domestic buildings, in order to limit the discussion the question of how the heating energy performance of a domestic building is measured has been considered. It is recognised that energy consumption is expansive and includes issues such as lighting, appliances and cooking (Palmer *et al*., 2011). The focus here is on the key variables that influence heating energy performance: fabric, systems and occupants.

2.1 What is measured when building performance is evaluated?

The measurement of energy consumption in domestic properties, as discussed by the interviewees, could be viewed as a mixed method case study (Johnson and Onwuegbuzie, 2004) reflecting the range of qualitative and quantitative factors as identified below. While larger statistical studies can describe performance at the highest level, such as Shipworth *et al*. (2010), the housing energy fact file (Palmer *et al*., 2011) or the national energy efficiency database framework (DECC, 2011), the BPE professionals interviewed here look at the underlying reasons that shape energy performance and so have a more detailed focus that considers the interrelationships between elements of individual properties or groups of properties.

Boundary conditions have a major impact on the performance of the properties (Karlsson and Moshfegh, 2006). Clearly, the external temperature will influence internal temperature and so must be measured. In addition, energy inputs from solar gain in the fabric and through glazing will impact the internal temperature of the property (CEBE, 2010). Wind will impact the performance of the fabric as it alters the convective heat loss of elements and can also lead to wind washing (Ito *et al*., 1972; Yazdanian and Klems, 1994), and although not widely researched, rain has an impact on the conductivity performance of the building fabric (Blocken and Carmeliet, 2004).

A further consideration is the fabric of the building itself. Major issues are the losses and gains related to the property through conduction and convection. Conduction gains and losses are through the different elements of the building fabric and are determined by the conductivity of the elements, measured in the U-value (Anderson, 2006). Typical approaches are heat flux measures of building elements (Baker, 2008) or whole house approaches, such as co-heating (Sutton *et al*., 2012). Heat may be lost or gained through convection, when air passes through the fabric of the building transmitting heat energy. This is commonly measured using an air permeability test, which measures the air supplied to the building per square metre using a pressure differential of 50 Pa (ATTMA, 2010). These types of analyses link to building surveying and pathology, the underlying factors in fabric performance, such as thermal bridging due to poor design or construction, which might drive actual performance, as highlighted by the ZCH (2014) report. Although important, these have not been directly covered as the study focuses on the standard data collection tools of domestic BPE as identified by the interviewees. The heating system performance is an additional element that requires an understanding of energy inputs and the efficiency of the system. This is commonly a heat source and a series of emitters, such as a wet radiator system. The heating system may be measured in terms of energy consumption and heating output, to understand the efficiency of the system (Energy Savings Trust, 2010).

The internal environment must be measured to understand the relationship between consumption and outcomes. This has an influence in locating energy efficiency in terms of outcomes for the occupant, that is, how much is energy is used to attain a certain level of comfort. To understand heating energy, the primary measure is internal temperature, generally gathered in multiple locations throughout the property. In addition, due to their impact on occupant comfort, relative humidity and internal ventilation data may be collected.

Finally, an understanding of the occupant is essential. How individuals manage their comfort, their physiology and psychology, as well as a number of socioeconomic factors (Nicol *et al*., 2012). These interviews have investigated the process of collecting data from the occupant and their role in the wider BPE process in occupied properties, rather than their influence on energy performance.

In summary, this study focused on the reasons for undertaking studies and the practical issues of collecting data and presenting results, rather than investigating the underlying theory of BPE and its constituent theoretical elements. The goal is to understand the practice of data collection and analysis that can influence findings from the practitioner perspective.

3. Methodology, sample and analysis

The study focuses on the practice and experience of experts in measuring the energy performance of domestic buildings in the UK. The study objectives were to explore the understanding experts had of their role in measurement, their practice and approach to measurement and their reflections about this process. The sample frame used to identify respondents (i.e. experts) was the Technology Strategy Board's BPE panel, which is made up of 42 academic and industry experts in the field. Each was contacted by way of e-mail or phone and the nature of the study discussed. This initial framing of the study considered BPE as a whole as a starting point. However, all of the responses came from the domestic BPE panel. At the time of the study, this panel contained 23 individual experts. Of these, nine agreed to participate in the study. The study took an exploratory approach, with no pre-formed hypothesis, in order to avoid a research bias. Semi-structured interview methods were used. As Burman (1994) identified, such methods offer opportunities not only to identify the details of what is done, but also the 'contradictions and complexities' (p. 50) as to how things work in practice. The question themes were

- how did the interviewee define BPE?
- what tests and data collection approaches did they take?
- how were tests defined and commissioned?
- what were the practical issues of data collection?
- what were the issues around data analysis and reporting?

The interviews were undertaken face to face and by way of telephone and were audio recorded. These interviews were then transcribed verbatim. All respondents were assured of their anonymity. The details of the sample are described in Table 1. The respondents came from a range of different backgrounds. Although most came from the building professions, two individuals with the least BPE experience came from a physics background, which may indicate an increased level of scientific engagement with buildings and energy. Those with the greatest experience came from backgrounds more traditionally associated with building performance, such as architects, energy managers and building services engineers, professions more closely associated with engineering rather than pure science.

The qualitative software package QSR Nvivo was used to store, manage and analyse the textual data. A sequential approach to thematic analysis was used following the guidelines of King and Horrocks (2010). The analytical strategy involved a process of reading and re-reading of the transcripts and sifting the text into key issues and themes.

4. Findings

The following section highlights the thematic responses from the interviewees. While the interviewees were asked to reflect on their own practice, they do consider the wider BPE sector as a whole.

4.1 What is domestic BPE and what is it for?

There was a shared view with regard to the context of what entailed building performance. All of the practitioners had been involved in both commercially funded and government funded projects.

> Different people do it (BPE) for different reasons. A lot of people… are quite interested in issues of health. It's [BPE]… to see if they are using energy in the same way. That's a starting point for a lot of projects…. It is things like this that clients are asking. Is this stuff that we spent a lot of money on and fitted actually working or not? Interviewee H

Interviewee	Background	Experience in BPE	Organisation
A	Building services	25 years	Consultant
B	Physics	2 years	University
C	Building physics	19 years	University
D	Building services	15 years	Consultancy
E	Structural engineer	8 years	Consultancy
F	Physics	3 years	Consultancy
G	Energy manager	35 years	Client
H	Architect	7 years	University
I	Post-occupancy evaluation	4 years	Contractor

Table 1. Description of sample

The performance gap between the designed and the actual performance of buildings was seen as the major issue by many of the interviewees.

> My own personal view is that it should be a fundamental part of the construction process. I can conceive of no other sort of design in which it wouldn't be acceptable to see if the thing you designed actually works or not. Interviewee H

There were concerns from six interviewees around the difficulties of defining research questions for BPE projects. Given the range of techniques available and the varying conditions between properties, the respondents indicated that, while often quantitative in nature, the studies appeared to be better defined as mixed method case studies. The propositions of those case studies are driven by the desired outcomes, with appropriate data collection being applied. However, seven of the interviewees highlighted that the question was often shaped by the more prosaic issues of who paid for the work and how much resource was available.

All of the interviewees' views on what elements constitute BPE were expressed in terms of the individual tests that were used in concert to establish the performance of the building. These included fabric tests, environmental monitoring and understanding of the occupant when addressing occupied properties. This reflects the perceived sociotechnical nature of the research question. The interviewee skill sets with regard to carrying out specific tests varied, but all understood the wider range of available tests. The greatest variation was between those who engaged with occupants and internal environments (three interviewees) and those who tended to focus solely around building fabric (five interviewees). Interviewee B reflected the whole house perspective that was shared by all of the interviewees.

> If you call a whole dwelling a product. That is looking at most aspects right from ventilation right through to fabric performance. Interviewee B

The fabric tests referenced in the interviews were thermography, air permeability tests, in situ U-values and whole house heating tests such as co-heating. All of these were viewed by at least one of the interviewees as not being without difficulties. Interviewees A and B identified that thermography has a powerful visual impact but also has a number of complexities in its delivery due to wind, solar and temperature differentials between the inside and outside of the properties for reliable results, issues also raised by Balaras and Argiriou (2002).

> Thermography is the flavour of the moment, because it's very visual and it's very useful too. But comparing two buildings at potentially two years apart in the study will yield different results. Interviewee A

Internal and external environmental monitoring were identified by all of the interviewees as within their skill sets. This included temperature and relative humidity, ventilation measures, sometimes using carbon dioxide as a proxy measure, energy consumption and weather data. Where the sample diverged was with their inclusion of resident data. This did not appear to be a philosophical decision, rather it was based around skill sets, as noted above. Interviewee B identified themselves as a fabric specialist.

> For me, personally, you have to understand how the fabric of the dwelling works before you can then ascribe anything to what an actual what the occupants… Interviewee B

Interviewee H identified themselves as a post-occupancy evaluation specialist and therefore focused more strongly on occupants as part of the research process.

> I think one of the other techniques that I've used pre retrofit would be something… like a comfort satisfaction study. That tends to point you in a much better direction than most data will, because that's the actual things that people notice in buildings that they actually care about. Interviewee H

Despite these differences, the view of the group was that all of the issues were important, but they focused on their specialisms, potentially identifying the need for multidisciplinary teams in the whole house assessment.

4.2 Clients for domestic BPE

The shaping of the research question, as well as the limitations of the study, were identified as being driven by the knowledge, needs and aspirations of the client.

> It does vary depending on the nature of the client and the project and certainly the funding behind it. Interviewee H

Key clients highlighted by the interviewees were the UK Technology Strategy Board, as part of their BPE programme, which given the nature of the sample was clear. Another key client group was UK social housing, which as large stockholders of properties appeared to be driving some of the market, particularly in terms of evaluating the performance of retrofit.

> Social Housing wanting to know what return they are getting on their investment [in retrofit]. Interviewee A

However, interviewee G stated another set of objectives for social housing.

> They [social housing providers] want somebody to say how well they've done and, indirectly, it's kudos, they want status and money. They have done it in order to attract attention and the attention comes back as a PR thing. Interviewee G

Manufacturers are also involved in commissioning BPE work in order to evaluate their products.

> We have, on occasion, worked for manufacturers where they are developing products. And in that sense, obviously it's essential they have a sort of before and after scenario. Interviewee E

The private commissioning of research of this type is not without its complications. The issue of bad news in consultancy work was raised by five of the interviewees in terms of how it impacted the independence of the research.

> There may need to be some degree of independence to this process in order that it's verifiable and that it's thorough and it's reportable and the people aren't 'burying the bodies', so to speak. That goes back to the question of what do people do about bad news? Interviewee H

There was also a perceived gap in understanding the need for effective monitoring by clients, which constrains not only the extent of monitoring, but also the perceived need.

> … that's usually down to the experience of the client in how to do an experiment. Largely, they are developers, builders, social housing and they come from a completely different industry and don't recognise that need at all. Interviewee F

4.3 Project constraints

The major constraints identified by the interviewees were the timing of the studies and costs. In terms of timing, difficulties were highlighted with regard to the ability of the interviewees to undertake effective pre- and post-monitoring, highlighted by interviewee A.

> I would say there is too little emphasis placed on pre-… Interviewee A

Another issue highlighted was the need to link monitoring to build programmes. This presented difficulties for two main reasons. The first was the issue of dealing with tests that are constrained by the heating season, such as thermography, co-heating and in situ U-values. The second was the issue of buildings not being settled after construction works, potentially giving rise to errors.

> Obviously, with construction timeframes… we've had a number of times [where] we've had to squeeze a test into the end of a heating season…. We might be testing buildings that are too green. They have got a lot of moisture in there. That causes problems because obviously your materials might have high thermal conductivity because they might have moisture in there and also that you find you bring out a lot of moisture into the dwelling and then you could have problems such as mould. Interviewee B

The commissioning client often constrained the project by their ability to fund the project fully to answer the question at hand. Three of the interviewees identified that budgets often put clients off engaging with the process.

> When they are in the audience who are wanting to understand more about BP, but not done it before themselves hear some of the project costs, they get absolutely horrified and go, how much? Interviewee A

This can also lead to issues in which the project may be potentially reduced. Interviewee D went on to indicate that the client could find people to deliver in the market place at reduced costs at the expense of rigour.

> When I mentioned £2000 to do a job on it they just said, well, it's far too expensive. So then the bottom line. What can you do for £750? I said, we won't be doing anything for £750 because there is nothing that we would put our name to that's going to help you or the people involved, so take it or leave it. Interviewee D

4.4 Equipment

Issues with equipment were a major issue for all of the interviewees. This was particularly the case when internal and external monitoring was undertaken. The interviewees identified four key issues: technical performance of the equipment, installation issues, battery life and communications.

The non-performance of equipment was a common problem.

> … a lot of the projects we are looking at bits of kit have gone wrong. Interview H

This was exacerbated by the fact that often it was difficult to establish when equipment failed, with failures often being discovered well into projects. Monitoring systems were often identified as being installed incorrectly, such as heat metering on heating systems, or sensors placed incorrectly leading to incorrect readings. The issue of communications, required when collecting data remotely, and battery life were also considered major issues by all the interviewees who used this equipment.

> Comms is the biggest problem and power is the second problem. Interviewee E

These basic technical issues can derail an expensive monitoring project.

> We use wireless sensors and they do fail. That is challenging and depending on when the battery goes, it can also be project killing as well. Interviewee F

Among those interviewees who undertook internal and external environmental monitoring, the consensus appeared to be that the market for equipment was immature, with improvements being made, but a perceived lack of robustness for field testing that injected a certain amount of risk into field-based data collection.

4.5 Occupants

Assessing properties in occupation gives a detailed understanding of the property in use, but proved a major issue for those interviewees that worked in occupied properties.

> The biggest problem tends to be access. Getting access to houses, particularly. Once your equipment is in, you are relying on a certain amount of goodwill and cooperation from people in there to give you

> reasonable access and, with the best will in the world, you can make all the best endeavours to make sure you get access and sometimes you can just turn up and if there is no-one in and so access is an issue. Interviewee A

This issue is also replicated in the authors' experience, when a 40 sample study was subject to drop out and replacement rates of the sample of some 40% of the original agreed properties despite incentives. In addition, access to the property does not guarantee co-operation.

> … in use monitoring, we have always got a problem with the people in there. We've got people… switching off loggers. Switching off sensors. Dropping sensors in the bath. Interviewee B

Additional examples include issues of removal of sensors because they thought they would affect pets and blowing smoke into sensors. This was not universal; interviewee F indicated high levels of engagement with residents. In terms of occupied properties, accessing homes and engaging with them was identified as an essential skill when undertaking domestic monitoring.

4.6 Standards and data analysis

The recent growth of interest in building energy performance was highlighted as a problem in terms of maintaining quality and standards. Interviewee I identified that a more detailed understanding of the practice in terms of setting questions, collecting data and drawing conclusions needed to be better established.

> … There is excitement that just needs to be curbed a little bit I guess and just make sure that we are doing it for the right reasons and we are monitoring the right thing. Interviewee I

However, the issue of standards, even between respected professionals, was a complex one, with two individuals stating that they often developed their own approaches to solve specific problems.

> For me it's very similar with experiments. So you are always looking for a common point. At the moment, I don't see any of those common points in the methods. I would do things differently. Interviewee G

However, despite stating their preference for their own solutions interviewee I did respond to the growth in the sector with recognition of a need for more formal standards.

> I think there is a need for it, because if more people start doing this then it needs to be more kind of structured. Interviewee I

The interviewees also considered how the data were presented in a way that decisions could be made.

> You just sit there and there is this wonderfully spiky line. What am I supposed to tell from that? Be a bit more savvy and think around it and start to come up with some more sensible presentations for data. Interviewee I

The interviewees also indicated issues of monitoring teams sometimes not being aware of what the data might mean; a lack of experience in understanding building performance might lead to an inability to spot errors in the data or the drawing of incorrect conclusions. This potentially links back to the skills gap that the growth in the sector had created.

5. Conclusions

This study explored the debate surrounding practical methodological considerations of domestic BPE. Due to the sample size the study can only suggest tentative conclusions. Issues of experimental design, data collection error and fieldwork practicalities are not uncommon to any data collection and analysis exercise of this type. However, the area of building performance, particularly around energy, is strategically important. The developing space for BPE in the domestic sector indicates that there are potential gaps in both measurement and analysis, which can undermine the need to address the performance gap by the wider construction industry.

Within the sector, there are movements to understand better the flow from data collection to actionable knowledge. It requires the development of a community of practice (Wenger and Snyder, 2000), in which the issues of equipment, data collection and data analysis can be effectively debated. This space needs to recognise its failures as much as its successes if the debate is to be extended and the situation improved. To some extent this is already happening with leading institutions, both academic and professional, looking to establish such a network, although this is in the developmental stage.

Although the Technology Strategy Board (2009) and the Energy Savings Trust (2005) have developed guidance for domestic monitoring, the adoption of standards outside their own funded work was unclear. Many of the individual tests have ISO or British standards (BSI, 1999; ISO, 1994) but the use of these requires commissioning clients to appreciate their existence. The distribution of standards among various bodies can mean that a mixed method case, such as that of domestic energy monitoring, brings a wide range of expertise to ensure key standards are recognised and adhered to.

The quality of the data collected is identified as only part of the problem; there is also the conversion of these data, if of good quality, into useable data. There are multiple data streams, and qualitative data, which need to be analysed and presented into actionable information. This creates an argument for both an improvement in more widely available, robust analytical tools, and also an improvement in interpretive skills. The quality of data collection, analysis and communication all need to improve better to support the real problem of improving the energy performance of buildings.

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Energy Monitoring in Retrofit Projects: Strategies, Tools and Practices

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Energy Monitoring in Retrofit Projects: Strategies, Tools and Practices

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Abstract

Many of the projections of the energy performance of retrofitted properties are based on models that may or may not accurately reflect the real falls in energy use and associated carbon dioxide emissions. The gap between as modelled and as built energy use has been apparent in the new build market for some time, and it is no less of an issue within retrofit projects. Evidence as to the current and potential future performance of the housing stock is required to help us more fully understand the direction of travel, as well as identifying effective upgrade approaches. There is substantial work concerning the findings from monitoring projects, but less information on strategies and practices to support effective monitoring of energy in buildings. Here we discuss some of the main considerations in developing a monitoring strategy and identify some of the main tools that are currently being used in practice to assess the energy performance of buildings and their occupants.

Keywords: *retrofit, monitoring, energy, data management, sensor technology, gas monitors,*

Introduction

The effective assessment of a property to understand its energy efficiency can initially appear to be a relatively simple task. However, when we investigate the field in more detail we recognise that there are a wide number of metrics that we can collect and a complex raft of reasons behind the numbers. Energy use within a property is driven by three main factors; the fabric, the systems and appliances that use energy within the building, and the energy consumption choices made by the occupants. While the role of people is important, here we will put more focus on the issues surrounding the physical aspects of energy use. Using evidence to determine a retrofit strategy seems an obvious approach to adopt, however, many of the decisions that are made in both new build and retrofit projects are based on energy modelling approaches, commonly the Standard Assessment Procedure (SAP) and the Reduced Data Standard Assessment Procedure (RdSAP), which are the current UK industry standards for assessment of domestic properties. While models are essential to an effective decision-making process, the potential weaknesses of an over-reliance on them are clear. Evidence on the actual against stated performance on a number of technologies has shown the gap between the two. For example, the under-performance of urban micro-wind, as discussed in the Warwick wind trials (Encraft, 2009), shows that a lack of performance data on a specific retrofit technology can lead to investment in a technology that is not justified by its performance.

Energy monitoring can be summed up as the regular collection and analysis of data concerning energy use, as well as the various contributory factors that influence energy consumption, such as temperature or building fabric performance, for example. Westergren (1999) defines an energy monitoring process as one that “measures energy use in relation to internal and external climate in different types of single-family houses during periods with and without heating. It is also expected to provide a basis for analysis and evaluation of energy efficiency measures”. This could be viewed as a fabric-oriented perspective and this perspective does cover a large proportion of energy use. However, we should also recognise that unregulated energy use, such as appliances is also part of the monitoring process, although this is often managed through behavioural change programmes with occupants rather than physical changes to properties fabric and systems.

Retrofit is still an emerging skill set; while many of the approaches and products are well known, the knowledge base to select the right options and deliver them is still emerging. Understanding the pre- and post-retrofit performance of a property gives us some indication of the potential improvement the retrofit measures have brought about. However, as we have stated previously, energy use is an interaction between the building fabric, the systems and appliances and the individuals who use the building (Santin et al 2009). It is important to understand what factors are encompassed in any particular data set. If we measure general energy use through bills or data loggers, we are not only looking at the efficiency of fabric and systems, but also behaviour; if we undertake a pressure test, we are solely considering the integrity of the building fabric. Although we do not consider human behaviour in detail in this section, it is essential to recognise where human factors are affecting outcomes. The mantra “buildings don’t use energy people do” (Janda 2011), which has become commonplace in the retrofit community, does have some truth, but the building and systems provide the vehicle for a households energy use. Poorly performing systems and fabric will undermine good behaviours.

In this chapter we consider two key elements of monitoring. Firstly we consider the types of issues we need to consider in the development of a monitoring strategy, such as identifying objectives. In the second part we look at the main tests and tools available to use when we are measuring the energy efficiency of buildings.

Energy Monitoring Strategies

What do we want to know?

As with any research question, framing what we want to know will to a large degree drive what strategies and practices that we ultimately adopt. If we wish to look at the performance of a specific element of a property, such as a wall, our approach will be different as compared to a whole house test with occupants. There are a number of standards that are available in the development of a monitoring strategy. In terms of assessing retrofit, which we will consider here, the UK’s Technology Strategy Board, a research funding body, has developed a set of guidelines (TSB 2012). These were specifically developed to address some of problems of predicted against actual performance of energy use of buildings. The Energy Saving Trust, a UK energy advisory service, has also developed a range of standards for energy monitoring (Energy Savings Trust 2005, 2008, 2012), which identifies factors such as equipment used, accuracy and calibration, and frequency of readings. Both these sets of documents are essential reading for any professional monitoring team.

Households use energy in a number of different ways. A commonly used concept here is to consider regulated and unregulated energy (Gill, 2011). Regulated energy is that covered by the building regulations covered by heating, hot water, lighting and any powered ventilation. Unregulated energy covers everything else, such as appliances and energy used for cooking. However, both of these categories of energy use can be strongly driven by human factors, giving widely different energy usage for the same property (Summerfield et al 2010). A more useful approach might be to think of the research problem in a systemic way, drawing the boundary from sub-elements, as might be tested using building fabric tests, to the wider fabric, which may be tested using approaches such as co-heating or pressure tests. Systems, such as heating and lighting may then be considered, with testing in situ for efficiency. Human behaviour may then be considered, if the whole household's performance forms part of the research question. Obviously, this can be expanded to consider communities or neighbourhoods, particularly in the context of communal energy systems. The effective drawing of boundaries based on the research question is an essential part of understanding what techniques can effectively be deployed (Von Bulow, 1989).

When should we measure?

Once we have established the boundary of the research question, we also need to consider when we need to measure. If data is gathered at both the pre- and post-retrofit stages, then an accurate conclusion can be reached as to the effectiveness of the installation and provide robust evidence as to whether the project actually produced a building that is more energy efficient with reduced carbon emissions. Importantly, it can also help address what elements of the refurbishment did or did not work.

For a successful project it is essential that the data captured covers all of these events outlined in Figure 1. Where properties have been void, this may not be possible, but this approach outlines the key stages for occupied properties.

The *pre-start occupied* phase is useful to give a baseline. This initial data may challenge existing assumptions about energy performance of the property. Understanding normal occupancy may require measuring through an entire heating season (Energy Saving Trust, 2008) to understand different patterns of behaviour over the year. The *installation phase,* although not important in terms of an overall monitoring strategy, raises a number of practical issues. It is important to remove any of the monitoring equipment that is likely to be damaged by dust, such as temperature sensors and other sensitive equipment. However, equipment such as electricity monitoring equipment if in a protected location may be left in place. The *post-construction un-occupied* phase presents opportunities to consider tests that the occupant may find intrusive, such as airtightness testing or thermography. Some may consider these kinds of tests outside the field of monitoring, however, where these are carried out as a comparative study of pre/post retrofit measures then they might be considered to fall within the scope of monitoring, albeit with a different approach to traditional monitoring. As with all monitoring, it should be carried out so that the two phases of data capture are carried out under similar conditions. For example, IR thermographs should be taken in similar weather conditions and of the same detail/façade locations. This will allow a true comparison to be carried out. Many of these tests are all made practically impossible to carry out when the building is occupied, as certain conditions internally and externally need to be met accurately with no disturbance. The *long-term occupied* stage is where many of the practical studies of retrofit have commenced, comparing the as modelled data with the data collected in this stage (Gentoo 2010). This not really a true comparison where we are assessing the impact of any retrofit interventions, rather it is an exercise in comparing the model with the real world data.

What data and analysis strategy do we need?

Once we have established the scope of the monitoring and the timings of the study, we need to consider the data that we might require to help us understand our research question. The wider the scope of the monitoring, the more important it is to have data on potential influencing factors. If we are considering long-term energy use by a household, understanding the weather data, such as Degree Day Data (Energy Saving Trust, 2008) is essential. Understanding the composition of a household in terms of demographics and lifestyle is also important (Gill, 2011) particularly when considering a cross-household comparison. Evaluating the performance of a physical retrofit needs to be understood in its wider context when considering in-use monitoring. An additional consideration is to identify, not only what monitoring and supporting data is required, but also how much data we actually need. Given the sophistication of digital data collection and storage, it can be tempting to collect vast quantities of data. However, if we have many data points, unless we have the resources and the tools to analyse this data, we are creating difficulty for ourselves. Huge quantities of data, while potentially valuable, may be difficult to manage within the context of a desktop spreadsheet and a limited array of statistical tools. Larger data sets may require approaches such as data mining (Figueiredo, 2005) to effectively extract meaning from them. It is important to be clear what the analytical strategy might be and effectively plan and resource it.

Effective scoping and management of the monitoring process is essential prior to the deployment of resources. Monitoring can be time consuming and expensive. It is essential that the identified monitoring strategy can be delivered using the available resources. It is also important that resource is spent not only on monitoring techniques and data collection, but that the analysis and reporting phases are also considered. In the next section we will look at some of the main ways of monitoring properties and consider some of the main issues in their use.

Energy Monitoring Tools

Energy Bills, Utility Monitoring and Smart Meters

All occupants are entitled to accurate billing data (HM Government 2009) and this provides the most accurate measure of actual energy use. It may also be possible to chart use through the year, to assess seasonal variation, although this requires accurate and regular meter readings to be taken, rather than estimated data. A new requirement is the Annual Energy Statement, introduced in 2010. This provides information on both the energy used and the price paid over the year, although take up has been poor (Cooper 2011).

There is a difference between billing/meter read information and utility monitoring. Monitoring equipment will read live data from the gas meter or, for electricity; it will measure the actual power being consumed at a given interval. Most monitoring devices allow for these intervals to be very short (seconds and minutes rather than the days and months, given on meter readings and bills). This allows a profile to be built up, whether in a tabular or a graphical format. This type of high frequency data allows the analysis of data to take place, and makes spotting trends in consumption patterns easy. This type of representation of data can also help in the diagnosis of faulty monitoring equipment using error-trapping techniques. Monitoring meters directly can be a complex problem; there is a wide variety of metering technology in use due to technological changes over the decades. This means we must be prepared to monitor many different types of meter.

The current UK Government is committed to the installation of smart meters for both gas and electricity by December 2019 (DECC, 2012). Smart metering will offer two main components; accurate billing information, provided electronically to the meter supplier and, secondly, feedback in terms of high granularity data concerning consumption. Additional data, such as voltage levels and CO_2 emissions, can also be transmitted to the consumer using an In-Home Display. The smart meter will electronically store 13 months worth of half hour frequency data. This will be stored on non-volatile memory, so will always be present even after power cuts. The technical standards for smart metering are still being finalised at the time of writing (DECC, 2012), so these details may well change. However, it is important to note that when commencing retrofit works on a domestic property after 2014, when the large scale rollout is due to take place, a check to should be made for a smart meter on either one of the applicable utilities. If one is present then, providing the occupier agrees, there may be 13 months of high granularity data available to use. Additionally, if monitored correctly using a "home area network" facility, the smart meter can be used to provide very accurate consumption figures (<1% tolerance) with a high frequency of reads. This makes the data more accurate than that which can be gathered using the current transformer (CT) clamp method. Given the accuracy of a smart meter and the frequency of reads taken they are certain to meet to meet the requirements laid down in the TSB standards for accuracy and frequency (DECC, 2012).

Gas

The most challenging utility to monitor, due to the differing number of meter types, is natural gas. When using retrofitted equipment, which will give the profile of gas use rather than just reading the meter at set periods, there are three main issues to be considered; *safety, permission and communication.*

The gas meter and the surrounding area is a hazardous area in terms of risk of explosion. It is for this reason that any devices adjacent to or fixed to a gas meter have to meet certain standards. These are commonly known as the Atex standards (EU, 2012). Due to this hazard, only metering products that meet this definition can be used in this zone. It is important to note that, although a standard domestic gas meter may be on the tenant's property, it very rarely is owned by the occupant. In most cases the gas transporter, such as National Grid in the UK, will own the meter. Many meters exist that have sockets (RJ-45 type) on the meter, which may or may not have a tamperproof sticker. It is generally considered that these sockets are not used to monitor the meters. It is far better and safer to use a proprietary solution.

There are several devices on the market available in the UK. To call these devices "meter readers" is inaccurate, although this is the common parlance. These devices measure the red dials on the gas meter turning around. As these dials (or red needle) make a complete pass round the readers recognise this using one of two ways: an optical sensor that can "see" the needle turning round, or measuring the magnetic field generated by the rotating dials. Dependant on the configuration of the gas meter (older ones may measure in ft^3, whilst most modern ones will measure in m^3) the units will be in a volumetric rate of how much gas is being consumed. This will generally not be in kWh. To convert the cubic measurements to kWh consumption requires several inputs into a formula, including the calorific value and any correction factors attributed to the supply (HM Government, 1996). It is important to note that, when comparing gas consumption taken from logging equipment, as against billing information, that the volumetric component of the bill is compared and not the kWh figure as this can vary, due to the conversion processes which takes into account factors such as the calorific value of gas.

Electricity

Compared with the other utilities, electricity is the easiest to measure. Correspondingly most of the studies carried out on energy consumption within properties are on electricity consumption. The equipment needed to monitor electricity is widely available and inexpensive. It does have some safety implications, but they are not as onerous as those for gas monitoring. It is advised that the installation instructions are rigidly adhered to, as different manufacturers recommend differing methods dependant on its product. The simplest type of electricity meter use current transformer technology to measure consumption. This measures the current flowing through the live cable between the main incoming meter and the consumer unit. As with all technologies these devices should be fitted in line with the manufacturer's instructions, as discrepancies in the install can lead to variances in the readings. For example, a CT clamp that is not perpendicular with the mains cable may give inaccurate readings due to the internal sensing method of the clamp.

It is often useful to have energy consumption data broken down into relevant circuits. This aids in visualising the consumption across the house, and also in diagnosing issues concerning high consumption, such as poorly performing ventilation systems. Clearly this information will not be available prior to any retrofit project. However, as some of these works are slightly invasive, they should certainly be considered during a retrofit project, as the data that they provide can be very useful in terms of deeming whether the project is a success.

Many devices are available that can log the amount of power consumed by an individual appliance. It is also possible to monitor multiple devices that send data back to a central data-gathering source. These devices are relatively inexpensive, easy to fit and are particularly helpful, as many of the modelling packages that are used to predict energy saving omit appliance consumption. This data can be used to supplement modelling data to more fully understand energy consumption.

Environmental Measures

Data collected from environmental monitors provide a context for the energy performance of a building.

Internal Climate

Much has been written on the subject of the "take-back effect" or "rebound effect" (Hong, 2006). This is where a household that has energy efficiency improvements increases their energy use to make their homes more comfortable. This phenomenon is often found where people may have been under heating their homes. In retrofitted properties less energy is needed to heat the home making certain levels of comfort cheaper; the savings are reclaimed as heat rather than money. In a study carried out across 274 pre intervention and 633 post intervention dwellings (Oreszeczyn, 2006), it was found that, following either a heating system or insulation improvement, temperatures would rise by 1.6 degrees Celsius in the living room and would rise by 2.8 degrees Celsius in the bedrooms. A further study (Hong, 2006) found that on average between 65-100% of the savings offered by the measures installed were "taken back" by the occupants through the raising of the internal temperatures of the living room and bedrooms. If we are to take account of this rebound effect, it is important that internal temperature is logged before and after the retrofit. This will indicate any changes in lifestyle that exists after the works have been completed.

Coupled with the occupancy data, the results can be very useful in indicating any changes in lifestyle.

There are many ways of logging temperature in properties. The simplest solution is a standalone system which is battery powered. These are relatively hardy units and will be suitable for most occupied properties. A more complicated solution would be to use a multi-node wireless system. This system will send all the data back to a central station. Some units will send data back to the practitioner over the mobile phone network for immediate analysis.

The issue of internal temperature monitoring is currently an area of research at the University of Salford. A current study noted that a typical living room with a central heating radiator, the maximum variation in temperature when the room had stopped demanding heat from a thermostat was 10.5 degrees Celsius. This was the difference in temperature gradient between skirting board height and ceiling height. This stresses how important it is to note where the sensors are mounted. Some issues to consider are;

- To measure temperature in a room relation with any correlation between the thermostat, it is essential to place a sensor directly adjacent to it. Failure to do so will give readings that do not relate to the thermostat itself.
- Sensors should always be placed out of direct sunlight, this avoid erroneous readings.
- Where possible the sensor should be placed in an airflow representative of the whole room, not above a radiator or a cold draught next to a door for instance.
- It is recommended to keep sensors away from cold surfaces, such as external walls, particularly if not insulated. The only exception to this of course, is if you are trying to gauge the wall temperature rather than surface temperature.
- The sensors should be kept away from all heat sources such as lamps or power transformers.

Another important factor of internal environment to consider is humidity. Humidity itself arguably does not have a direct effect on the fuel consumption of a domestic property. However the perception of poor air quality and "mugginess" can lead people to allow for more ventilation in a property. This can lead to unwanted and uncontrolled ventilation even when the heating is switched on. Changes in humidity levels in a building can also be an indicating factor of occupancy. Behaviour which can cause damage to the building fabric, such as drying washing on radiators in unventilated rooms can also be detected if the sensors are well placed and of high enough sensitivity. As with the measurement of temperature, sensor placement is important. Humidity sensing equipment should also be located with care away from all sources of moisture, such as sinks, showers and tumble dryers.

External Climate

A significant factor in the running cost of any building is the external weather conditions. It is also one of the most variable factors in the UK, as we have extremely wide ranging weather conditions. This requires that the external weather temperature data is normalised so that similar periods can be compared like for like. This allows for pre and post scenarios to be compared. The Carbon Trust provides an excellent "practical guide" to degree-day usage (Carbon Trust, 2010).

Collecting local climate information generally requires a waterproof sensor arrangement mounted on a north facing preferably sheltered wall. Care should be taken to ensure that the sighting is representative of the locale. It should not be located in areas of direct sunlight, unless this can be accounted for as part of the data analysis. A tool such as a portable weather station will generally suffice however for longer-term logging a weather station can be mounted to the external wall of the building.

Detection of Movement

Occupants play a major role in energy use. Therefore, in terms of energy monitoring, to find out when a building or room is occupied is extremely helpful. A common way of doing this is to use Passive Infrared (PIR) detectors. This data can then be cross-referenced against energy use to identify possible energy wastage in a building. It is worth noting that PIR only detects movement of infrared emitting objects breaking its beam. As such it would not pick up sedentary people, and can also detect things such as pets or coal fires. These limitations require that the sensors are closely positioned and data well analysed. Using occupancy data will enable to the practitioner to compare the occupancy of the building before and after the retrofit. A reasonable assumption would be that if a room/building is being used more the more energy is likely to be used.

Fabric Investigation

Many buildings in the UK have poor fabric performance, which in turn contributes to low levels of energy efficiency. If we consider that 65.7% of the average properties energy use is heating (Parker, 2011), then the role of fabric is vitally important in reducing energy use and carbon emissions from properties.

Air Permeability Testing

Currently, compulsory air tightness testing only applies to new build property and large extensions (DCLG, 2010); retrofit projects are not currently included within these regulations. However, as we have become accustomed to the "build tight, ventilate right" philosophy, there has been a growing demand for air permeability testing. The air tightness testing process is relatively straightforward; a large diameter fan is placed in an external doorframe of the house. The test is only aimed at identifying unintended ventilation losses, rather than managed ventilation. All ventilation systems and vents are sealed over prior to the test. This fan pressurises and then depressurises the building. The rate at which the building then leaks air during this process is given, in m^3 of air that leaves the building over a given period, per m^2 of floor area.

Testing should be carried out pre/post retrofit to allow a comparison to be carried out. Some retrofit projects have also carried out tests mid way through the construction work to make sure that all ducts and air infiltration paths have been correctly sealed as the work progresses. Examples of air leakage, some typical examples of typical unintended air infiltration points are as follows:

- Chimney stacks
- Poorly fitted loft hatches
- Cracks in the building fabric
- Gaps in floorboards and poor wall/floor junctions
- Poorly sealed service entrances through walls

Localised testing can be carried out under pressurised conditions using a small smoke pencil. This can be used along with a smoke machine to identify air leakage paths in roof details and windows. With the draughts being drawn into the building having an effect on the smoke that is clearly visible. Pressurised testing is also a useful addition to infrared thermography, as described below.

Thermography

Thermography, or thermal imaging, relies on the fact that any surface that is above 273 degrees Celsius will emit radiant energy. The thermal camera will convert this radiant heat to a visual image. The use of this method has increased significantly in the last 10 years. This is mainly due to the decrease in the costs of thermal cameras. The thermal image is mapped using differing colours, each relating to a specific temperature. This identifies, with careful interpretation, the amount of heat emitted by a wall, roof or other building element. There are several benefits associated thermography:

- Large areas can be covered in very short periods of time, using suitable wide-angle lenses.
- When carried out correctly the difference between pre/post retrofit can be illustrated in a way that is easy for the layperson to comprehend.
- A cost effective way of gathering surface temperature readings for large areas
- Defects/omissions in constructions can be easily spotted and re-inspected when completed.

As stated previously, thermography can be used with air pressure testing. The pressure draws air through leakage points and shows a temperature differential, which will be clearly shown in any thermal images.

However, thermography is methodology that requires careful analysis, a genuine understanding of building physics and a careful set up/pre survey routine. Without all of these an accurate thermographic survey is impossible. The British Standard for Thermography (BS EN 13187:1999) (BSI, 1999) provides a robust model to help undertake thermography. This guide dictates how the thermography should be carried out, and in what format the report should be structured in.

U-Value Measurement and Calculation

U-values, which measure the coefficient of the heat loss through a building element, such as doors, walls and windows, are now part of the design process in most retrofit specifications. However, these figures are often produced using software and may not be strictly accurate in terms of how the building actually performs, and how it will perform post-retrofit. In most instances no testing will be carried out to investigate an element's U-Value. This is beginning to change as in-situ U-Value testing becomes more popular. Several studies have been carried out recently highlighting large differences between calculated U-Values and those measured in the field. A recent study (Rye, 2010) found significant differences in U-Values that were calculated using a software package and those which were measured on-site using heat flux meters. This was particularly true of traditional vernacular forms of construction such as rubble filled stone and wattle and daub walls.

The monitoring process is relatively straightforward, however the equipment required is specialist and fairly expensive. The basic methodology involves two sensors placed either side of a building element and measuring the flow of temperature between the two (Rye, 2010). However, this relatively simple idea translates into a complex and time-consuming task.

Co-Heating Test

Co-heating is a comprehensive monitoring approach in term of assigning an energy efficiency figure to a building. The co-heating method is simple: the building is heated using electric heaters to 25 degrees Celsius. This must be done for a period of 1 to 3 weeks and is best undertaken outside of the winter months. A differential of 10 degrees Celsius between inside and outside should be achieved. The energy consumed by the electric heaters to keep the building in a steady state condition then this is the amount of energy (in Watts per Kelvin) required to heat the building, which includes any heat loss through fabric and background ventilation. The full methodology is published in a paper published by the Centre for the Built Environment at Leeds Metropolitan University (Centre for the Built Environment , 2010). As the paper discusses, the list of equipment needed is lengthy, and precise, and there are a number of conditions that must be met. The methodology is highly detailed, and the timescale of testing is long. However, the test is seen by many in industry to be a good standard of gaining a true figure of the energy efficiency of a domestic property.

Conclusions

There are many methods of measuring the performance of retrofit interventions. Due to this, the decisions over which type of monitoring to use and when can be a complicated one. It is a decision that must be made right at the outset of the project if the practitioner is to make full use of pre/post data. In fact, if a full study is to be carried out then this decision may be required up to 1 year before the refurbishment takes place on site. The decision-making process will contain many strands; economy will most likely come first in many projects. The cost of the equipment and expertise must be offset against the value of the information. If the building to be assessed is a trial property that mirrors the property attributes of many other properties that are also in line to be refurbished, then the findings of this data may be used to inform the decision-making process for the remainder of the properties.

Timescale is also an important driver for monitoring projects. Monitoring takes time to set up and once the project is complete then the data processing and analysis can also take some time. It is important the data is made available in a format that is easily understood by decision-makers who can effectively use it to compare pre and post retrofit, or to compare projects. The issue of occupant disruptions is also an important factor. You may require them to provide bill data, access to their homes and ensure that they do not damage equipment. This requires a level of engagement, but also a well-designed monitoring strategy to ensure that these types of risks are minimised. It needs to be recognised that domestic monitoring activities are undertaken in people's homes.

All of these factors bring us back to the issue of a well-designed, coherent monitoring strategy. We have seen the range of available data collection approaches that might be taken. The retrofit agenda has a real requirement for robust data to inform the evidence base. Only by appropriate collection and analysis can we achieve this. Poorly installed equipment, failing to understand the measures or weak analysis do not deliver the data required to help us ensure we are adopting the correct retrofit strategies.

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List of Figure Captions

Figure 1 – Potential Monitoring Stages for Retrofit

QUB: Validation of a Rapid Energy Diagnosis Method for Buildings.

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QUB: Validation of a Rapid Energy Diagnosis Method for Buildings

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Abstract

This paper presents an innovative and simple method for the experimental measurement of the total heat loss coefficient of a building envelope, and its validation. The heat loss coefficient being the sum of the real U-Value of the house and its infiltration losses, this method is called QUB (Quick U-value of Buildings). It only uses the temperature responses to two different constant power excitations, done during two consecutive nights of experiments, which makes it possible to do a complete test in about 48 hours. While the experimental heat loss coefficient cannot be used for energy consumption prediction, it can be used to assess the quality of the construction by comparing it to calculated values or to previous measurements, for instance done before improvements. QUB is validated by comparing its results to those obtained in a unique facility where steady-state can be reached experimentally: the Energy House, developed by the University of Salford, built inside a chamber whose temperature can be regulated. Steady-state and QUB values of the total heat loss coefficient are compared, showing very good agreement between both methods.

1. Introduction

Environmental concerns have led many governments to pass laws and standards designed to improve the energy efficiency of buildings. Yet energy consumption is highly dependent on the occupant's behaviour, so a building's energy efficiency must be evaluated by one of three methods:

- calculations based on the building design
- long campaigns of measurements coupled with statistical methods able to dissociate the impact of occupant's behaviour, the meteorological conditions and the intrinsic efficiency of the building
- experimental measurements short enough to be done without occupancy and to limit the impact of the weather variations.

Calculations are the most common evaluations but are insufficient: they do not take into account construction imperfections. Long experimental measurements cannot be done on many buildings, so they are better seen as an academic tool than as a candidate for large-scale use. The interest of shorter experiments depends on the actual measurement time: the shorter they are, the more useful they can be. Besides, all these methods suffer from several common problems. One is that the energy consumption depends on many factors (U-values, solar factors and inertia for each room coupled with their specific orientation and complete weather data, for instance); another is the difficulty to validate them because of the lack of adapted experimental facilities. These difficulties compound each other: it is nearly impossible to measure all the parameters and validate them independently from each other. A possibility is to use for validation not the energy consumption itself, but a global parameter, easier to measure and calculate, which can give indirect indications on the quality of the construction.

One such key thermal estimator of a building is K_0, its Heat Loss Coefficient. This coefficient, expressed in W/K, represents the power needed to keep the internal temperature of a house constant when the external temperature is also constant (hence it is equal to the building energy losses for a given temperature difference). This definition is based on steady-state conditions, so this parameter cannot be fully correlated with energy consumption. Yet, it is still representative of the building energy efficiency. If it could be measured directly, it could thus be used, for instance to compare theoretical and experimental values of K_0 to assess the quality of the construction, or to compare values obtained before and after renovation.

In this paper, the authors present a new dynamic method, called QUB (Quick U-value of Buildings), which aims at estimating K_0 in less than 48 hours and with a reasonable uncertainty (about ± 15%). Its theoretical bases are explained, a model of the thermal behaviour of a building is described, and the validation methodology is presented. Basically, it is the comparison with steady-state estimates of K_0. The difficulty, of course, is obtaining steady-state values in a building. For this, the Energy House of the University of Salford has been used. This unique facility is a house reconstructed inside a climatic chamber, enabling steady-state experiments. All validations, virtual and experimental, show a very good agreement between steady-state and dynamic, or QUB, results.

2. The QUB Method

The simplest model one can use to represent a building submitted to transient heat transfer is probably the lumped capacitance analysis with internal energy generation. It supposes that the interior of the building is at homogeneous temperature, that all exchanges happen by convection with a medium of homogeneous temperature through an infinitely thin interface, and that the exterior temperature is constant. Thus, it is an R-C model with only one resistance and one capacity. The well-known equation [1] is:

$$\mathrm{C}\mathrm{d}\mathrm{T}^{*} = (\mathrm{q} - \mathrm{K}_0\mathrm{T}^{*})\mathrm{d}t \tag{1}$$

Where C is the internal heat capacity of the house (defined as the total energy needed to increase the interior temperature by 1 K, at a constant exterior temperature), q the internal power brought by all heating sources inside the house and possibly the solar gain, K_0 is the total heat loss coefficient of the building and T^* is the difference between the interior and exterior temperatures.

If two separate experiments 1 and 2 are done, with two different powers, if we assume K_0 and C to be constant during these two experiments and if we note $\alpha = dT^*/dt$, it can be easily shown [2] that:

$$K_0 = \frac{\alpha_1 q_2 - \alpha_2 q_1}{\alpha_1 T_2^* - \alpha_2 T_1^*} \tag{2}$$

$$C = \frac{q_1 T_2^* - q_2 T_1^*}{\alpha_1 T_2^* - \alpha_2 T_1^*} \tag{3}$$

Thus it is quite easy to calculate K_0 from only two experiments if the temperature variations can indeed be considered linear and if the temperature difference can be considered constant.

Of course, such a model is too crude to represent the real behaviour of a building; more resistances and capacities are needed for that. A larger RC network, with an indefinite number of nodes n is necessary. With a unique internal ambient temperature, hence homogeneous inside the building, the problem takes the form of a system of n differential equations with n unknown temperatures (the system is non-homogeneous because a heat flux can be applied on each node). The shape of the solution of such a system is well known. It is the sum of the general solution of the homogeneous system and a particular solution of the non-homogeneous system. The solution of the homogenous system can be expressed as:

$$[T^*]=\sum_{i=1}^{n} c_i[X_i]e^{-t/\tau_i} \tag{4}$$

All exponential are negative, as temperatures in this case cannot physically tend to infinity when time does. A particular solution is the steady-state condition, where $[T^*] = [T^*]_{t\to\infty}$ is a constant vector. So the general solution is:

$$[T^*]=\sum_{i=1}^{n} c_i[X_i]e^{-t/\tau_i}+[T^*]_{t\to\infty} \tag{5}$$

The initial conditions are given by $[T^*]_{t=0}$:

$$[T^*]_{t=0}=\sum_{i=1}^{n} c_i[X_i]+[T^*]_{t\to\infty} \tag{6}$$

By combining (5) and (6), but only for the line concerning interior temperature, we obtain:

$$\frac{T_I^*(t)-T_{I,t\to\infty}^*}{T_I^*(0)-T_{I,t\to\infty}^*}=\frac{\sum_{i=1}^{n}\alpha_i e^{-t/\tau_i}}{\sum_{i=1}^{n}\alpha_i} \tag{7}$$

If the interior air is heated by pure convection, the steady-state temperature is given by:

$$T_{I,t\to\infty}^*=q/K_0 \tag{8}$$

So if the time constants of the building are sufficiently different, there is always a time after which only the largest time constant can be supposed to have a significant impact. Then:

$$\frac{T_I^*(t)-q/K_0}{T_I^*(0)-q/K_0}\approx\frac{\alpha_n}{\sum_{i=1}^{n}\alpha_i}e^{-t/\tau_n}\approx\beta e^{-t/\tau_n} \tag{9}$$

$$\frac{T_I^{*\prime}(t)}{T_I^*(0)-q/K_0}\approx-\frac{1}{\tau_n}\beta e^{-t/\tau_n}\approx-\frac{1}{\tau_n}\frac{T_I^*(t)-q/K_0}{T_I^*(0)-q/K_0} \tag{10}$$

The derivate T' being the slope α, (10) directly leads to (2). By noting $C = \tau_n.K_0$, (3) is also obtained. It can be also noted that in this case, equation (10) between the temperature and its derivate can be simplified to (1): after some time, the problem with multiple nodes and time constants is equivalent to the simpler problem with only one time constant.

The coefficient K_0 is the sum of all loss coefficients for all parts of the building, and the analysis is much simpler if all rooms can be considered at the same temperature. The easiest way to achieve this result is to try to use a homogeneous heating. It is possible to average all temperatures and calculate one average heat loss coefficient, or to separate them in different zones and compute and add each zone's heat loss coefficient (for example when there are several floors). This is also true for C, which is the sum of all the thermal masses of each part of the building.

K_0 is usually composed of two contributions: the heat loss by transmission through the building envelope (K_{01}) and the power needed for heating the outside air which is penetrating in the house ($f.C_{p\text{-}air}$):

$$K_0 = K_{01} + f.C_{p\text{-}air} \tag{11}$$

where f is the flux of air entering in the house (ventilation air flow + eventual air leaks) and $C_{p\text{-}air}$ is the total heat capacity of the air (considering a sole heat loss coefficient K_{01} is a strong assumption, as a building exchanges heat with both exterior air and ground; so this model actually assumes that ground temperature is equal to outside air temperature). While both values K_0 and K_{01} are of interest, a method such as the one presented here cannot differentiate them. To do so, the air exchange rate must be evaluated separately.

An important remaining question is: how long does it take for all the short-term thermal effects to become negligible? This is in part related to the number of time constants needed to fit the model. It has been shown in [3] that two time constants are sufficient to model a simple building. Besides, in our case, it is preferred to do the experiments at night in an empty building, which makes the thermal responses simpler to analyse (no occupancy, no solar radiation, hence more stable conditions). This leads us to believe that the number of time constants required is generally 2, which means that in a few hours, all short-term effects have subsided. With n = 2, the RC system has two capacities (and three nodes, as external ambient temperature is considered constant), and can be represented graphically by Figure 1 if the heat is dissipated entirely by convection. The two interior nodes are considered to be the interior air (I) and wall (W) conditions.

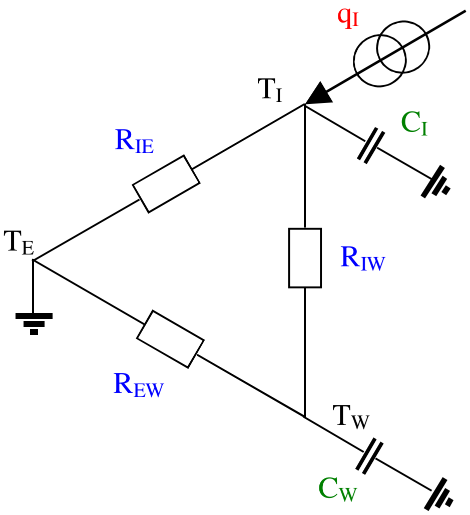

Figure 1: Diagram of the 3R-2C Model

Such a model can be solved numerically, but also analytically, for instance using Laplace transforms, with one simple hypothesis (that $C_I << C_W$ and $R_{IW} << R_{IE}$ because internal inertia is much lower than wall inertia, and because infiltrations have a much higher thermal resistance than internal convection).

The solution of this system is then:

$$\frac{T_I^*(t) - q/K_0}{T_I^*(0) - q/K_0} = \frac{(A_I - 1/\tau_1)e^{-t/\tau_1} - (A_I - 1/\tau_2)e^{-t/\tau_2}}{1/\tau_2 - 1/\tau_1} \tag{12}$$

$$A_I = \frac{1}{C_W}\left(\frac{1}{R_{IW}} + \frac{1}{R_{EW}}\right) + \frac{1}{C_I}\left(\frac{T_{W0}^* - T_{I,ss}^*}{(T_{I0}^* - T_{I,ss}^*)R_{IW}} + \frac{q_I R_{IE} - T_{I,ss}^*}{(T_{I0}^* - T_{I,ss}^*)R_{IE}}\right) \tag{13}$$

$$\begin{cases} \dfrac{1}{\tau_2} = \dfrac{\dfrac{1}{C_I C_W}\left(\dfrac{R_{IW} + R_{EW} + R_{IE}}{R_{IW}R_{EW}R_{IE}}\right)}{\dfrac{1}{C_I}\left(\dfrac{1}{R_{IW}} + \dfrac{1}{R_{IE}}\right) + \dfrac{1}{C_W}\left(\dfrac{1}{R_{IW}} + \dfrac{1}{R_{EW}}\right)} \\ \dfrac{1}{\tau_1} = \left[\dfrac{1}{C_I}\left(\dfrac{1}{R_{IW}} + \dfrac{1}{R_{IE}}\right) + \dfrac{1}{C_W}\left(\dfrac{1}{R_{IW}} + \dfrac{1}{R_{EW}}\right)\right] - \dfrac{1}{\tau_2} \end{cases} \tag{14}$$

Solution in node W can be obtained easily from (9) and (10), by inverting all I's and W's, as the system is symmetrical, and by noting $q_W = 0$. This is necessary, because the air temperature depends on the wall initial temperature, and the initial temperature for the second phase requires the wall temperature to be calculated for the first phase.

This model, when compared to experimental tests, can show that this approach is often sufficient to model the dynamics of a building. Besides, the term in $\exp(-t/\tau_1)$ usually disappears rather quickly, leaving only one time constant to describe the temperature evolution, thus leading to (10) and hence to (2) and (3), the original QUB equations. While this is obviously insufficient to prove the validity of the QUB method, it nonetheless shows that despite its apparent simplicity, it might be possible to apply it to complex buildings. What is left is proving experimentally that the value obtained is reasonably close to the real K_0.

3. Experimental set-up: The Energy House in Salford

The Energy House is constructed to meet the specification of a typical 1910 terraced property from the UK that has been through reasonable modifications (Figure 2). At the time of the validation exercise the building was uninsulated throughout. The house is located in the middle of a well insulated concrete chamber which has a solid concrete floor. It consists of a test house, connected via a party wall to a smaller neighbouring building (Annex). The heating system is a gas condensing combination boiler fed via a wet system to radiators in each room in the test house and electric panel heaters in the neighboring house

The chamber itself is cooled by an air handling unit that is supplied with cooling by 4 No. condenser units, with a total of 60 kW of cooling (15 kW per unit). This is supplied to the chamber via a ducted HVAC system. This system reacts to the heat load of the house in the chamber and maintains a setpoint of ± 0.5 °C.

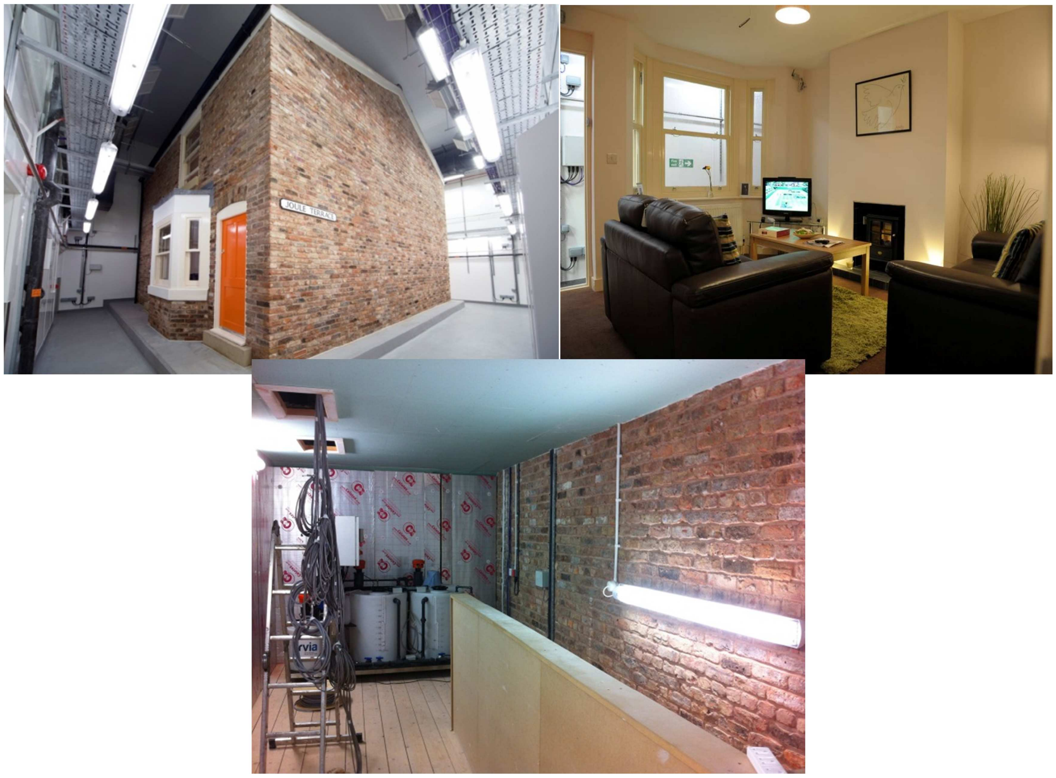

Figure 2: View of exterior and interior of the main house, and the neighbouring property of the Energy House in the University of Salford

Construction of Test Building (No1)

- Solid brick walls 225.5 mm thick arranged in English bond (with every fifth course being a header row), with 9 mm lime putty mortar. 12.5 mm hard wall plaster to inside face of wall with 2 mm skim as finishing coat. Magnolia paint to internal face of wall.
- The house is built off a reinforced concrete raft with no insulation added. A 200 mm gap exists between the house and this raft; this forms a ventilated floorspace and allows for a constant airflow beneath the house. The floor is suspended on 200 mm timbers and is finished off with 22 m floor boards (non interlocking and non-sealed).
- The windows are single glazed and of a sliding sash type. The doors are single skinned timber panel doors; the rear door is half glazed with single glazing.
- The roof is a timber rather and purlin roof with no insulation at the time of the first tests. A layer of mineral wool type insulation (100mm) has been added in time for the second tests. There is a small amount of eaves ventilation, sarking felt is installed.
- The party wall is a solid wall construction to match the external walls.
- By regulating the house temperature and following gas consumption during several days, it is possible to evaluate the heat loss coefficient of the building, but this is not highly accurate as it requires the use of an energy conversion coefficient for the gas flow rate. Thus, it has been preferred to estimate it with additional electric heaters.

Construction of Neighbouring Building (No2)

- This building has a layer (60 mm) of closed cell foil backed insulation, to the external facing walls only, and not the party wall.

- The external facing walls are solid brick as above.
- The gable of this building is concrete block (2 skins of 100 mm with a 20 mm air gap).
- The loft has 200 mm of insulation.
- The doors are single skinned timber panel doors, the rear door is half glazed with single glazing.
- The floors are constructed in the same manner as the other building.
- The neighbouring building can be open to the climatic chamber or regulated in temperature, so that the test building can be considered an isolated house or a house in contact to another occupied one. For simplicity, all tests here described have been done by considering that the house is isolated (neighbouring building doors open).

The chamber was set to 5.5 °C and allowed to settle for a period of 48 h whilst the heating system kept the house at about 20 °C before the first tests. It can be seen from Figure 3 and 4 (section 4) that the chamber performs to its tolerance of ± 0.5 °C in the vast majority of the experiment. After the main heating system in the hose was used to lift the temperature to an approximate of 20 °C then it was disabled and the electric heating took over. Following this the chamber was sealed and no access was permitted.

During the experiment the following conditions were put in place: all external windows and doors were closed, whilst the internal doors were fully opened to allow free flow. The gas heating system was disabled.

The temperature in the house is measured using wireless RTD sensor devices in the geometric centre of each room, at a height of 1.2 m. Measurements are taken once every minute. The same type of device is used to monitor the chamber at a height of 2.4 m (approximately half the height of the house itself) taken at the front, side and rear of the house. This figure is then averaged and shown in the results. The quoted accuracy for these sensors (calibrated at source) is ± 0.4 °C.

The electric heating elements were monitored using a wireless plug based energy monitoring platform that has an accuracy of ± 0.1 W. Readings were taken from these each minute in terms of energy consumption.

The monitoring equipment also has its own inherent energy use, this has been calculated to equate to 30 W (supposed to be 15 W on ground floor and 15 W on first floor). This has been added as incidental heat gain in section 4.

The final heat loss figure for the property can be compared to a basic energy modelling package (SAP) which is currently the tool used to predict energy consumption for new build properties in England and Wales to support the building regulation approval procedure. A model was constructed of the Energy House using SAP. Table 1 gives the output of the calculation. The SAP calculation defaults to a U value of 0.0 for a party wall (when a neighbouring building is in place in other words it assumes the neighbouring building is occupied and heated to the exact same level). Yet, during the present tests, the neighbouring building is considered to be at exterior temperature, so the U-Value of the party wall must be calculated. SAP assumes this value to be the same as for the external walls (2.1 W/m^{2}K).

The house itself is currently rated according to the SAP process as having a Heat transfer coefficient of a yearly average figure of 386.44 W/K (304.90 W/K without party wall losses). This does not include for ventilation heat loss and has been adjusted using the calculation in SAP 2009 (9.90). This includes an air permeability figure of 19.399 m^3/h.m^2 at 50 Pa. This equates to a SAP value of 42.24 (band E). But during the tests, it can be argued that the pressure gradient is probably very low, and so that the air flow cannot be as important as the one caused in real exterior conditions, so the heat losses caused by the infiltration are not taken into account here.

	No loft insulation			**With loft insulation**		
Element	**Net Area (m^2)**	**U Value ($W/m^2.K$)**	**A x U (W/K)**	**Net Area (m^2)**	**U Value ($W/m^2.K$)**	**A x U (W/K)**
Windows	10.42	4.03	41.99	10.42	4.03	41.99
Doors	1.76	3	5.28	1.76	3	5.28
Door (half glazed)	1.76	3.9	6.86	1.76	3.9	6.86
Ground Floor	28.37	1.2	34.04	28.37	1.2	34.04
External Wall	62.8	2.1	131.88	62.8	2.1	131.88
Party Wall	38.83	2.1	81.54	38.83	2.1	81.54
Roof	28.19	2.3	64.84	28.19	0.4	11.28
Thermal bridges	-	-	20	-	-	20
Total	172.13	**-**	**386.44**	172.13	**-**	**332.88**

Table 1: Results of the SAP calculations

Even without the infiltrations, the results are probably still overestimated. The U-Values for the different brick walls are estimated at 2.1 $W/m^2.K$, in part because bricks are porous and their conductivity increases with the humidity. But the humidity in the chamber is quite lower than that of a real house. Different estimations with heat flow meters, though not very accurate, were closer to 1.5 $W/m^2.K$, for instance. Besides, the neighbouring property was not heated and the external doors were left open to mimic an open area (a detached house), so the air temperature in the neighbouring building is considered equal to the chamber temperature for simplification. However this was not entirely perfect as the neighbouring building tends cool very slowly, especially the first floor. Instead of about 5.5°C like in the chamber, the average temperature in the neighbouring property was closer to 6 – 7 °C on ground floor and 8 – 9 °C on first floor.

4. Experimental validation

The experimental validation consists in the comparison between estimations of K_0 in the Energy House made by two different methods: a steady-state measurement and dynamic QUB measurements. All have been done with the exterior (chamber) temperature regulated at 5 °C. In all cases, the heating sources were a set of low power (approx. 110 W) electrical heaters, for which the power could be measured accurately. The experiments were held in July and November, 2012, with very different external conditions (which should not have any effect on our experiments), but with additional insulation in the second case, as explained in §3.

Steady-states measurements are easy to control: external temperature is regulated several days, heating power is kept constant, and one waits until all temperatures are stabilized on both floors (at least 12 hours), which takes approximately five days. An example is shown on Figure 3 (average temperatures). The green line is exterior temperature, whose average value is 5.55 K. Considering that the temperature differences are estimated at 13.9 K for the ground floor and 15.2 K for the first floor and are known at about ± 0.5 K; and that the power has been measured at 2129 ± 30 W in the ground floor and 1664 ± 30 W on the first floor, the value of K_0 can easily be calculated for each floor (ground floor GF and first floor 1F). One average temperature and one total power are considered for each floor. Thus we have:

$$K_0 = K_{0,GF} + K_{0,1F} = 153.2 \pm 7.7 + 109.5 \pm 5.6 = 262.7 \pm 13.3 \text{ W/K} \tag{12}$$

Uncertainties are probably correlated, so summed arithmetically rather than geometrically.

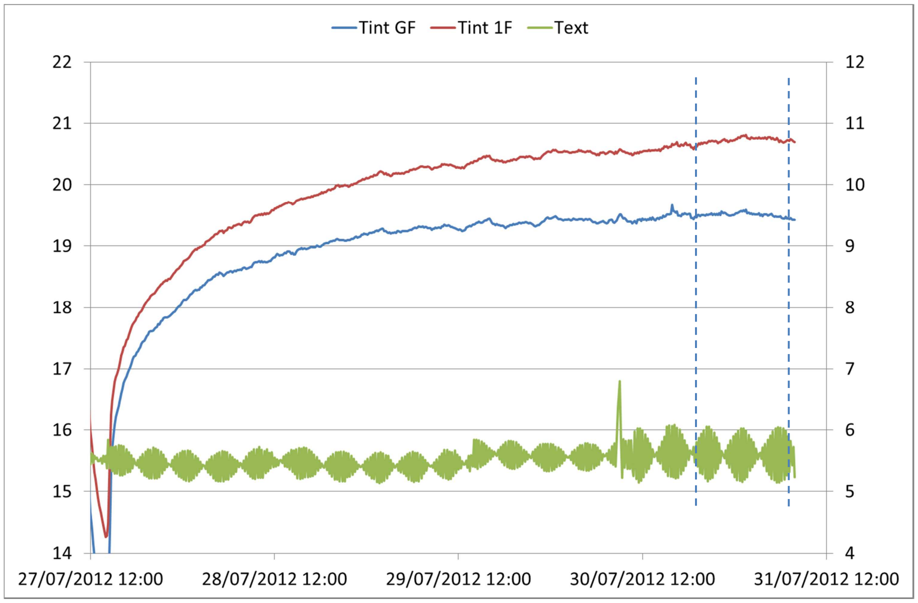

Figure 3: Steady-state measurements

A second steady-state measurement has been done with the insulation in the roof. In this second case, the steady-state measurement was:

$$K_0 = K_{0,GF} + K_{0,1F} = 126.4 \pm 9.2 + 89.1 \pm 6.7 = 215.4 \pm 15.9 \text{ W/K} \tag{13}$$

The uncertainty is slightly higher in the second case because the temperature stability was estimated to be about ± 0.7 K rather than ± 0.5 K. In all cases, while the chamber temperature was not perfectly stable, it was estimated to be on average known with a very good accuracy.

The QUB trials have been made with the same equipment, but a higher power. During the heating phase, a constant power is applied in the building. Then it is entirely stopped for the cooling phase. The only power left is the one necessary for the electronic equipment, and is about 30 W. One example is presented in Figure 4. It shows, for each floor, the temperature evolution and two curves derived from the 3R-2C model. One is the best fit found for this case, the second is the same case without the short term effects, leaving only one exponential term in equation (12) (as if we had $A_I = 1/\tau_1$). It thus shows the exponential trend towards which the model tends for the long times.

Figure 4 shows that the model fits rather well the data: although three or more time constants would be needed for a perfect fit, two seem sufficient in these specific conditions. Besides, the first time constant has significant effects for only four hours in this specific case. After that, the temperature behaves as a single exponential function, which tends to prove that the QUB method can indeed be applied.

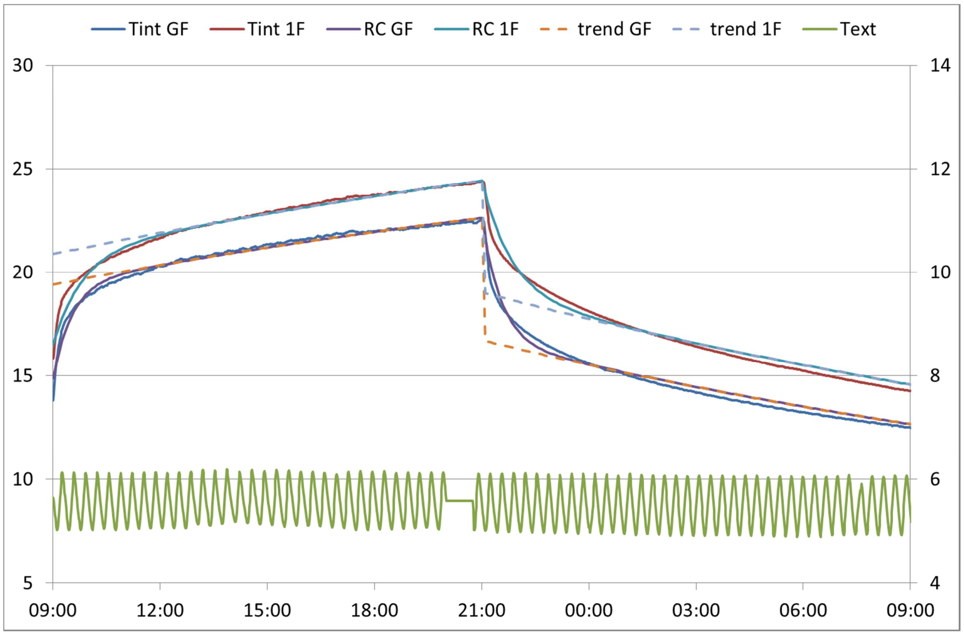

Figure 4: Experimental and calculated temperature evolutions

Two estimations of the indicator K_0 can be made for each floor. The first is via the QUB method, the second via the 3R-2C model. K_0 is the conductance of the system presented in Figure 1 in steady-state conditions, so:

$$K_0 = \frac{R_{IE} + R_{IW} + R_{EW}}{R_{IE}\left(R_{IW} + R_{EW}\right)}$$

Table 2 presents, for each floor, the characteristics of the model fit. It presents the measured powers, the three resistances (and their equivalent surface transmittance U, equivalent to a heat transfer coefficient or a U-Value) and two inertias of the RC network, and the physical outputs of the model: the short-term and long-term time constants, K_0, C and the overall experimental U-Value of the house (K_0 divided by the heat transfer area, 172.17 m^2).

As can be seen, the estimation of K_0 is quite close to the steady-state measurement. Besides, the parameters seem to make sense on a physical point of view. Yet, the model needs to fit 5 physical parameters (when the power is known) while others are actually unknown and only estimated or fitted, like the initial average wall temperature, whereas only one parameter is of real interest, K_0 (a second one if there is an interest in C). The QUB method, on the other hand, is easier to implement, requiring only powers, average temperatures and slopes. Requiring only one calculation for the one parameter we're interested in, it is thus much easier to use. As a consequence, it is possible for a technician rather than a scientist to use it.

	Ground Floor	**First Floor**
Heating power (W)	3208	2816
Cooling power (W)	25	22
R_{IW} (K/W)	0.0025	0.0026
R_{IE} (K/W)	0.0125	0.0246
R_{EW} (K/W)	0.0136	0.0121
U_{IW} ($W/m^2.K$)	4.655	4.427
U_{IE} ($W/m^2.K$)	0.918	0.467
U_{EW} ($W/m^2.K$)	0.846	0.952
C_I (J/K)	$9.68x10^5$	$1.37x10^6$
C_W (J/K)	$1.23x10^7$	$1.12x10^7$
τ_1	1893 s = 31 min 33 s	2909 s = 48 min 29 s
τ_2	94375 s = 26 h 12 min 55 s	106005 s = 29 h 26 min 45 s
K_0 (W/K)	141.9	108.6
C (J/K)	$1.34x10^7$	$1.15 x10^7$
$K_{0,tot}$ (W/K)	250.5	
C_{tot} (J/K)	$2.49 x10^7$	
U-Value ($W/m^2.K$)	1.45	

Table 2: Inputs and outputs of the 3R-2C model

For the tests presented on Fig. 4, Table 3 shows for each floor the estimations of the parameters needed to calculate K_0 and C by the QUB method. The exterior temperature is supposed to be constant at 5.6 °C during the entire test. The powers during the heating phase are slightly different from Table 2, because powers are not averaged during the same period: the entire heating or cooling phases in the previous case, only the duration used for the calculations here.

Characteristic	Ground Floor	First Floor
Heating power (W)	3163	2779
Cooling power (W)	15	15
$T^*_{I,heating}$ (°C)	22.3 – 5.6 = 16.7	26.2 – 5.6 = 21.0
$T^*_{I,cooling}$ (°C)	12.8 – 5.6 = 7.2	17.8 – 5.6 = 12.6
$T'_{I,heating}$ (K/day)	3.68	4.56
$T'_{I,cooling}$ (K/day)	-5.63	-7.39
K_0 (W/K)	148.2	115.6
C (J/K)	$1.60x10^7$	$1.19x10^7$
$K_{0,tot}$ (W/K)	263.8	
C_{tot} (J/K)	$2.80x10^7$	
U-Value ($W/m^2.K$)	1.52	

Table 3: Inputs and outputs of the QUB measurement

Finally, Table 4 presents all estimations of K_0 (in W/K) for the three cases studied. A first remark is that the experimental estimations of K_0 are very close to each other. Differences between the steady-state values and other measurements are inferior to 7% in all cases, and are compatible with the uncertainty of the steady-state measurement alone. The uncertainty of the other methods is much less clear. For the 3R-2C model, the uncertainty of the model fit can be calculated, but it can be assumed that it is inferior to the uncertainty linked to the choice of the very simple model in the first place, which is much harder to estimate.

Case	No roof insulation		Insulated roof
Test Number	1	2	3
K_0 steady-state	262.7		215.4
K_0 QUB	274.5	263.8	229.8
K_0 3R-2C model	270.9	250.5	227.6
K_0 SAP	386.4		332.9

Table 4: All estimations of K_0: steady-state, QUB, 3R-2C model and SAP

QUB uncertainties have two origins. The first, like for 3R-2C model, is the uncertainty that the underlying model used to represent the data can really be applied. The model is also very simple, so this uncertainty cannot be neglected, although it is very difficult to estimate. The second main source of uncertainty is related to the choice of the time period during which we analyse the data, and especially estimate the slope. This can be represented by the dispersion in the results we obtain when we change the period used to calculate the temperature slope, and is about ± 10 W/K at the maximum (although in some cases, “blips” in the data can create lager dispersions, so care is required when the data are analysed). More generally, work is still in progress to estimate limits and uncertainties of the QUB method, but it seems possible to affirm that the total uncertainty is about ± 10 – 15 %.

The second remark is that the effect of the roof insulation is clearly visible with all methods, creating a difference of about 40 W/K between the two cases, which is roughly in line with the difference obtained with SAP (54 W/K). On the other hand, absolute values of the SAP method are quite high; some of it can be explained by the different overestimations presented in section 3.

5. Conclusion

The QUB method is a very simple approach to calculate the total heat loss coefficient of a building, based on the hypothesis that when a constant power is applied, the temperature evolutions after a few hours become a simple exponential decay. This property enables a very quick and simple calculation of the heat losses coefficient, which only requires that two periods are studied, each with a specific power.

This paper first presents a simple RC model of a building which shows that the hypothesis underlying the model is valid, but cannot specify the time needed to reach this simple exponential decay. In a second part, the characteristics of the Energy House of the University of Salford are presented; and it is explained why this facility is ideal for the experimental validation of the QUB method.

This experimental validation shows two key points. The first is that a RC model with three resistances and two capacities is sufficient to model with reasonable accuracy the Energy

House when submitted to a QUB test. Such a model has two time constants, and the effects of the shortest one become negligible after about four hours. The second point is that the heat loss coefficients calculated with QUB are in very good agreement with those given by the 3R-2C model, and, more importantly, with those obtained with a steady-state experiment. The Energy House is, to the authors' knowledge, the only facility in the world where a building can be put in steady-state, and the results presented here are the first where this property has been used to validate a dynamic measurement. In other words, the QUB method seems to be the first dynamic method for estimating the energy performance of a building to have been validated with a steady-state reference.

While this can be considered a very strong first step, many more can be done in order to improve our understanding of this method. The first is of course to multiply measurements in different conditions (related to the weather, the house construction mode, the experimental setup…) and if possible to couple them with numerical modelling. The first aim would be to quantify the QUB method's limitations. Concerning trials on the Energy House, the subject of the neighbouring building is a problem that needs more investigation, and for the next round of trials we anticipate that this will be addressed by using the heating equipment in the neighbouring property to bring it in line with being a neighbouring heated property. We realise that at the moment the air flow rates, temperature levels and convection surface resistances do not reflect what would be found in either a neighbouring property or in the outside air of a building. We could thus compare more effectively the QUB and steady-state measurements with the SAP methodology.

Aknowledgements

This work is the result of the collaboration of many people. In the University of Salford, the Energy House was conceived by Professor Nigel Mellors. The measurements and data processing have been greatly helped by Arun Kundgol.

For Saint-Gobain, the first tests were done in collaboration with Eric Mangematin (SG Habitat), while the second were led by Florent Alzetto (SG Recherche), who also did the data analysis and processing with the help of Didier Gossard (SG Isover). The model has been developed based on exchanges with Jérôme Gilles (SG HPM) and Didier Roux (SG Group), who first developed the QUB method.

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Annex: Drawings of the Energy House

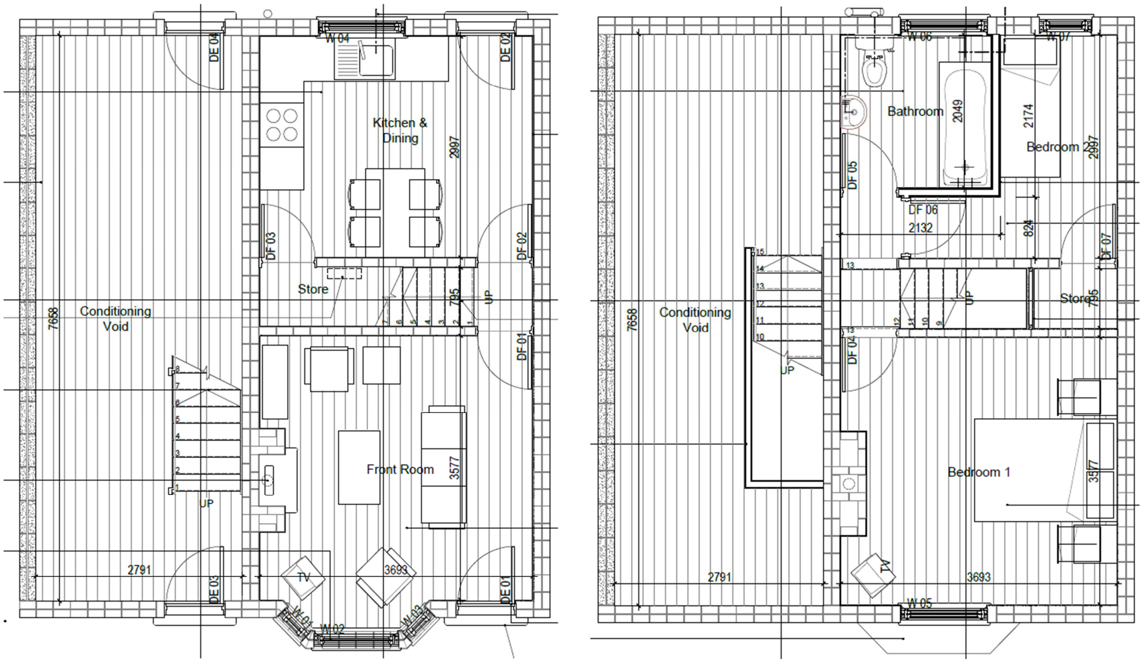

Figure A1: Floor Plans of the ground (left) and first (right) floors of the Energy House

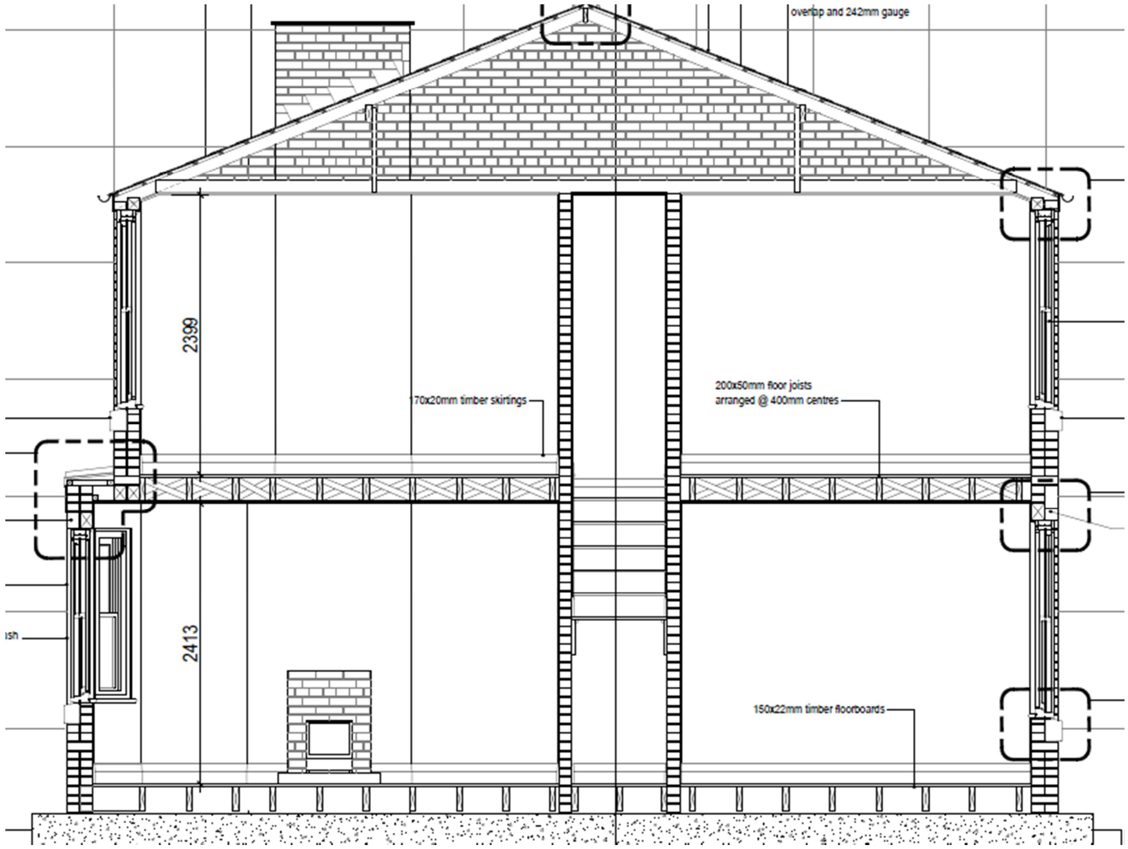

Figure A2: Section of Energy House

Understanding Our Heritage : Monitoring of energy and environmental performance of traditional terraced houses of Northern England

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Enegry Efficency and Comfort of Historic Buildings. Brussels. Retrieved from http://www.eechb.eu/eechb-2016/

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Comfort of Historic Buildings

Understanding Our Heritage: Monitoring of energy and environmental performance of traditional terraced houses of Northern England.

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Abstract *– Existing buildings play a key role in the achievement of the ambitious energy saving and greenhouse gas reduction targets that Europe has fixed for 2020 and 2050. Research has demonstrated that the impact in terms of decrease of energy use and CO2 will be strong, considering that, in Europe, 80% of the 2030 building stock already exists and 30% are historical buildings. To achieve these goals, reliable data about energy consumption, building components and systems performance of the existing building stock is needed to implement adequate strategies.*

United Kingdom (UK) is one of the most advanced European countries in regards to the implementation of regulations and programs to measure and assess the real performance of its old buildings. One of these programs is the Green Deal Go Early Project (GDGE) that the University of Salford has conducted for the UK Government during 2015 and which first discussions are presented in this paper. The values obtained from the monitoring of 16 solid-wall pre-1919 Victorian terraced houses in Greater Manchester are in accordance to those extracted from the BRE report on "In-situ measurements of Wall U-values in English Housing", what validates the methodology followed to approach the monitoring of these case study houses as well as the preliminary results. This alignment provides a closer definition of the real U-value of solid wall housing typology confronted with those currently provided by the Standard Assessment Procedure (SAP) and Reduced Data Standard Assessment Procedure (RdSAP), leading the way to a better understanding of the performance of historic buildings and hence an improvement in the retrofitting strategies.

Keywords – Traditional Housing; Monitoring; Energy Performance; Northern England; Terraced Houses

1. INTRODUCTION

The urban fabric of European cities is largely shaped by old and inefficient residential buildings whose energy demand can exceed 200kWh/m per year [1]. More than 40% of our European residential buildings have been constructed before the 1960s when energy building regulations were very limited [2]. As a matter of fact, the energy used in domestic buildings contribute a large percentage of the world's carbon emissions [3]: while modern building techniques are able to produce dwellings with a low in-use energy requirement, a greater impact can be made by improving the existing, poorly performing housing stock [4].

Additionally, architectural heritage deserves very particular attention within a sustainable architectural approach, with regard to sustainable energy development and historic buildings protection [5]. Preservation of the architectural heritage is considered a fundamental issue in the life of modern societies [6] contributing significantly to the value of the city by branding the city´s character. The need of preserving historical constructions is thus not only a cultural requirement, but also an economical and developmental demand [7].

In United Kingdom (UK), the number of new buildings contributes at the most 1% per year to building stock [8] whilst the other 99% are already built buildings. In fact, UK is one of the countries in Europe with the largest components of older buildings [9]: 21% of UK housing were built before 1919 and the advent of cavity walls [10]. Terraced houses account for 6.788.000 [11] what supposes a 29.9% of the total building stock [12]. Moreover, from the 3.076.000 dwellings in North West England (where Greater Manchester is sited), 35.5% are terraced houses [12]. The retrofitting of this residential stock could so provide considerable potential in energy conservation and sustainability benefits [13]. However, the achievement of the benefits reaped from the retrofitting could be jeopardised by the scarcity of knowledge about the behaviour of historic buildings and its consumption patterns, what supposes a major obstacle to take right decisions over a specific building stock.

This research seeks to address the following two questions: first, the need to establish an efficient monitoring system assuring good data availability and data quality; and second, the need to develop a systematic understanding, methodology and analysis when approaching these buildings which incorporates the many interactions both within specific elements and at a whole house level including technical factors and user behaviour [14]. It reviews the research conducted on 16 Victorian terraced houses sited in the area of Great Manchester and it is the result of a two-year monitoring of pre and post-retrofitted housing developed under the Green Deal Go Early (GDGE) project run by the University of Salford for the UK Government. Whether some air test results and Energy Performance Certificates (EPC) energy use calculations are provided, this paper does not present results but preliminary descriptions and discussions. Therefore, no results chapter has been provided.

2. STUDIED SAMPLE: TERRACED HOUSES OF NORTHERN ENGLAND

Our targeted building stock is described by English Heritage as "a property built prior to 1919 with solid walls constructed of moisture-permeable materials" [14]. This stock is defined by a solid two layers of brick non-insulated envelope. The insulation of solid wall housing is indeed one of the greatest challenges for energy efficiency policy, but it also potentially offers some of the most significant savings [15].

The Building Research Establishment (BRE) [16] defines two types of housing among this stock: Standard and Non-Standard. Standard buildings are those with less than 330mm wall thickness while Non-Standard are those beyond. Only two of our examples are Non-Standard houses with a triple brick solid wall dated before 1800. They have been considered as part of the sample because the time period, wall structure and material use.

Table 1. Housing samples definition and identification

ID	Archetype	Standard/Non-Standard
C1 - C18	Semi-detached Pre1800 brick.	Non-Standard
C8 - C9 - C10 - C12 - C14 - C15, S2	Semi-detached pre 1919 solid wall.	Standard
C6-C17	Mid terraced pre 1919 solid wall.	Standard
S3 - V1 - V3 - V4	End terraced pre 1919 solid wall.	Standard
V2	Terraced pre 1919 solid wall.	Standard

As aforementioned, all buildings improved in this study had solid walls with no cavity. Insulation was placed on the inside or outside face of the buildings during the retrofitting respecting the original fabric and the authenticity of the historic values of the buildings. In most cases, the insulation was placed on the outside of the buildings around the rear and sides, and the façade was preserved by installing insulation on the inside across the front elevation although internal insulation caused much more disruption to the occupants, removing some of the living space. The insulation layers also needed to 'overlap' somewhat to prevent the brickwork becoming a cold bridge. On a couple of the buildings, thin tiles that resemble the original brickwork where placed over the insulation to mimic the original appearance.

3. METHODOLOGY

The methodology followed in the project focuses on gathering and storing data from buildings that could be analysed in the future. The relevant steps for this paper are building selection and data collection, which correspond respectively to the processes to *identify and select buildings to monitor* and the *collection of quantitative and qualitative data* from the selected buildings.

3.1 BUILDING SELECTION

The eligible dwellings are a sub-set of those that forms the GDGE monitoring project. Started in 2012, this project included in-use performance monitoring and fabric testing of domestic properties across greater Manchester with the aim of investigating the effectiveness of the UK government's Green Deal (GD) program. This report concerns itself with the terraced archetype. Sixteen properties have been classified by experimental group: either 'Control' (unaltered, no retrofit measures) or 'Retrofit' (significant energy efficiency measures applied), and by ownership status: 'Owner Occupied' (owned by the occupant) or Housing Association (owned by a third body, responsible for the retrofit measures, and rented to the occupant). Figure 1 shows how the sample properties are distributed regarding to these indicators:

Carbon Coop: Properties recruited through a cooperative community benefit society formed by householders from Greater Manchester. The houses included are mid- and end-terraced houses.

Control Group: Unimproved end terraced houses.

Housing association: recruited from a housing association in Greater Manchester, the retrofit houses are all end terraces.

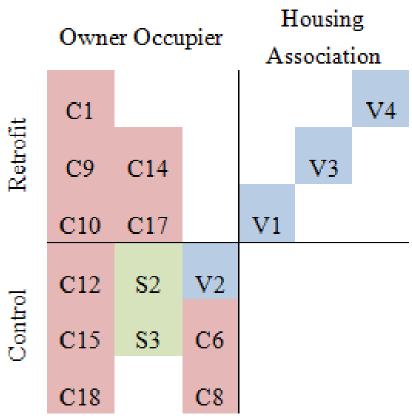


Figure 1: Classification of sample properties

3.2 DATA COLLECTION

The goal of this task is to collect dwelling quantitative and qualitative data as follows: quantitative data about the house as a whole is collected by direct *monitoring* with sensors and by the *availability of EPCs*; quantitative data of the building fabric is collected using both testing methods (*U-value* and *air tightness*) and *thermography;* and finally, qualitative data about user satisfaction with the retrofitting is gathered with a survey.

3.2.1 Whole House Methods

Monitoring: The monitoring period, between 2013 and 2015, comprised the adoption of retrofit strategies in some of the housing examples what provides pre and post retrofitting measures to the study. The monitoring equipment included small, battery powered sensors that communicated wirelessly with a central ‘hub’ that periodically stored/updated data into a central server. Data includes information of primary energy consumption (gas and electricity), internal conditions (temperature, relative humidity and CO2 emissions) and external temperature.

Energy Performance Certificates (EPC) In many cases, EPCs where available for retrofit houses in their pre-retrofit state, allowing a before and after comparison. In the UK, EPCs are generated using a reduced version of the Standard Assessment Procedure and presented as a band A to G (A is higher efficiency) and a score 1 to 100(100 is higher efficiency) [12].

3.2.2 Building Fabric Methods

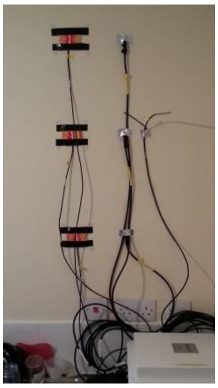


Figure 3: U value measurement

Figure 4: Air tightness test

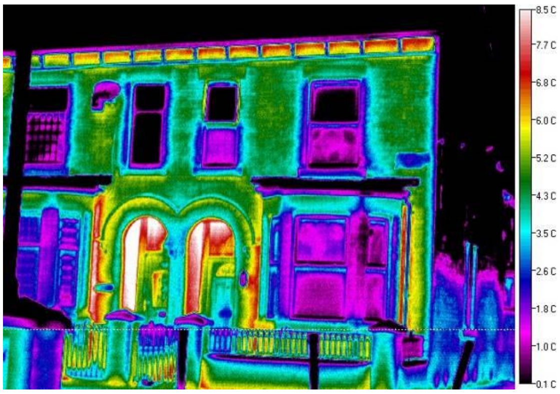


Figure 5: Thermographic image

U- value testing: The U values of several of the houses where measured according to ISO 9869-1:2014 [17] (Figure 3, above). U values were also calculated using BS EN ISO 6946:2007 methodology [18].

Air tightness testing: Air tightness tests using the ‘blower door’ method (figure 4, above) were carried out to determine the rate of air infiltration. The test gives a result as a q50 value, being the volume of air (m3) infiltrating the building envelope (m2) per hour (hr) at a pressure difference of 50 pascals (50pa). The tests conformed to BS EN 13829:2001 methodology [17].

Thermography: For maximum accuracy, and in conformity with the BS EN 13187:1999 methodology [18] (Figure 5), the surveys where carried out in the evening at least 2 hours after sunset when the internal temperatures of the building where a minimum of 10°C higher than external air temperature.

3.2.3 User Methods

User Survey: The households filled in a personal survey conducted by the expert before and after the retrofitting. This survey gives a qualitative approach to the measures. The preliminary findings of the project indicate that it is very difficult to disaggregate the effects of fabric improvement from the occupant's behaviour.

4. FIRST OUTCOMES AND DISCUSSION

This paper presents the preliminary outcomes of the monitoring of 16 terraced dwellings as well as the methodology followed. The obtained data is being processed using a bottom-up and top-down approach:

Bottom-Up: Energy consumption is a key indicator to evaluate the improvement of a retrofit strategy. Gas and electricity consumption has been measured in all the selected houses. A first problem encountered was that primary energy use data cannot be compared between houses directly as the monitoring interval was not identical. As an assumption, degree day regression was used to normalize the energy use against external temperature. Graphics comparing the consumption and the degree day regression assumption has been developed for all the houses what allows direct comparison of energy data from multiple houses over different time periods (see Figure 6 and 7). The distribution of the values in figure 7 display a strong positive correlation, with an r^2 value of 0.77. This is at the high end of the range of r^2 values indicating that the energy use in this house is particularly responsive to changes in temperature, suggesting an effective use of heating controls.

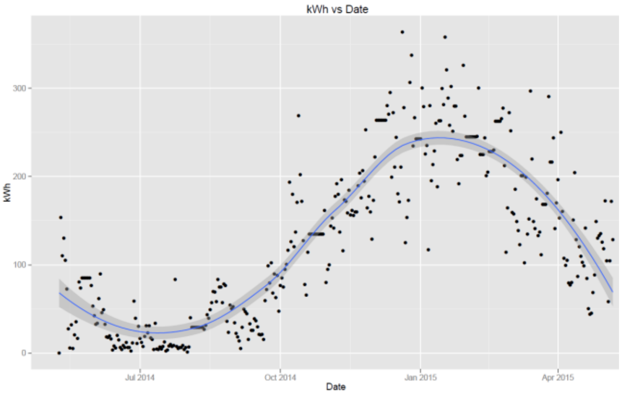
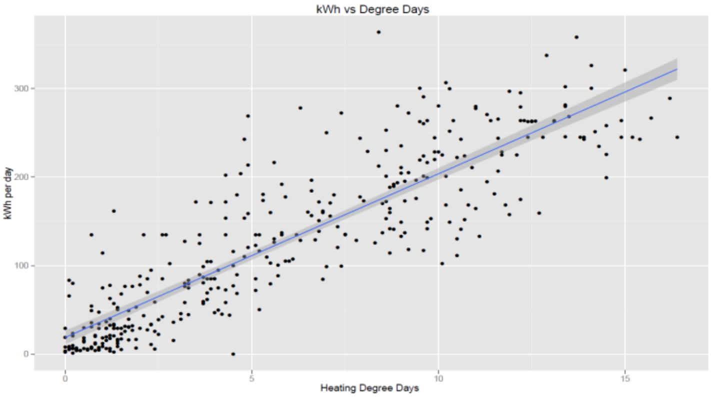


Figure 6: kWh gas use by date (example)



Regression figures: Intercept = 19 Slope = 18 R squared = 0.77

Figure 7: Degree day regression on same data

Table 2. Summary of results compared with those of the BRE report [13]

Retrofit improvements	Archetype	U-Value Measured_Mean (W/m K)	Measured U-Values BRE_Mean (W/m K)	Percentage difference
As built	Semi-detached Pre1800 brick.	1.6	1.28	25%
	Semi-detached pre 1919 solid wall.	1.3	1.57	-17%
	End terraced pre 1919 solid wall.	2.38*	1.57	-50%
External wall insulation	Semi-detached Pre1800 brick.	0.4	1.28	69%
	Semi-detached pre 1919 solid wall.	0.29	1.57	82%
	Mid terraced pre 1919 solid wall.	0.32	1.57	80%

In 2014, BRE published their report about in-situ measurements of wall U-values in English Housing [16]. This report concludes that the averages of the measures values for solid un-insulated walls are below the standard values used in the RdSAP methodology and below the mean of the theoretical calculated U-value regarding to the wall typology. Table 2 shows the comparison of those results with the ones measured in the monitored housing. The U-values of the ‘as built’ pre retrofit properties fall within an acceptable margin of the BRE report. Differences could be due to the number of examples used for the different studies - 300 in the case of BRE - that provides them with more accurate averages. The improved properties with 'external wall insulation' show a sizable improvement when compared to the same archetypes in the BRE report. The U-value measured from the End terraced pre 1919 solid wall (* above) is particularly high, possibly due to the deterioration of the building fabric due to damp. However, the figure is within the 99% confidence interval of the BRE report sample (assuming normal distribution, within three standard deviations from the mean), suggesting that although unusually high, the value is not necessarily in error.

Top-Down: the GDGE project has provided data of pre and post retrofit measures. Among the 16 sample cases, half of them were retrofitted. Figures 8 and 9 show the impact of retrofitting strategies on air infiltration (q50) and primary energy consumption calculated from the EPC [16]. Regarding to EPC rating, important improvements could be appreciated in the semi-detached solid wall typology. During the measurements, it was noted that unimproved properties can be more airtight than expected due to regular maintenance; the attitude of the occupants towards draught proofing has a large effect on the q50 value. Conversely, the disruption to the building fabric caused by the retrofit measures, particularly the installation of internal or external insulation, can potentially cause disturbances to the fabric that lead to an increase in the infiltration rate.

The results presented in this paper are just a preliminary overlook of the datasets collected during the last two years. A methodology has been established to approach a unified understanding of the outcomes that could be compared through all the housing examples. Some assumptions have been made in the adoption of this methodology that need refining in the ongoing analysis.

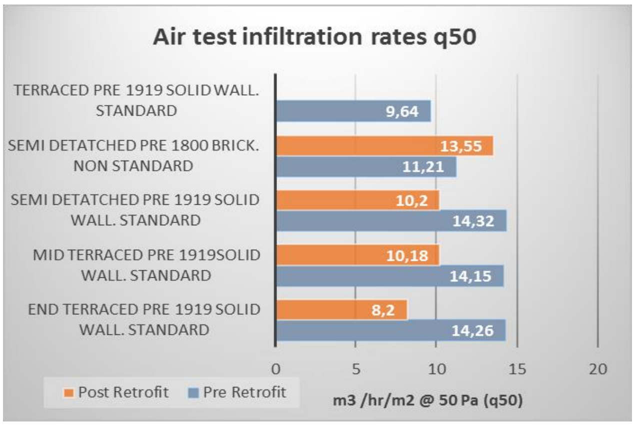


Figure 8: Air infiltration rates pre and post retrofit

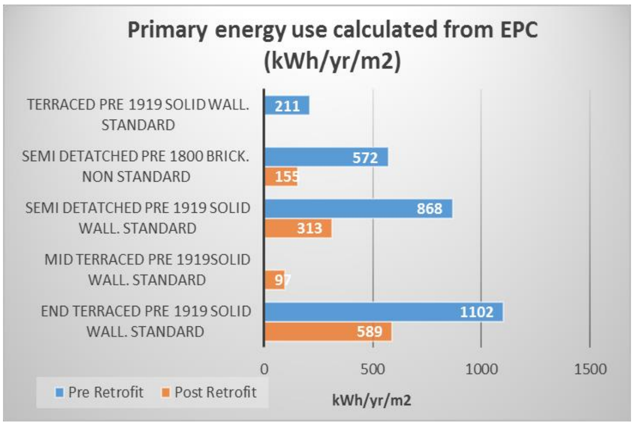


Figure 9: Primary energy use pre and post retrofit (Figures from EPC)

Currently, the data has been processed in the micro-scale by looking to individual measures separately by individual housing. Some clues of a wider look have already been introduced in the discussion but more work has to be done in proposing global reliable values that define the whole building stock.

5. CONCLUSION

The approach to traditional buildings needs a systematic understanding, methodology and analysis. This paper presents the results of a two years monitoring of pre and post retrofitted examples of solid wall terraced buildings in the area of Greater Manchester. The outcomes of this study serve as base to a better understanding of the performance of these buildings. The results included in this paper suggest consistent improvement in air infiltration rates, U-Values and EPC calculated energy use estimates. As the analysis progresses more detail into the effectiveness of the retrofit measures will emerge, which will contribute to further programs of retrofit measures promising reductions in energy consumption and CO^2 emissions in the whole building stock.

The green deal, now defunct, relied on a "golden rule": that the occupants will always be paying less for their heating even with the additional surcharge added to their bills to pay for the improvements. The preliminary findings of the project indicate that it is very difficult to disaggregate the effects of fabric improvement from the occupant's behaviour, for example, comfort taking, ventilation practices, secondary heating. Therefore, a simple calculation based on estimated energy saving will be insufficient. For future government initiatives for retrofit, a different finance mechanism should be considered.

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Thermal insulation for buildings — Reflective insulation products — Determination of the declared thermal performance

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The UK participation in its preparation was entrusted by Technical Committee B/540, Energy performance of materials components and buildings, to Subcommittee B/540/9, Reflective insulation and in-situ testing.

A list of organizations represented on this committee can be obtained on request to its secretary.

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Amendments/corrigenda issued since publication

Date	Text affected
31 March 2015	Implementation of CEN amendment A1:2015

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NORME EUROPÉENNE
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EN 16012:2012+A1

February 2015

ICS 91.100.60

Supersedes EN 16012:2012

English Version

Thermal insulation for buildings - Reflective insulation products - Determination of the declared thermal performance

Isolation thermique des bâtiments - Produits d'isolation réfléchissants - Détermination de la performance thermique déclarée

Wärmedämmstoffe für Gebäude - Reflektierende Wärmedämm-Produkte - Bestimmung der Nennwerte der wärmetechnischen Eigenschaften

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Ref. No. EN 16012:2012+A1:2015 E

Contents

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Foreword

This document (EN 16012:2012+A1:2015) has been prepared by Technical Committee CEN/TC 89 “Thermal performance of buildings and building components”, the secretariat of which is held by SIS.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by August 2015, and conflicting national standards shall be withdrawn at the latest by August 2015.

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According to the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this European Standard: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, Former Yugoslav Republic of Macedonia, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and the United Kingdom.

Introduction

Reflective (low emissivity at the appropriate wavelength) surfaces are utilized in a number of ways to enhance the thermal performance of insulating products. Their role is to reduce the heat transfer by thermal radiation in some parts of the system. This is achieved because low emissivity surfaces reduce the radiant heat transferred through a product that is wholly or partially transparent to infra-red radiation (e.g. very low density fibrous insulation). They will also reduce the radiant heat transfer across any air gap or gaps that are present in the system. In some cases, air gaps can be an intrinsic part of the structure and in other cases the insulation can be installed in such a way as to deliberately create an air gap between the reflective surfaces and the structure.

Unless otherwise stipulated by the manufacturer, the declared thermal performance should include an adjacent vertical air space on either side of the product, and the declared thermal performance should also include a statement of the thickness of these airspaces included as part of the declared value. The declared value can, alternatively, be given as the combination of the thermal resistance of the “core” of the product together with the measured value of the emissivity of the surfaces.

Since all conventional thermal insulation products declare their thermal performance on the basis of the value to be expected over a reasonable working life, this is also addressed in a limited manner in this standard in the assessment of emissivity of the surface(s) of reflective insulation. In the absence of any quantified and certified data on the aged performance of a facing over a normal lifetime for a building material, the ageing of the low emissivity surface is assessed by use of an accelerated ageing procedure.

How the thermal properties of insulation materials that utilize reflective surfaces are determined will depend on the form in which they are sold and how they are intended to be used. This standard describes a number of different approaches which can be utilized and specifies which approach to use for the different types of product. Where a product is already subject to a product specification that describes procedures for the measurement of the aged 90/90 fractile thermal conductivity or thermal resistance of the core insulation material, the following guidance should only be used to determine the component of its thermal performance that depends on the emissivity of its external faces. However, it should be remembered that the declared value is only the first step, giving comparative performance values under specified conditions, and the design value can give more information for use by the designer in specific applications, especially under different climatic conditions.

1 Scope

This European Standard describes a set of procedures for using existing standardized CEN or ISO test and calculation methods to determine the declared thermal performance of reflective insulation products. This European Standard supports and does not replace existing CEN or ISO test methods.

This European Standard applies to any thermal insulation product that derives a proportion of its claimed thermal properties from the presence of one or more reflective or low emissivity surfaces together with any associated airspace(s). It does not replace the existing procedures for the determination of the thermal performance of products already covered by an existing harmonized product standard where the declared value of these products does not specifically include any claims attributable to the emissivity of the facing.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 823:1994, *Thermal insulating products for building applications — Determination of thickness*

EN 1946-1, *Thermal performance of building products and components — Specific criteria for the assessment of laboratories measuring heat transfer properties — Part 1: Common crieteria*

EN 1946-2, *Thermal performance of building products and components - Specific criteria for the assessment of laboratories measuring heat transfer properties - Part 2: Measurements by guarded hot plate method*

EN 1946-3, *Thermal performance of building products and components - Specific criteria for the assessment of laboratories measuring heat transfer properties - Part 3: Measurements by heat flow meter method*

EN 1946-4, *Thermal performance of building products and components - Specific criteria for the assessment of laboratories measuring heat transfer properties - Part 4: Measurements by hot box methods*

EN 12664, *Thermal performance of building materials and products - Determination of thermal resistance by means of guarded hot plate and heat flow meter methods - Dry and moist products of medium and low thermal resistance*

EN 12667, *Thermal performance of building materials and products - Determination of thermal resistance by means of guarded hot plate and heat flow meter methods - Products of high and medium thermal resistance*

EN ISO 6946, *Building components and building elements — Thermal resistance and thermal transmittance — Calculation method (ISO 6946)*

EN ISO 7345, *Thermal insulation — Physical quantities and definitions (ISO 7345)*

EN ISO 8990, *Thermal insulation — Determination of steady-state thermal transmission properties — Calibrated and guarded hot box (ISO 8990)*

EN ISO 9229, *Thermal Insulation — Vocabulary (ISO 9229)*

EN ISO 9288, *Thermal insulation — Heat transfer by radiation — Physical quantities and definitions (ISO 9288)*

EN ISO 10456, *Building materials and products — Hygrothermal properties — Tabulated design values and procedures for determining declared and design thermal values (ISO 10456)*

ISO 8301:1991, *Thermal insulation — Determination of steady-state thermal resistance and related properties — Heat flow meter apparatus*

ISO 8302:1991, *Thermal insulation — Determination of steady-state thermal resistance and related properties — Guarded hot plate apparatus*

ISO/IEC Guide 98-3, *Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

3 Terms, definitions, symbols and units

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in EN ISO 7345, EN ISO 9288, EN ISO 9229 and the following apply.

3.1.1
declared thermal performance
value of thermal performance, declared by a manufacturer, which is derived from measured values under the specified conditions and rules given in this standard

3.1.2
indentation
concave depression in the surface of the facing (foil) such that shallow air pockets are created when the surface is in contact with a smooth flat plate

3.1.3
core thermal resistance
thermal resistance of the product from face to face at the tested thickness, excluding the contribution of any low emissivity outer surface or any air space(s) adjacent to the product

3.1.4
emissivity
ratio of the energy radiated by a surface relative to the energy radiated by a blackbody at the same temperature

3.1.5
reflective surface
low emissivity surface
surface which has a low emissivity at the appropriate wavelength within the temperature range found in building elements

3.1.6
reflective insulation
insulation product which has one or both external face(s) comprising a reflective surface

Note 1 to entry It is a measure of a material's ability to radiate heat.

3.2 Symbols and units

For the purposes of this standard, the following symbols and units apply.

Symbol	Quantity	Unit
P	perimeter	M
A1〉 R	thermal resistance	$m^2 \cdot K/W$ 〈A1
U	sensor signal	V
ε	emissivity	-
λ	thermal conductivity	$W/(m \cdot K)$
Φ	heat flow rate	W
Ψ	linear thermal transmittance	$W/(m \cdot K)$
$\Delta\theta$	temperature difference	K

Subscripts	
L	low
H	high
e	edge
sur	surround
D	declared
A1〉 90/90	90 % fractile with a confidence level of 90 % 〈A1

4 Description of product types

4.1 Product classification

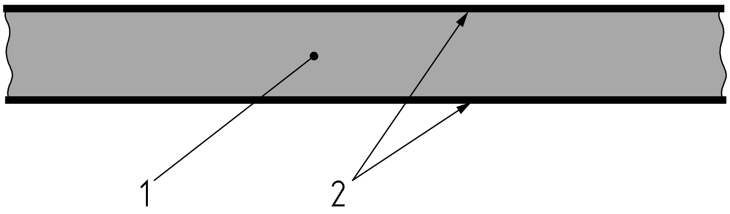
This clause describes the various generic product types to which this standard refers. Product type is defined solely for the purpose of selecting the most appropriate test method (product type number does not refer to a generic species of product). Together with 4.2, 4.3 and 4.4, the flow charts in Annexes A, B and C shall be followed in assigning a given product to a product type.

In 4.2, 4.3 and 4.4, the product type is determined by reference to its compressibility or otherwise to achieve flat parallel surfaces. This implies the removal of measurable air-gaps between the specimen and the hot and cold plates of the test apparatus whilst not unduly reducing the overall thickness of the specimen to be tested. When using the weighted plate method from EN 823:1994 there shall be no residual air spaces between the weighted plate and the specimen surface. The weight of plate used for the thickness measurement shall be the lowest of either plate sufficient to eliminate air gaps. The thickness measured under the chosen plate shall be the thickness subsequently used for the measurement of the core thermal resistance and given in the test report.

4.2 Product Type 1

A product shall be classified as Type 1 when it has a regular geometry with parallel faces or is compressible so that the product can be contained between the hot and cold plates of the apparatus without significantly changing its core thermal properties. This is achieved when its surfaces are smooth and flat with no discernible depth of pattern or indentation.

EXAMPLES Including (but not limited to) foam insulation with aluminium foil facing on each side (see Figure 1), mineral wool faced with aluminium foil, multi-foil insulation product which is stitched or seamed only at the edges and substantially flat with parallel faces (see also the limitation in Clause 1).



Key

1 insulation core

2 low emissivity surface or surfaces

NOTE The emissivity of each of the outer surfaces can be different or the product can be faced on only one side.

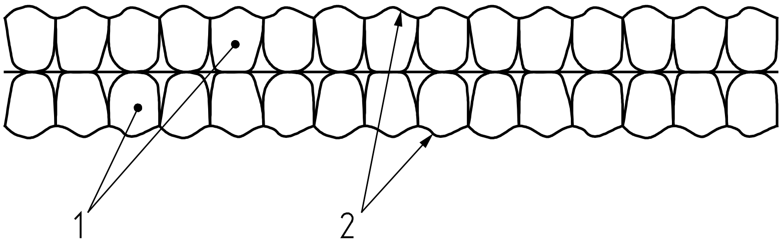
Figure 1 — Example of insulation material with reflective facing on each side

4.3 Product Type 2

A product shall be classified as Type 2 when it has a regular geometry with parallel faces or is compressible so that the product can be contained between the test apparatus hot and cold plates without changing its core thermal properties. The surface or surfaces shall not be flat and smooth and can have indentations of less than 5 mm depth when measured using the pin and plate described in EN 823:1994, subclause B.1, or an alternative method with at least the same level of accuracy. The pin shall be placed in the lowest point of any indentation but shall not pierce the surface.

NOTE If the indentations are 5 mm or greater, it is product Type 3.

EXAMPLES Including, but not limited to, some types of bubble foil insulation with reflective surfaces (see Figure 2).



Key

1 air filled plastic bubbles

2 reflective surface(s)

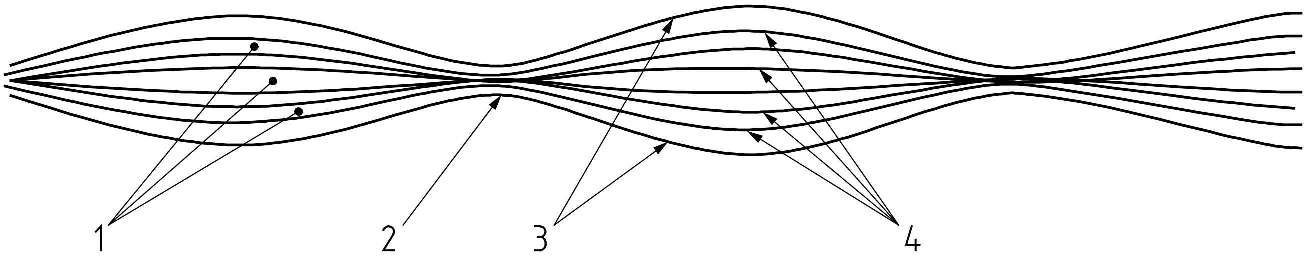
Figure 2 — Example of bubble foil insulation with reflective surfaces

4.4 Product Type 3

A product shall be classified as Type 3 when it has irregular thickness geometry, does not have flat parallel faces, or cannot be compressed to produce flat and parallel faces without changing its core thermal properties. Product Type 3 shall not be measured in a guarded hot plate or heat flow meter apparatus.

NOTE 1 Its surfaces might or might not have indentations, the depth of which is not limited to any specific value.

NOTE 2 It could include stitching or seams. A typical example would be the stitched multi-foil reflective insulation products, or sealed “pockets” or “pillows” made from reflective foil sheets, as shown in Figure 3.



Key

1 insulation layer(s) between foil – such as foam or wadding

2 welded or stitched fabrication feature

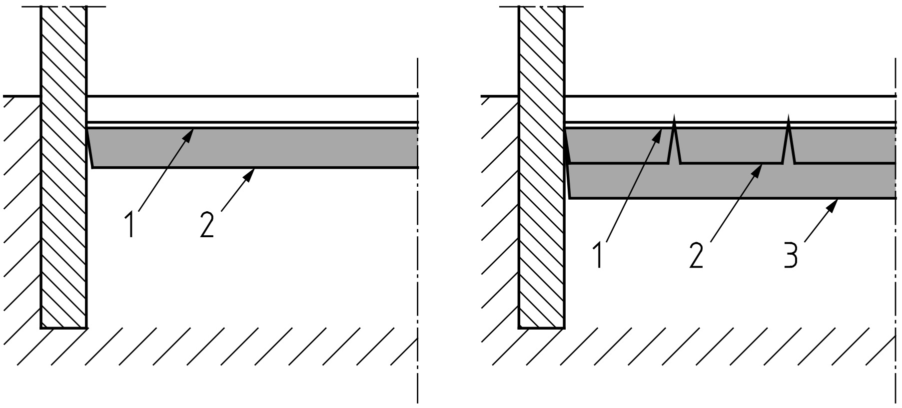
3 low emissivity external surface or surfaces

4 intermediate layers of foil

Figure 3 – Example of stitched multi-foil insulation

4.5 Product Type 4

Product Type 4 is a thin film or sheet, less than 2 mm thickness, used singly or in multiple layers, which makes use of a low emissivity surface to increase the thermal resistance of adjacent or enclosed air space(s), but which has no significant thermal resistance of its own. See Figure 4.



Key

Left picture: 2-layer foil system (1 and 2) with one air layer in-between

Right picture: 3-layer foil system (foil layers 1, 2 and 3) with two air layers in between

Figure 4 – Example of multiple layers of product Type 4 under flooring

5 Methods of assessment

5.1 General

In addition to the general requirements for testing thermal performance in accordance with EN 12664, EN 12667 and EN ISO 8990, the specific requirements for mounting of specimens given in 5.4−5.8 shall also be followed. The measurement of thermal performance of reflective insulation products Type 1, Type 2 and Type 3 shall require the measurement of the thickness of the specimens.

5.2 Thickness measurement

With the exception of thin single layer films or sheets, the thickness of all types of product which are in excess of 2 mm nominal declared thickness shall be determined using the procedures in A1⟩ EN 823 ⟨A1, using the lowest weight of plate permitted by the test method that substantially eliminates any air gaps A1⟩ , except that the minimum weight of plate may be reduced from 50 Pa to 25 Pa ⟨A1. The thickness of thin films and sheets with a nominal, declared thickness of < 2 mm does not need to be measured.

5.3 A1⟩ Test specimens ⟨A1

A1⟩

5.3.1 Size and number of specimens

The specimen size shall be appropriate to the apparatus being used. In the absence of harmonised product specifications for any product type and to permit statistical calculation of the thermal performance, a minimum of 3 samples shall be tested, taken from at least 3 different production batches wherever possible. Where a harmonised product specification exists, the rules from that standard should be followed. ⟨A1

A1⟩

5.3.2 Conditioning and specimen preparation ⟨A1

Except for the measurement of emissivity, where special conditioning requirements exist, all test specimens shall be stored for at least 6 h at (23 ± 5) °C. In cases of dispute, they shall be stored at (23 ± 2) °C and (50 ± 5) % relative humidity for the time specified in any relevant harmonized product standard, or for a minimum of 6 hours.

NOTE 5.7.2 specifies the procedure to be followed to determine the conditioning of specimens to be used in Hot Box measurements where the emissivity of the facing could be subject to ageing. 5.9 and Annex D specify the conditioning (ageing) requirements for specimens for emissivity measurement.

In the case of products supplied in compressed form, the material shall be allowed to recover fully before conditioning for test. This shall be for a minimum of 6 hours or longer if recommended by the manufacturer. In cases of dispute, the procedure specified in EN 823:1994, Annex A shall be followed.

5.4 Determination of thermal resistance – outline

Four different methods are defined in this standard. Some methods are more appropriate than others for different forms of reflective insulation materials which have been described in Clause 4 of this standard. The actual measured performance using each method gives comparable performance values.

Of the four methods, three provide a measurement of thermal resistance as follows:

- METHOD A: Guarded Hot Plate Apparatus meeting the requirements of ISO 8302, EN 1946-2, EN 12664 and EN 12667;

- METHOD B: Heat Flow Meter Apparatus meeting the requirements of ISO 8301, EN 1946-3, EN 12664 and EN 12667;
- METHOD C: Hot Box Apparatus meeting the requirements of EN ISO 8990 and EN 1946-4 (see 5.7)

and the fourth method is based upon the measurement of surface emissivity:

- METHOD D: Measurement of emissivity and calculation.

The choice of method relevant for each product type is elaborated in 5.5–5.8, together with the flow charts in Annexes A, B and C. The surface of the material shall be assessed as given in Clause 4 to determine the appropriate product type and test method, which shall be specified in the test report.

[A1⟩ The declared thermal resistance, R_D shall be given as limit values representing at least 90 % of the production, determined with a confidence level of 90 % according to the calculation rules given in EN ISO 10456. ⟨A1]

5.5 Determination of core thermal resistance of Product Type 1

5.5.1 Product thickness greater than 20 mm

5.5.1.1 Thermal resistance expected to be greater than 0,5 m²·K/W

Use either:

- METHOD A: Measure in a guarded hot plate apparatus, or
- METHOD B: Measure in a heat flow meter apparatus.

5.5.1.2 Thermal resistance expected to be 0,5 m²·K/W or less

Use either:

- METHOD A: Measure in a guarded hot plate apparatus, or
- METHOD B: Measure in a heat flow meter apparatus.

In each case thermocouples shall be attached to the specimen surface (using the procedures specified in EN 12664).

5.5.2 Product thickness less than or equal to 20 mm

5.5.2.1 Thermal resistance expected to be greater than 0,5 m²·K/W

Use either:

- METHOD A: Measure in a guarded hot plate apparatus using thermocouples embedded in the hot and cold plates, or
- METHOD B: Measure in a heat flow meter apparatus using the “dummy specimen” technique given in Annex E.

5.5.2.2 Thermal resistance expected to be 0,5 m²·K/W or less

Use either:

- METHOD A: Measure in a guarded hot plate apparatus using thermocouples attached to the specimen surface (the procedures specified in EN 12664 shall be used), or
- METHOD B: Measure in a heat flow meter apparatus using the “dummy specimen” technique given in Annex E.

If thermocouples are to be fixed to aluminium or other metal foil, the bare thermocouple wire shall be electrically isolated from the foil by a strip of thin adhesive tape.

5.5.3 For all thicknesses and nominal thermal resistances

As an alternative to the options described in 5.5.1 and 5.5.2 above, any Type 1 product may also be measured using the procedure described as METHOD C in 5.7 below.

5.6 Determination of core thermal resistance of Product Type 2

5.6.1 Product Type 2 with surface indentations less than 2 mm in depth

Treat as Product Type 1 (see 5.5 to select appropriate methodology depending upon thickness and expected thermal resistance).

5.6.2 Product Type 2 with surface indentations greater than or equal to 2 mm, but less than 5 mm in depth

Use METHOD A or METHOD B: Measure in a guarded hot plate apparatus or heat flow meter apparatus using thermocouples attached to the specimen surface (using the procedures specified in EN 12664).

Specimen preparation: fill indentations with aqueous gel and cover with a thin layer of low conductivity film such as polyethylene. Then treat specimen as Product Type 1 to measure core thermal resistance (see 5.5 to select appropriate methodology).

5.6.3 Product Type 2 with surface indentations 5 mm in depth or greater

Where the surface indentations are 5 mm in depth or greater, the product shall be treated as if it were Product Type 3 (see 5.7).

5.6.4 For all thicknesses and/or nominal thermal resistances

As an alternative to the options described in 5.6.1 to 5.6.3, any Type 2 product may also be measured using the procedure described as METHOD C in 5.7.

5.7 Determination of core thermal resistance of Product Type 3 (METHOD C)

5.7.1 Principle

The thermal resistance of an air cavity insulated with the product mounted in the centre of the air cavity, is determined by measurement in a hot box apparatus that conforms to the requirements of EN ISO 8990. The thermal resistance of the two air cavities is calculated and deducted from the measured total thermal resistance to give the core thermal resistance of the product.

5.7.2 Determination of the need for specimen conditioning

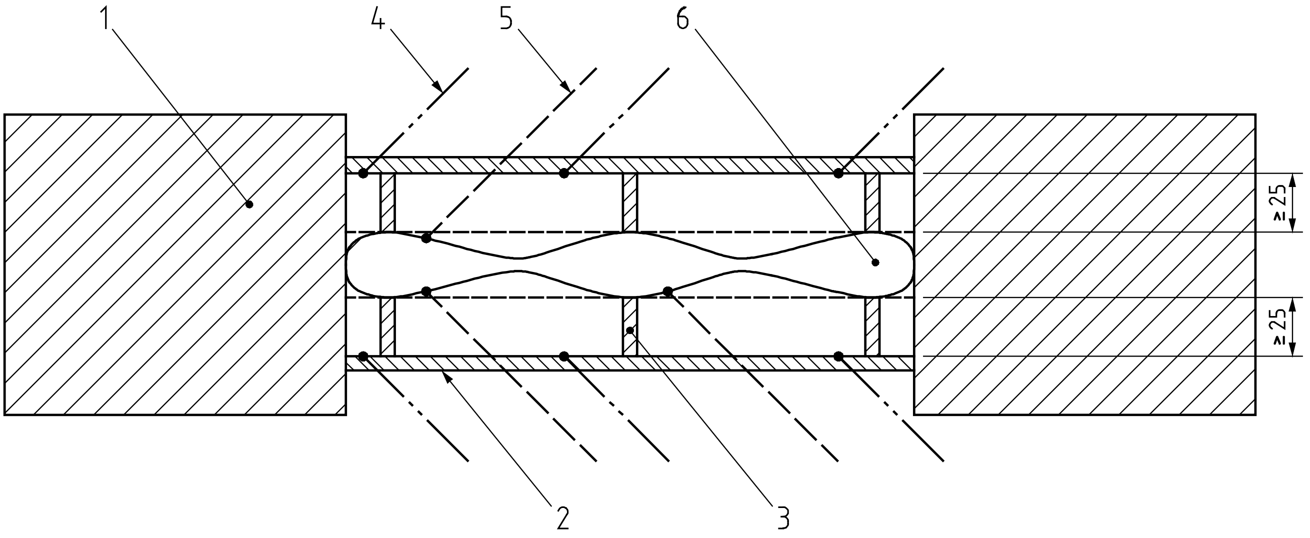
a) Measure the emissivity of the facing "as received" and after conditioning (ageing) using the procedure in Annex D.

b) If the difference between the two measurements is 0,02 or less, then the ageing is considered negligible and within uncertain limits for the test; therefore the test specimen for hot box can be the material as supplied (with no further need for ageing).

c) If the difference between the emissivity of “as received” and aged specimens is greater than 0,02 then the insulation material to be used in the hot box shall be tested after undergoing conditioning according to A1⟩ D.5.3 ⟨A1, taking care not to damage the test specimen.

5.7.3 Air cavity and specimen installation

Measure the thermal resistance of an air cavity insulated with a specimen that is representative of the test product including any stitching or welding in the body of the material.



Key

1 hot box surround panel

2 cavity walls

3 small expanded polystyrene pillars

4 thermocouples measuring the INSIDE surface temperature of the cavity walls

5 thermocouples measuring the surface temperature of the specimen

6 test specimen

Figure 5 — Typical test element used to measure the thermal resistance of an insulated air cavity

This arrangement measures the thermal resistance of the insulated air cavity without the need to measure the core thermal resistance of the material, emissivity or cavity geometries. The following conditions shall apply.

a) External “walls” to form the cavity shall be made from a suitable dry material such as plywood or MDF.

b) The length and width of the test specimen and associated air cavity shall not be less than 1 m × 1 m.

c) Air cavities created each side of the product shall be at least 25 mm deep at any point.

d) An appropriate number of expanded polystyrene pillars shall be used between the plywood and the product to ensure air cavity depths are maintained during the test. Each EPS pillar shall have a cross section of 20 mm × 20 mm and a thermal conductivity of less than 0,04 W/(m·K).

e) The product being tested shall be taped to the surround panel using low emissivity tape as recommended by the manufacturer.

f) Overlapped joints shall be avoided.

g) At least 9 thermocouples shall be fixed to the inside of each cavity wall, installed in the centres of squares of equal area.

NOTE The thermal resistance of these walls is not part of the measured value.

h) At least 5 thermocouples shall be fixed to each side of the product (using low emissivity tape). If the product has a metallic surface the thermocouples shall be fixed on top of a layer of thin adhesive tape to stop them being electrically connected.

i) The surround panel shall be between 100 mm and 300 mm thick, made from a material with a thermal conductivity < 0,04 W/(m·K)

5.7.4 Hot box test conditions

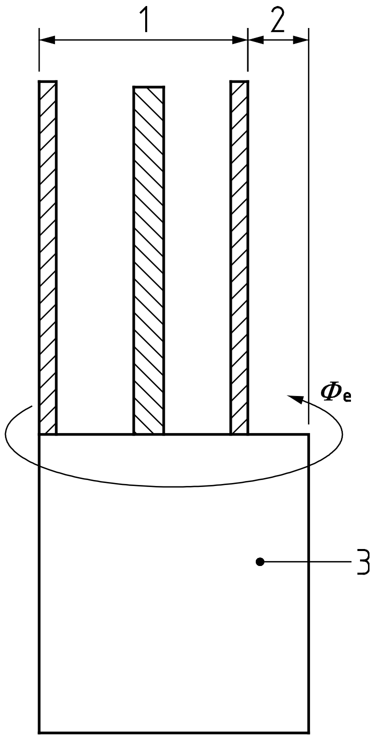
The surround panel, with the air cavities, shall be installed between the warm and cold chambers of the hot box apparatus, which can then be positioned to the appropriate specimen orientation (if required) and the target temperature difference established between the two chambers. For measurement of the declared thermal performance of products, the specimens shall be mounted vertically with horizontal heat flow, and the test conditions shall be selected to establish a temperature difference of (10 ± 1) K across the air cavity, as measured with the thermocouples mounted on the internal cavity wall surfaces, and a mean test temperature of (15 ± 2) °C.

NOTE Other specimen orientations may be used to obtain information on the performance of products in various building applications.

Cavity orientation and heat flow direction shall be specified in the test report.

5.7.5 Allowance for heat transfer around the specimen (Edge surround)

When measuring a test element installed in a surround panel, there will be a small additional heat transfer around the specimen perimeter through the surround panel (see Figure 6) which shall be taken into account.



Key

1 test element thickness

2 reveal depth

3 surround panel

Figure 6 — Heat transfer around the specimen perimeter

This additional heat flow is expressed as the linear thermal transmittance, Ψ_e, associated with the test element and surround panel and its value can be obtained from Table 1. The boundary heat flow, Φ_e, shall be calculated using Equation (1).

$$\Phi_e = \Psi_e P \Delta\theta \tag{1}$$

where

P is the perimeter of the air cavity, in m;

$\Delta\theta$ is the air temperature difference between warm and cold chambers, in K.

The heat flow through the test element shall be corrected for this boundary heat flow when calculating the thermal resistance of the air cavity from the measured data.

Table 1 — Linear thermal transmittance for insulated cavity in a surround panel

Overall cavity thickness mm	**Hot side reveal depth** mm	Ψ_e W/(m·K)		
		λ_{sur} = 0,030 W/(m·K)	λ_{sur} = 0,035 W/(m·K)	λ_{sur} = 0,040 W/(m·K)
124	26	0,0005	0,0007	0,0008
124	76	0,0033	0,0039	0,0044
124	126	0,0064	0,0073	0,0084

Values of Ψ_e for intermediate values λ_{sur} can be obtained by linear interpolation.

NOTE 1 The linear thermal transmittance values shown in Table 1 have been calculated assuming the following:

- the reflective insulation product is in the centre of the cavity;
- there is a 30 mm air cavity each side of the product under test;
- the emissivity of the external surfaces of the product under test is 0,05;
- the effective thermal conductivity of the product under test is 0,032 W/(m·K);
- the effective thickness of the product under test is 30 mm;
- the walls of the cavity are made from 17 mm thick plywood;
- the thermal conductivity of the plywood is 0,16 W/(m·K);
- the insulated cavity is mounted vertically with horizontal heat flow.

NOTE 2 For a 2 m x 1 m cavity measured in a surround panel 2,4 m x 2,4 m and 200 mm thick which has a thermal conductivity of 0,035 W/(m·K) the boundary loss Φ_e will be about 1,6 % of the total power into the hot box.

5.7.6 Calculating the core thermal resistance of the product

a. Use the procedures in EN ISO 6946 and the measured temperatures to calculate the thermal resistance of each air cavity using the emissivity determined in accordance with 5.9.2 and Annex D. The emissivity of the plywood (or other similar material) walls of the cavity shall be assumed to be 0.9.

b. Derive the thermal resistance of the complete insulated air cavity from the hot box data.

c. Derive the core thermal resistance of the product from a) and b).

5.8 Determination of the thermal performance of Product Type 4

The core thermal resistance of Product Type 4 is assumed to be negligible. The thermal performance of the specified system or installed product shall be determined using METHOD D; the measured value of the surface emissivity shall be determined in accordance with 5.9.2, and the thermal performance of the product together with an airspace or airspaces shall be calculated according to EN ISO 6946 at a nominal mean temperature of 15 °C, and a temperature difference of 10 K across the sum of the air cavities.

NOTE Specific designs and installations of Product Type 4 materials can be tested using METHOD C, the hot box according to EN ISO 8990, but in view of the range of possible installed variations in this product type, it is not possible to standardize the large variety of possible designs.

5.9 Emissivity

5.9.1 General

The emissivity of the reflective surface is a fundamentally important parameter affecting the thermal resistance of an adjacent airspace, and which, depending upon the type of facing material and the way in which it is used, may change over time due to ageing (e.g. oxidation; corrosion; exposure to UV radiation, elevated or low temperature, humidity). Long term functionality of a low emissivity surface in its application is primarily linked to the ability of the material to resist this ageing. Generally, the ageing effect due to corrosion is limited to bright aluminium foil surfaces without any protective coating, but reflective facings which have only minimal surface protection can also be prone to ageing.

This standard does not attempt to address the influence of ageing of protected foils due to exposure to UV light but it can be considered important in certain applications where the product could be exposed to sunlight for any length of time and additional information should be sought from the manufacturer regarding this property.

In certain applications, dust collection on upward facing surfaces can also reduce the benefit of the low emissivity surface, but as this is application-specific, it is not addressed in this standard.

Ageing of the low emissivity surface due to oxidation or corrosion is relevant for any application and could be addressed in a relevant European product standard for the product type concerned, but in the absence of any harmonized procedures for the product measurement of emissivity shall be carried out on specimens that have been conditioned in accordance with 5.9.2.3 and Annex D.

NOTE The types of materials, protective surfaces and their thicknesses used in reflective insulation products can cover a wide range of specifications and hence properties. The possible surface emissivity and the potential impact of ageing for any particular specimen can be very difficult to determine without direct measurement. It is therefore impossible to provide tabulated values, or default values, that would encompass every possible variation. Furthermore, identification of the actual facing, the coating, and its resistance to ageing is even more difficult after the product is placed on the market. Hence the use of default values cannot be recommended and measurement is the only accurate procedure.

5.9.2 Measurement of emissivity

5.9.2.1 Procedure

The emissivity shall be measured using the apparatus defined in Annex D (or other equipment giving at least the same level of accuracy and validated against the total hemispherical integrative sphere method, which is the fundamental physical reference procedure).

5.9.2.2 Size and number of specimens

See D.5.2 in Annex D.

5.9.2.3 Specimen preparation and conditioning

Wherever possible, the outer low emissivity facing of composite type products should be very carefully removed from the specimens prior to testing, provided this does not damage the facing. This makes the measurement of emissivity easier to carry out. If the facing cannot easily be removed, special precautions should be taken (see D.6 in Annex D) to prevent overheating of the specimen during test.

Unless ageing conditions are specified elsewhere in a European Technical Specification for the product type, each specimen for measurement of emissivity shall be subject to conditioning using the procedure in Annex D. The edges of each specimen shall be protected from moisture ingress as described in D.5.3 using self-adhesive waterproof aluminium foil tape prior to conditioning.

6 Uncertainty

6.1 General

The measurement standards ISO 8301, ISO 8302, EN ISO 8990 and EN 1946, Parts 1 to 4 assist with establishing measurement uncertainties. The accreditation standard ISO 17025 requires the methods in the ISO Guide to Uncertainty in Measurements (GUM) to be used.

The following subclauses identify the additional sources of measurement uncertainty that will be associated with the measurements specified in this standard.

6.2 Thickness measurements

If thermal resistance is measured, the thickness is required to define the product and set the separation of the plates in a hot plate measurement. The method set out in EN 823:1994 shall be used but it might be necessary for manufacturers of these products to agree the most appropriate load to be applied to the product whilst making those measurements. This measurement could introduce additional errors and shall be assessed by those carrying out the measurements.

6.3 Use of surface thermocouples on thin samples in a guarded hot plate or in heat flow meter measurement

Surface thermocouples shall be used when the thermal resistance of the specimen is below 0,5 $m^2 \cdot K/W$ and this procedure is always associated with additional measurement errors which need to be determined.

6.4 Use of dummy insulation specimens

The measurement error associated with the measurement of the dummy specimens (see Annex E) shall be combined with the measurement uncertainty associated with the test method itself using the procedures set out in ISO/IEC Guide 98-3.

6.5 Derivation of the core resistance of a Type 3 Product from hot box measurements

Each step of this process will have a measurement and/or calculation uncertainty, including:

i) the “normal” measurement uncertainty associated with the hot box measurement of the insulated air cavity;

ii) measurement of the air cavity depths;

iii) the emissivity of the test material surface 1;

iv) the emissivity of the test material surface 2;

v) the emissivity of the internal cavity walls (both walls assumed to be the same);

vi) the uncertainty in the temperature difference between the cold face of the test element and the internal cold face of the cavity;

vii) the uncertainty in the temperature difference between the warm face of the test element and the internal warm face of the cavity;

viii) the calculated thermal resistance of the cold side air cavity;

ix) the calculated thermal resistance of the warm side air.

Each of these possible sources of uncertainty shall be evaluated and combined in accordance with GUM, and the range of uncertainty included in the report.

7 Expression of results

7.1 Results derived from hot plate and emissivity measurements (Products Type 1 & 2)

[A1⟩ The thermal performance determined in accordance with this standard shall be established from a minimum of 3 test results and calculated using the 90/90 fractile rules according to EN ISO 10456 as:

a) the 90/90 fractile value of the thermal resistance of the core as determined in Clause 5, rounded downwards to the nearest 0,01 m^2·K/W, together with;

b) the 90/90 fractile value of the emissivity of the surface or surfaces (if different) as determined by D7, expressed to two decimal places, and

c) optionally, depending upon the intended application, the 90/90 fractile value of the thermal resistance of the core together with the thermal resistance of one or two adjacent (vertical) airspace(s) and the specification of the air space(s), rounded downwards to the nearest 0,05 m^2·K/W by:

1) Calculating the thermal resistance of the air cavities adjacent to the product using standardized calculation procedures specified in EN ISO 6946;

2) Using the emissivity of the surfaces from the procedure specified in 5.9;

3) Using the core thermal resistance determined from the procedures specified in 5.5 or 5.6;

4) Using a temperature difference across each air cavity of 5 K, if this calculation is being carried out for the purpose of product comparison. Alternatively, the air cavity thermal resistance may be calculated using a temperature difference suitable for the application. The temperature difference used shall be stated with the declared thermal resistance.

NOTE This calculation will not be able to take account of the effects of overlapping the products (where the foil surface on the cold side is brought directly through to the warm side). ⟨A1]

7.2 Results derived from hot box and emissivity measurements (Product Types 1, 2 & 3)

[A1⟩ The thermal performance determined in accordance with this standard shall be established from a minimum of 3 test results and calculated using the 90/90 fractile rules according to EN ISO 10456 as:

a) the 90/90 fractile value of the thermal resistance of the core together with the thermal resistance of the vertical air space(s), rounded downwards to the nearest 0,05 m^{2}K/W, and the specification of the air space(s), together with,

b) the 90/90 fractile value of the measured emissivity of the surfaces expressed to two decimal places, and

c) the 90/90 fractile value of the thermal resistance of the core as determined in 5.7, rounded downwards to the nearest 0,01 m^2·K/W. ⟨A1]

7.3 Results derived from emissivity measurements only (product Type 4)

[A1⟩ The thermal performance determined in accordance with this standard shall be established using a minimum of 3 test results and calculated using the 90/90 fractile rules according to EN ISO 10456 as:

a) the 90/90 fractile value of the measured emissivity of the surface (or surfaces) expressed to two decimal places, together with;

b) the calculated thermal resistance of associated (vertical) air space(s), rounded downwards to the nearest 0,05 $m^2 \cdot K/W$, the specification of the air space(s), the temperature differences used and the calculation method used. ⟨A1⟩

8 Report

The report shall include at least the following details:

a) description of the product, to include at least the product name, types of facing and degree of any printing on the surface;

b) product manufacturer or supplier;

c) the product type determined (1, 2, 3 or 4);

d) the test method used and the conditions of test, including hot and cold face temperatures and direction of heat flow;

e) the thickness used for the test and the weight of plate used for the test;

f) the declared thermal performance of the product as described in Clause 7 for the relevant product type;

g) date of test;

h) range of uncertainty of the test result.

Annex A
(normative)

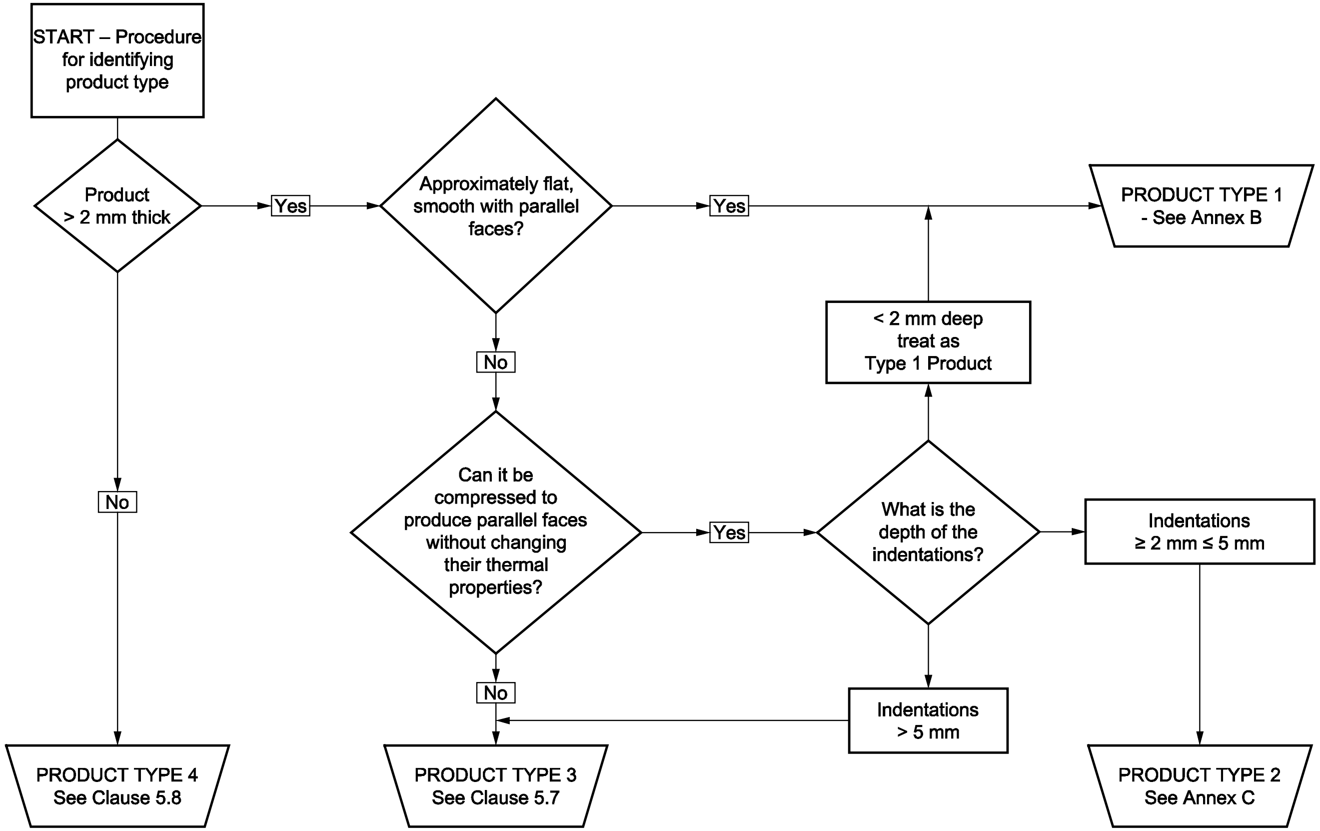


Figure A.1 - Decision making flow chart for identification of product types

Annex B
(normative)

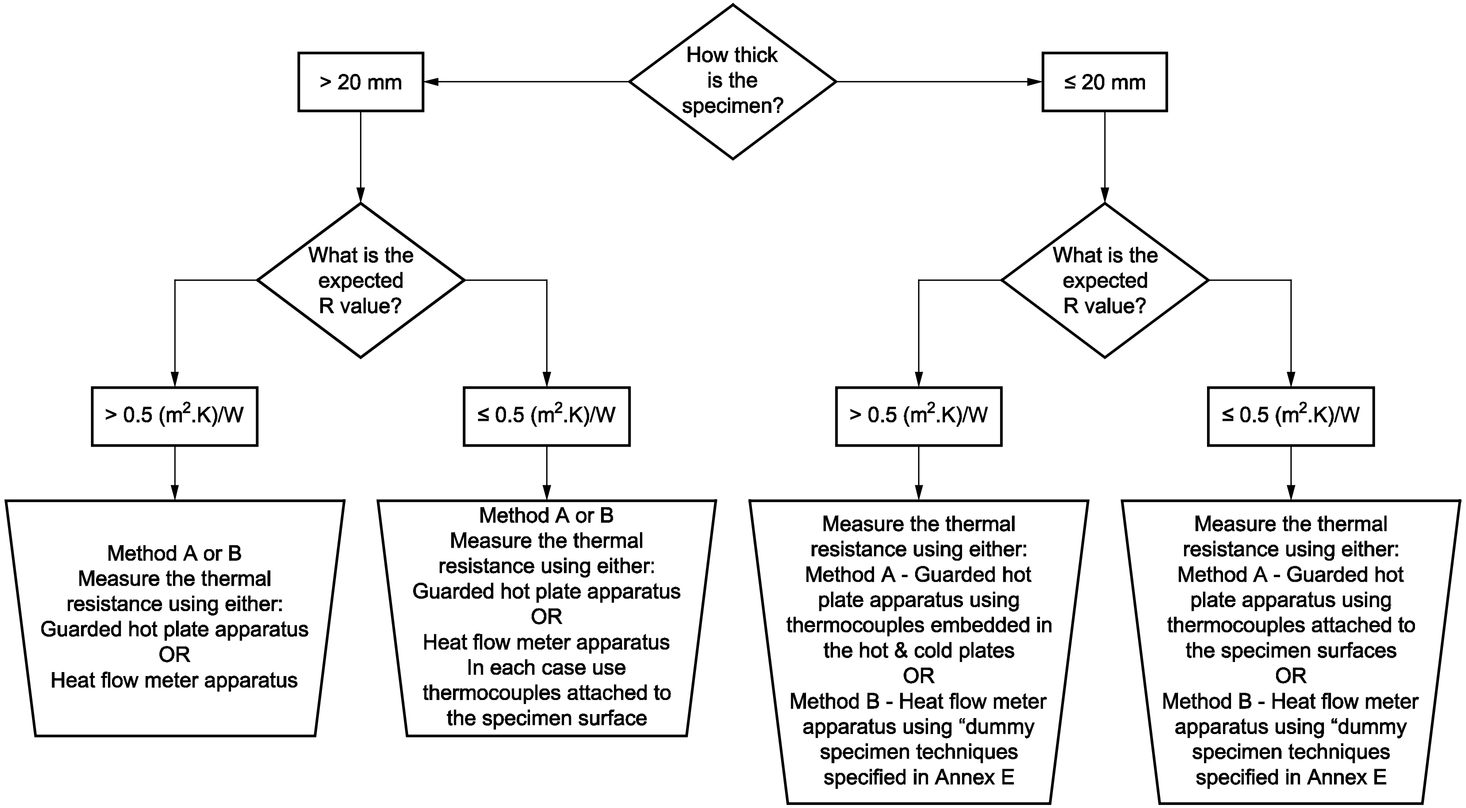


Figure B.1 - Selection of test methodology for product type 1 when using a hot plate method

Annex C
(normative)

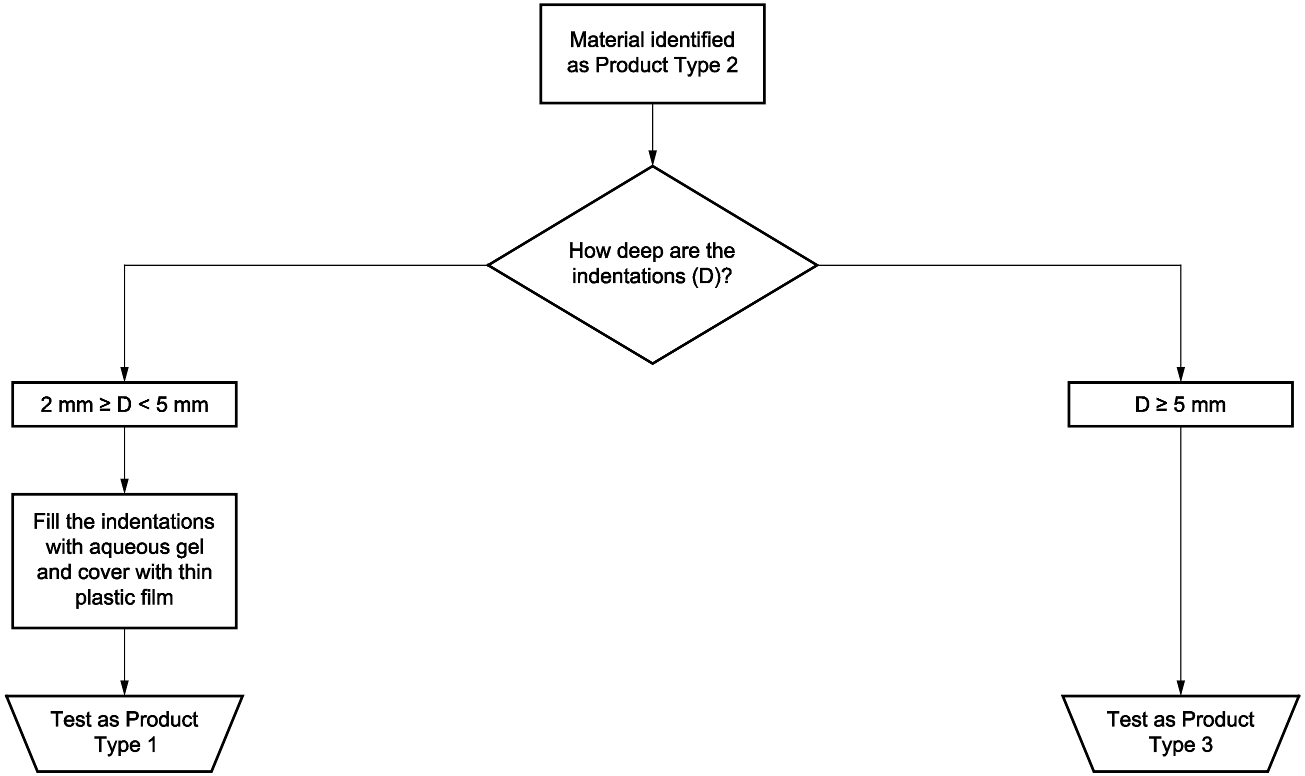


Figure C.1 - Selection of the measurement technique for product type 2

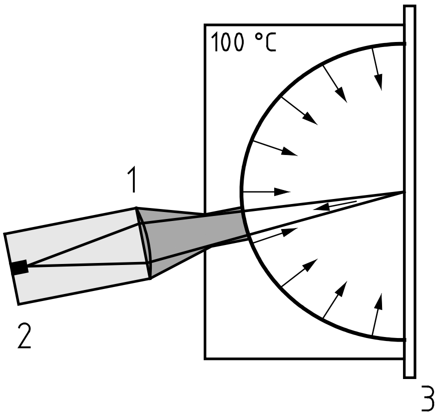
Annex D
(normative)

Measurement of emissivity using a Thermal Infra-Red apparatus

D.1 Principle of the hemispherical blackbody radiator[1)]

The hemispherical radiator (half sphere) in the form of a blackbody uses the thermal infra-red radiation principle (TIR-principle). The temperature of the blackbody is set and controlled at 100 °C.

The hemispherical shape of the radiator is necessary in order to achieve a complete and homogenous illumination of the measurement surface allowing the emissivity of rough and structured surfaces to be measured correctly. Part of the energy reflected and emitted by the specimen passes through a small opening in the hemispherical radiator and is focussed onto an infra-red sensor by an infra-red lens. The infra-red sensor changes the incident thermal radiation into a voltage signal in a broad band and linear manner (the voltage signal is proportional to the reflected thermal energy). At any given temperature of a blackbody, the spectral distribution of the thermal radiation is given by Planck's law. The radiator's temperature has been chosen to be 100 °C so that the corresponding spectrum has its peak at a wavelength of circa 8 µm and more than 97 % of the radiant energy is in the wavelength range from 2,5 µm to 40 µm.



Key

1 IR lens

2 thermopile IR sensor

3 sample

Figure D.1 — Schematic diagram of typical thermal infra-red apparatus

D.2 Description of suitable hemispherical blackbody radiator and specimen holder

In order to reduce errors related to the hemispherical blackbody radiator (henceforth referred to as "apparatus") to a minimum, the half sphere should have a diameter of not less than 70 mm. The distance of the specimen surface to the apparatus shall be approximately 2 mm. The axis of the infra-red sensor and

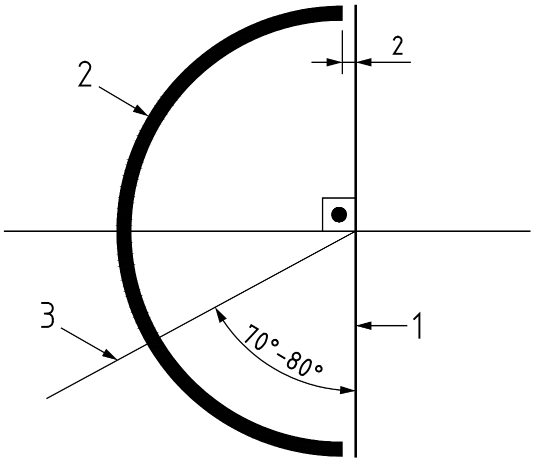
---

[1)] The TIR (Thermal Infra-Red) apparatus described in this standard has previously been developed and specified in EN 15976 (see Bibliography).

infra-red lens assembly shall point at the centre of the specimen and shall be between 70° and 80° to the specimen surface.

An adequate electronic method to evaluate the measuring signals should be applied. In order to avoid heating of the specimen, the measuring time should be limited to a maximum of 3 seconds.

The specimen holder should have a solid flat front surface with a minimum of 140 by 140 mm. The fixing of the specimen onto the specimen holder should be adapted to the type of material being tested. The specimen shall be flat and wrinkle-free over the whole surface. Thin materials may be wrapped around the left and the right edges of the specimen holder and then fixed on both sides by magnetic strips. For metal foils, heat-sink coupling is very important (use heat conductance paste to couple to the heat sink) and a massive aluminium plate as a heat sink should be used. For thick and stiff materials, fixing should be adapted on a case-by-case basis (clamps, hooks, etc.). The specimen shall be maintained parallel to the apparatus during measurement. The distance of 2 mm between specimen and apparatus shall be pre-defined by spacers, which should also prevent any rocking of the specimen.



Key

1 specimen

2 test equipment

3 IR beam

Figure D.2 — Arrangement of thermal infra-red apparatus and specimen

D.3 Calibration standards

The apparatus requires calibration against accurately defined low and high emissivity standards. Typical calibration standards for a low emitting surface should have $0{,}01 < \varepsilon_L < 0{,}02$. For a high emitting surface, the calibration standard should have $\varepsilon_H > 0{,}94$. The recommended reference standards should be based on:

— low emissive standard: polished aluminium surface;

— high emissive standard: black light trap surface.

Calibration standards shall be certified by the manufacturer of the apparatus or by an independent institute, accompanied by a certificate showing the measured emissivity. The calibration standards shall be recertified (or replaced by new certified standards) at least every two years.

D.4 Calculation of the emissivity

The emissivity is determined from comparing the measured result for the specimen with the two calibration standards. With the sensor signals (U, U_H and U_L) and the known emissivity of calibration standards (ε_L and ε_H), the emissivity, ε, of the specimen shall be calculated by:

$$\epsilon = \epsilon_H - (\epsilon_H - \epsilon_L) \times (U_H - U) / (U_H - U_L) \tag{D.1}$$

NOTE The measurement range of the apparatus is limited to values between those of the two calibration standards used, hence within the emissivity range of 0,02–0,94. However, there are practical limits to the measurement of very low values of emissivity, irrespective of the method used. Errors increase significantly below emissivity 0,05.

D.5 Sampling and preparation of the test specimens

D.5.1 Sampling

A sample of an undamaged reflective insulation product shall be selected at random from a batch of production material or from product placed on the market.

D.5.2 Dimensions and numbers of specimens

A1⟩ A minimum of three specimens should be taken from the sample to be representative of the length and width of the product to include a representative area of any printing or perforation where relevant. If the faces of the product differ then a minimum of three specimens shall be taken from each face. The specimen size should be adapted to the size of the specimen holder and to the fixing system of the specimen holder (see D.6), but shall be at least 250 mm by 250 mm. ⟨A1

D.5.3 Conditioning of specimens for ageing

The specimens shall be exposed in a climatic chamber to 90 % relative humidity and 70 °C temperature for a period of 28 days. The edges of the specimens shall be adequately protected by securing self-adhesive aluminium foil tape around each edge of the specimen from the upper surface to the lower surface, to prevent ingress of moisture through the cut edge. After the conditioning process, the specimens shall then be allowed to stabilize for a minimum of two hours at a temperature of (23 ± 2) °C and relative humidity of (50 ± 20) %.

D.6 Procedure for measurement of specimens

The apparatus shall be switched on at least 2 hours before calibration and before commencing measurements. The apparatus shall be installed in a fixed position and shall not be moved during measurement. Special precautions should be taken to ensure that the calibration standards, the specimens and the apparatus are brought to equilibrium in the same standard climatic conditions. Air currents and draughts in the measuring area shall be avoided.

The specimen shall be brought up to the apparatus in a vertical orientation, pressed against the spacers around the measuring window of the apparatus and the apparatus shall be activated to begin measurement. The emissivity shall be measured in five positions on each specimen. In order to avoid changes in the specimen temperature during the measurement, the time that the specimen is left in the measuring position shall be reduced to a minimum. Between specimen positioning and start of measurement, no more than 1 second shall pass. If this speed of measurement is not achieved, or if the measurement is otherwise interrupted, or if the measurement on a specimen is to be repeated, the specimen should be withdrawn from the apparatus for the time it needs to cool down to laboratory temperature. Rapid movement of the specimen over the apparatus while measuring is possible, but coupling of the specimen to a massive aluminium block by heat conductance paste gives the most consistent results. The higher the emissivity and/or the lower the specific heat capacity of the material, the longer the specimen will need to cool down to laboratory temperature.

In order to reduce measurement variability to a minimum (laboratory, specimen and apparatus related), the apparatus shall be recalibrated using the two calibration standards at least once per hour of use.

NOTE In order to measure values with highest possible repeatability, the following should be observed:

a) all corresponding tests should be carried out by the same person;

b) re-calibrate the apparatus for each specimen;

c) use heat conductance paste and a massive aluminium heat-sink;

d) measure only reflective sheets, not the additional wadding or other materials in between the foil and the heat-sink;

e) ensure the measuring time is less than 1,5 seconds;

f) allow enough time for apparatus to heat up before starting the test (approximately 2 hours).

D.7 Expression of results

[A1⟩ The emissivity of the specimen shall be expressed to 2 decimal places. All single measurements resulting in an emissivity < 0,02 or > 0,94 (measurement range of the apparatus) should be set to 0,02 or 0,94 respectively. The emissivity mean value, all the single values per specimen and the standard deviation of the results from the tested product shall be included on the test report. The emissivity mean-value shall be rounded to two decimal places.

The mean value (one test result) from any one sample shall be derived from a minimum of 3 specimens taken from the sample with five measurements being taken on each specimen. The declared value for a product shall be based upon a minimum of 3 test results (wherever possible from at least 3 different production batches) calculated using the 90/90 fractile rules from EN ISO 10456. The manufacturer may use a higher number of test results (samples) in the calculation. A mean value below 0,05 is declared as 0,05. ⟨A1]

Annex E
(normative)

“Dummy specimen” technique for the heat flow meter apparatus

E.1 Principle

Heat flow meter apparatus needs to be calibrated with reference materials having similar thermal performance to the materials being tested. As most heat flow meter apparatus will not have been calibrated with thin reference materials (< 20 mm thick), a method is given in this annex to ensure that thermal resistance measurements made on such thin materials, in a heat flow meter apparatus, conform to ISO 8301. This method is referred to as the “dummy specimens” method.

E.2 Procedure

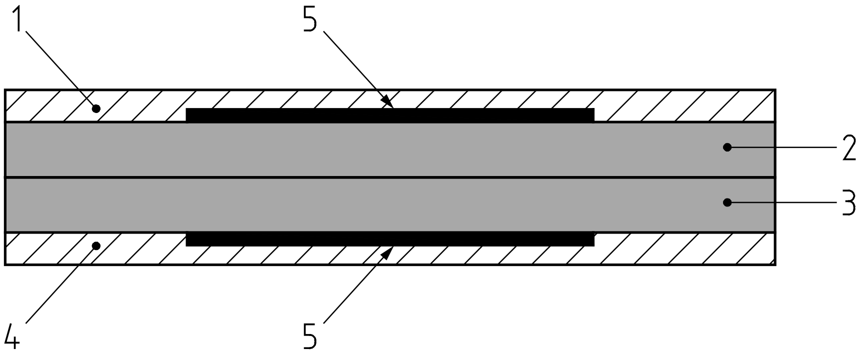
In this method, a pair of “dummy specimens” each not less than 10 mm thick shall be used to make a composite specimen of a thickness that is covered by the reference samples used to calibrate the heat flow meter apparatus. Two measurements shall be made using the specimen arrangements illustrated in Figures E.1 and E.2:

1) using only the two dummy specimens, to determine their combined thermal resistance;

2) with the specimen under test sandwiched between the two dummy specimens.

3) The thickness of the test specimen shall be maintained by the use of suitable low conductivity spacers set to the measured thickness of the test specimen and placed between the dummy specimens outside the metering area.

The thermal resistance of the material under test shall then be derived from the results of these two measurements as the difference in thermal resistance between the second test and the first test.



Key

1 cold plate

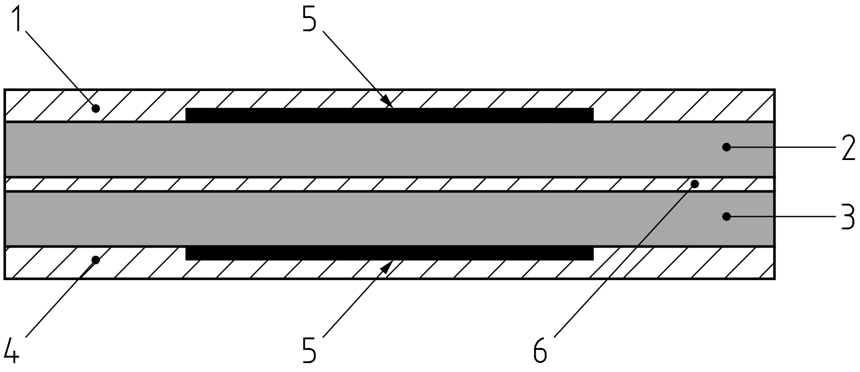
2 dummy specimen 1

3 dummy specimen 2

4 hot Plate

5 Heat Flux Transducer

Figure E.1 — Schematic diagram of dummy specimen arrangement



Key

1 cold plate

2 dummy specimen 1

3 dummy specimen 2

4 hot Plate

5 Heat Flux Transducer

6 thin specimen being tested

Figure E.2 — Schematic diagram of dummy specimen arrangement with specimen under test

E.3 Specimens of low thermal resistance

In the case where the test specimen (excluding the dummy specimens) is expected to have a thermal resistance of less than 0,5 m^2.K/W, surface thermocouples shall also still be used.

E.4 Calibration

To achieve a 10 K temperature difference across the test specimen requires a temperature difference of approximately 50 K across the whole stack. This requires a separate calibration file to be established with this temperature difference across the reference specimen.

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UK Patent Filing for Heat Flux Sensing Device.

Fitton, R., Busby, P., & Benjaber, M. (2016).

Retrieved from https://www.ipo.gov.uk
Patent Application GB 1609035.9
20/5/2016

Heat Flux Sensing Device

Technical Field of the Invention

The present invention relates to a heat flux sensing device and in particular to a heat flux sensing device adapted for monitoring the thermal performance of a building.

Background to the Invention

In order to study energy efficiency in buildings, it is necessary to gain an understanding of energy losses within said buildings. One such energy loss is from the heat flux through the walls of a building. This can be assessed by affixing a heat flux sensor to the wall being monitored. In order to generate accurate measurements, the heat flux sensor must be closely and securely fitted to the wall.

Some accurate heat flux sensors are rather fragile. In particular, the connection between the sensor and the power/data wires is prone to breakage under mechanical stress. Accordingly, whilst it is relatively straight forward to fit sensors securely in position, for instance using adhesive, it is difficult to subsequently remove the heat flux sensor without damage. This limits the prospects of the reusability of the senor. Accordingly, it is typical to provide a measurement rig adapted to securely affix the heat flux sensor to the wall. Conventional measurement rigs are very expensive and somewhat bulky. Furthermore, these rigs are difficult to set up and require a wired power and data connection in order to operate.

Whilst it is possible to use rather more robust heavy duty heat flux sensors, these can be less suitable. In addition, they typically require secure mounting using tape. Tape mounting can have an influence on local heat flows. More pertinently, in order to ensure that the sensor is held in secure contact with a surface, the tape must be relatively ineleactic and be backed with strong adhesive. If not, the sensor will gradually move out of position as the tape stenches or as it peels away from the wall surface. Use of such strong tape typically causes damage to the wall upon removal. This can be a disincentive to a building owner in terms of conducting tests and/or the cost of making good such damage negatively impacts on the desirability of carrying out testing.

To obtain detailed overall measurements of the heat flux within a room, it is typically necessary to utilise separate dedicated sensors to measure other relevant quantities such as the air temperature and/or the wall temperature. Measuring such quantities spaced apart from the heat flux sensor reduces the accuracy of the energy flow model. Additionally, a relatively bulky mounting rig for the heat flux sensor can also impact on the local heat flux. Furthermore, if the sensors are tape mounted, this can create significant dame, particularly where each is separately tape mounted.

It is therefore an object of the present invention to provide a heat flux sensing device that at least partially overcomes or alleviates at least some of the above problems.

Summary of the Invention

According to a first aspect of the present invention there is provided a heat flux sensing device comprising: a heat flux sensor; a support frame upon which the heat flux sensor is mounted; a housing provided around the support frame, the housing comprising a heat flux opening corresponding to the dimensions of the support frame; and biasing means operable to urge the support frame to project out of the heat flux opening.

By urging the support frame to project out of the housing, the biasing means hence urge the heat flux sensor to project out of the housing. When the housing is affixed to a wall or other surface, this therefore ensures that the heat flux sensor remains in good contact with the wall or surface, without putting excess stress on the heat flux sensor during operation or installation or removal. Furthermore, enables good contact between the sensor and surface even when held in position using relatively weak adhesive means, tape or mounting rigs.

The support frame is preferably mounted to the rear of the heat flux sensor. The support frame preferably corresponds to the shape of the heat flux sensor. In a preferred embodiment, the support frame comprises an extended duct having a cross-section corresponding to the shape of the heat flux sensor.

The heat flux opening may be provided in a front face of the housing. In some embodiments, a rear opening may be provided in a rear face of the housing. The rear opening may also correspond to the support frame. This provides additional freedom of movement for the frame within the housing. Beneficially, it also allows an external force to be applied to the frame against the bias provided by the biasing means. This can enable the heat flux sensor to be withdrawn behind the front face of the housing whilst the external force is applied. This can prevent the heat flux sensor being damaged during installation or removal of the device.

In some embodiments, the support frame may be provided with one or more projecting ribs. In such embodiments, the heat flux opening and rear opening may comprise corresponding notches. The notches and ribs help locate the frame in position relative to the housing and limit undesired motion of the support frame relative to the housing.

The ribs may be spaced to enable a connection wire for the heat flux sensor to lie there between. The ribs thereby provide additional protection to the connection wire for the heat flux sensor. The ribs may be provided with an end bar connecting them at the front of the frame. The end bar can provide additional protection for the connection wire of the heat flux sensor.

The biasing means may comprise one or more springs. The support frame may comprise one or more spring anchors for retaining the springs.

The or each spring may be mounted between spring anchors. The spring anchors may be provided upon the rear face of the housing and side arms projecting from the supporting frame.

The housing may be provided with fixing means operable for affixing the housing to a surface. Typically, the surface is a wall. The surface may alternatively be a floor or ceiling. The fixing means may be temporary fixing means or permanent fixing means. In one embodiment, the fixing means comprise adhesive or one or more adhesive strips or pads. Preferably, the adhesive strips or pads are removable adhesive strips or pads. Since the biasing means acts to urge the heat flux sensor into contact with the surface, removable adhesive strips or pads are sufficient to hold the device in position. Accordingly, if the device is removed, these strips or pads can be removed without damaging the surface.

The heat flux sensor may be a heat flux sensor of any suitable form, including but not limited to thermoelectrice heat flux sensors. Suitable heat flux sensors include, but are not limited to those supplied by Hukseflux, greenTEG and Omega.

The device may incorporate one or more additional sensors. In one embodiment, the device further comprises a surface temperature sensor. The surface temperature sensor may be a contactless temperature sensor. Preferably said sensor comprises an infra red sensor. The surface temperature sensor may be mounted within the housing and aligned with a surface temperature opening provided in the front face of the housing. Most preferably, the surface temperature opening is provided adjacent to the heat flux opening.

Additionally or alternatively, the device may comprise an air temperature sensor. The air temperature sensor may be an air temperature sensor of any suitable form. The air temperature sensor may be provided within the housing. The air temperature sensor m provided adjacent to one or more airflow openings. The airflow opening may be provided to enable a flow of ambient air through the housing.

Where the device is provided with both a surface temperature sensor and an air temperature sensor, the device can readily provide measurements of heat flux through a surface, the temperature of the surface and the temperature of the ambient air. This can enable measurement and/or monitoring of the surface heat resistance.

The device may be provided with a power supply. The power supply may comprise a battery. The battery may be mounted within the housing.

The device may be provided with a communication unit. The communication unit may be operable to communicate data from the device to external devices. The communication unit may also be able to receive data or control instructions from external devices. Preferably, the communication unit is a wireless communication unit operable to utilise a wireless data link. Suitable data links may include but are not limited to Wifi, Zigbeee or similar links such as those using the ISM band.

The device may comprise a processing unit. The processing unit may be operable to control operation of the device. The processing unit may comprise a microcontroller. The device may comprise a data storage unit. The data storage unit may be operable to store data generated by the sensor. The data storage unit is preferably a solid state data storage unit. In some embodiments, the solid state data storage unit may be a removable data storage unit such as a flash memory device.

According to a second aspect of the invention there is provided a heat flux sensing device comprising: a housing, a heat flux sensor provided within an opening in a front face of the housing, the heat flux sensor operable to measure heat flux from a surface to which the housing is fixed; a surface temperature sensor operable to measure the surface temperature of a surface to which the housing is fixed, the surface temperature sensor mounted within the housing and aligned with a surface temperature opening in the front face of the housing; and an air temperature sensor mounted adjacent to one or more airflow openings and operable to measure the temperature of air within the housing.

The heat flux sensing device of the second aspect of the present invention may incorporate any or all features of the first aspect of the present invention as desired or required.

A heat flux sensing device of the second aspect of the invention can readily provide measurements of heat flux through a surface, the temperature of the surface and the temperature of the ambient air. This can enable measurement and/or monitoring of the surface heat resistance.

A method of monitoring heat flux comprising the steps of affixing a heat flux sensing device according to the first aspect or the second aspect of the present invention to a surface; and monitoring the output of the heat flux sensing device.

The method of the third aspect of the present invention may incorporate any or all features of the first or second aspects of the present invention as desired or required.

Detailed Description of the Invention

In order that the invention may be more clearly understood an embodiment thereof will now be described, by way of example only, with reference to the accompanying drawings, of which:

Figure 1	is a schematic block diagram of an embodiment of the heat flux sensing device of the invention;
Figure 2	is a view of the front face of the housing of the heat flux sensing device of the invention;
Figure 3	is a view of the rear face of the housing of the heat flux sensing device of the invention;
Figure 4	is a partial cutaway view illustrating the mounting of the heat flux sensor and support frame relative to the rear face of the housing;

Figure 5	is a partial cutaway view illustrating the mounting of the heat flux sensor and support frame relative to the rear face of the housing and other components of the device; and
Figure 4	is a partial cutaway view illustrating the mounting of the heat flux sensor and support frame relative to the front face of the housing and other components of the device;

Turning now to figure 1, a heat flux sensing device 1 comprises a heat flux sensor 11 operable to measure heat flux from a surface, in this example a wall, to which the device 1 is fixed. A surface temperature sensor 16, typically an IR sensor, is operable to measure the surface temperature of the surface to which the device 1 is fixed. An air temperature sensor 17 is operable to measure the temperature of ambient air local to the device 1. The device 1 further comprises a microcontroller 12 operable to monitor the operation of the sensors 11, 16, 17. The microcontroller 12 is connected to a data store 14 for storing details of the outputs of sensors 11, 16, 17. The microcontroller 12 is also connected to a communication unit 13 for wirelessly communicating details of the outputs of sensors 11, 16, 17 to external devices. The sensors 11, 16, 17, microcontroller 12, data store 14 and communications unit 15 are powered by a battery 15.

Turning to figures 2&3, the device 1 is provided within a housing 20. The housing 20 has a front face 21, intended in use to be fixed to the wall, and a rear face 22. A heat flux opening 23 is provided in the front face 21 for the heat flux sensor 11. The heat flux opening 23 allows the heat flux sensor 11 to be positioned in contact with the wall.

A surface temperature opening 24 is provided for the surface temperature sensor 16. The opening 24 allows the surface temperature sensor 16 to view the wall and thereby detect the surface temperature of the wall.

Airflow openings 25 are provided to enable ambient air to circulate through the housing 20. The air temperature sensor 17 is provided adjacent to the airflow openings such that the temperature of the ambient air can be measured.

As can be seen in figure 3, the rear face 22 has an opening 23a corresponding to the heat flux opening 23.

In order to achieve optimum performance, the heat flux sensor 11 must be closely and securely fitted to the wall. To this end, the heat flux sensor 11 is mounted on a support frame 30. The support frame 30 has the form of a duct with a cross-section corresponding to the shape of the heat flux sensor 11 and the heat flux opening 23.

The support frame 30 is provided with side arms 31 upon which are provided spring anchors 39. Corresponding spring anchors 29 are provided on the interior of the rear face 22. Springs 32 are mounted between the corresponding spring anchors 29, 39. The springs 32 are operable to urge the support frame 30 away from the rear face 22. As a consequence, the support frame 30 is urged to project out of the heat flux opening 23 and thus, in the absence of any other forces, the heat flux sensor 11 projects proud of the front face 21, as illustrated in figure 2. When front face 21 is affixed to the wall, the springs 32 act to urge the heat flux sensor into a close and secure fitting with the wall. As there is provision for relative movement between the heat flux sensor 11 and the housing 20 and it is the housing 20 that is directly affixed to the wall, minimal stress is applied to the heat flux sensor 11 during installation or removal of the device 1 or from unexpected impacts during monitoring operation.

The support frame 30 is also provided with a pair of ribs 37, the ribs connected by an end bar 38 at the front of the frame 30. Between the ribs 37 is provided a passage for a serial connection cable 11a connecting the heat flux sensor 11 to the microcontroller 12. The cable 11a is protected by the ribs 37 and end bar 38. The cable 11a gradually transitions to a non-serial cable 11b before connection to the microcontroller 12. The openings 23a, 23 are provided with notches 27, 28 to accommodate the ribs 37 and end bar 38 respectively. An additional benefit of the ribs 37, end bar 38 and notches 27, 28 is to help confine the relative motion of the support frame 30 and the housing 20.

Turing now to figures 5 & 6, the relative positions of the remaining components within the housing 20 is illustrated. The battery 15 is provided at the opposite end of housing 20 to the heat flux sensor 11. Between the battery 15 and heat flux sensor 11 is provided a circuit board 10 upon which is provided the microcontroller 12, data store 14 and air temperature sensor 17.

The communications unit 13 is mounted separately to the circuit board 10 on an antenna means 18 to enable transmission and receipt of wireless communication signals. The communications unit 13 typically comprises an RF (radio frequency) transceiver operable according to a standard data transfer protocol such as Bluetooth, Zigbee or the like.

Whilst the above embodiments relate to a combined device incorporating both a surface temperature sensor 16 and an air temperature sensor 17, the skilled man will appreciate that either or both sensors 16, 17 can be omitted if a pure heat flux sensing device 1 is desired.

The above embodiment is described by way of example only. Many variations are possible without departing from the scope of the invention as defined in the appended claims.

CLAIMS

1. A heat flux sensing device comprising: a heat flux sensor; a support frame upon which the heat flux sensor is mounted; a housing provided around the support frame, the housing comprising a heat flux opening corresponding to the dimensions of the support frame; and biasing means operable to urge the support frame to project out of the heat flux opening.

2. A heat flux sensing device as claimed in claim 1 wherein the support frame is mounted to the rear of the heat flux sensor.

3. A heat flux sensing device as claimed in any preceding claim wherein the heat flux opening is provided in a front face of the housing.

4. A heat flux sensing device as claimed in any preceding claim wherein a rear opening is provided in a rear face of the housing.

5. A heat flux sensing device as claimed in any preceding claim wherein the support frame is provided with one or more projecting ribs.

6. A heat flux sensing device as claimed in claim 5 wherein the heat flux opening and rear opening may comprise corresponding notches.

7. A heat flux sensing device as claimed in claim 5 or claim 6 wherein the ribs are spaced to enable a connection wire for the heat flux sensor to lie therebetween.

8. A heat flux sensing device as claimed in any one of claims 5 to 7 wherein the ribs are provided with an end bar connecting them at the front of the frame.

9. A heat flux sensing device as claimed in any preceding claim wherein the biasing means may comprise one or more springs mounted between spring anchors provided upon the rear face of the housing and side arms projecting from the supporting frame.

10. A heat flux sensing device as claimed in any preceding claim wherein the device further comprises a surface temperature sensor mounted within the housing and aligned with a surface temperature opening provided in the front face of the housing.

11. A heat flux sensing device as claimed in any preceding claim wherein the device comprises an air temperature sensor provided adjacent to one or more airflow openings in the housing.

12. A heat flux sensing device as claimed in any preceding claim wherein the device is provided with a communication unit operable to communicate data from the device to external devices or to receive data or control instructions from external devices.

13. A heat flux sensing device as claimed in any preceding claim wherein the device comprises a processing unit operable to control operation of the device.

14. A heat flux sensing device as claimed in any preceding claim wherein the device comprises a data storage unit operable to store data generated by the sensor.

15. A heat flux sensing device comprising: a housing, a heat flux sensor provided within an opening in a front face of the housing, the heat flux sensor operable to measure heat flux from a surface to which the housing is fixed; a surface

temperature sensor operable to measure the surface temperature of a surface to which the housing is fixed, the surface temperature sensor mounted within the housing and aligned with a surface temperature opening in the front face of the housing; and an air temperature sensor mounted adjacent to one or more airflow openings and operable to measure the temperature of air within the housing.

16. A heat flux sensing device as claimed in claim 15 wherein the device is provided with a communication unit operable to communicate data from the device to external devices or to receive data or control instructions from external devices.

17. A heat flux sensing device as claimed in claim 15 or claim 16 wherein the device comprises a processing unit operable to control operation of the device.

18. A heat flux sensing device as claimed in any one of claims 15 to 17 wherein the device comprises a data storage unit operable to store data generated by the sensor.

19. A method of monitoring heat flux comprising the steps of affixing a heat flux sensing device according to any preceding claim to a surface; and monitoring the output of the heat flux sensing device.

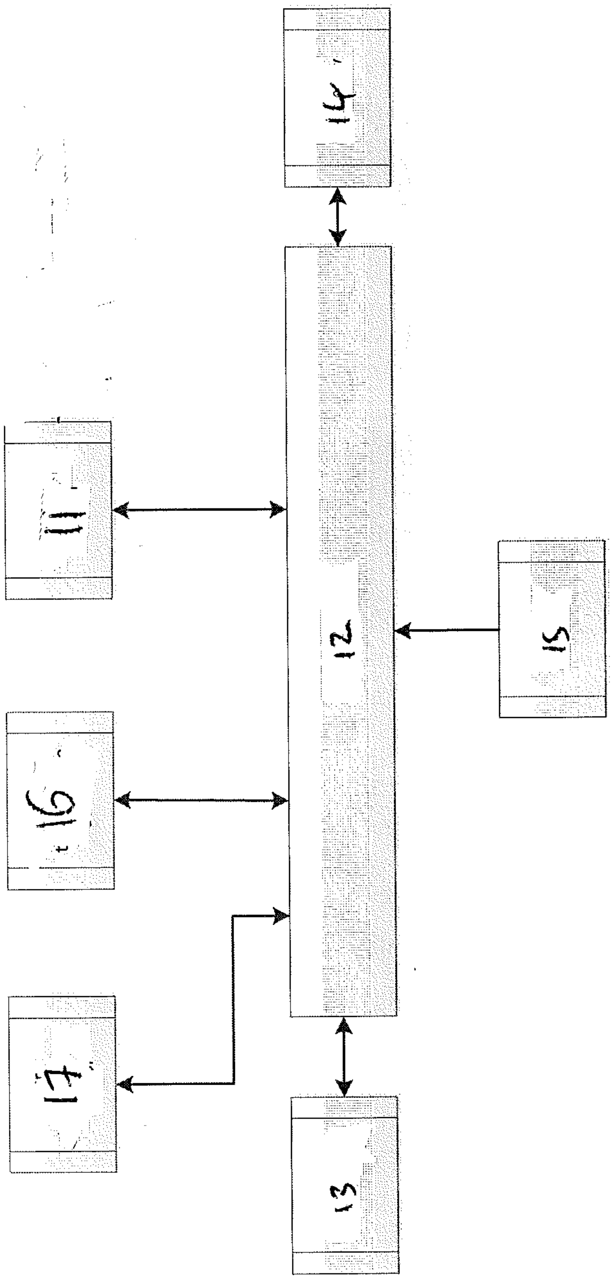

Figure 1

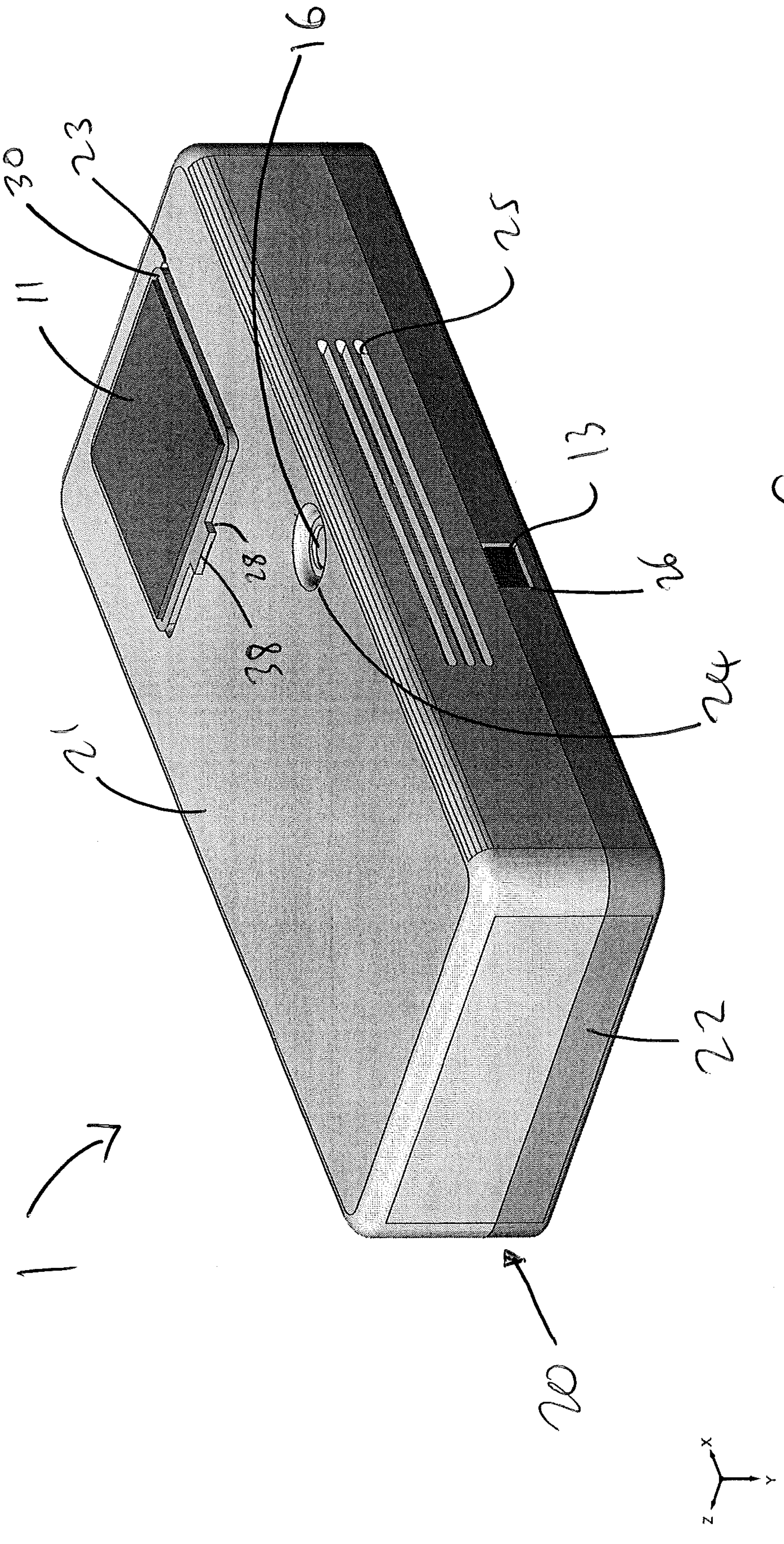

Figure 2

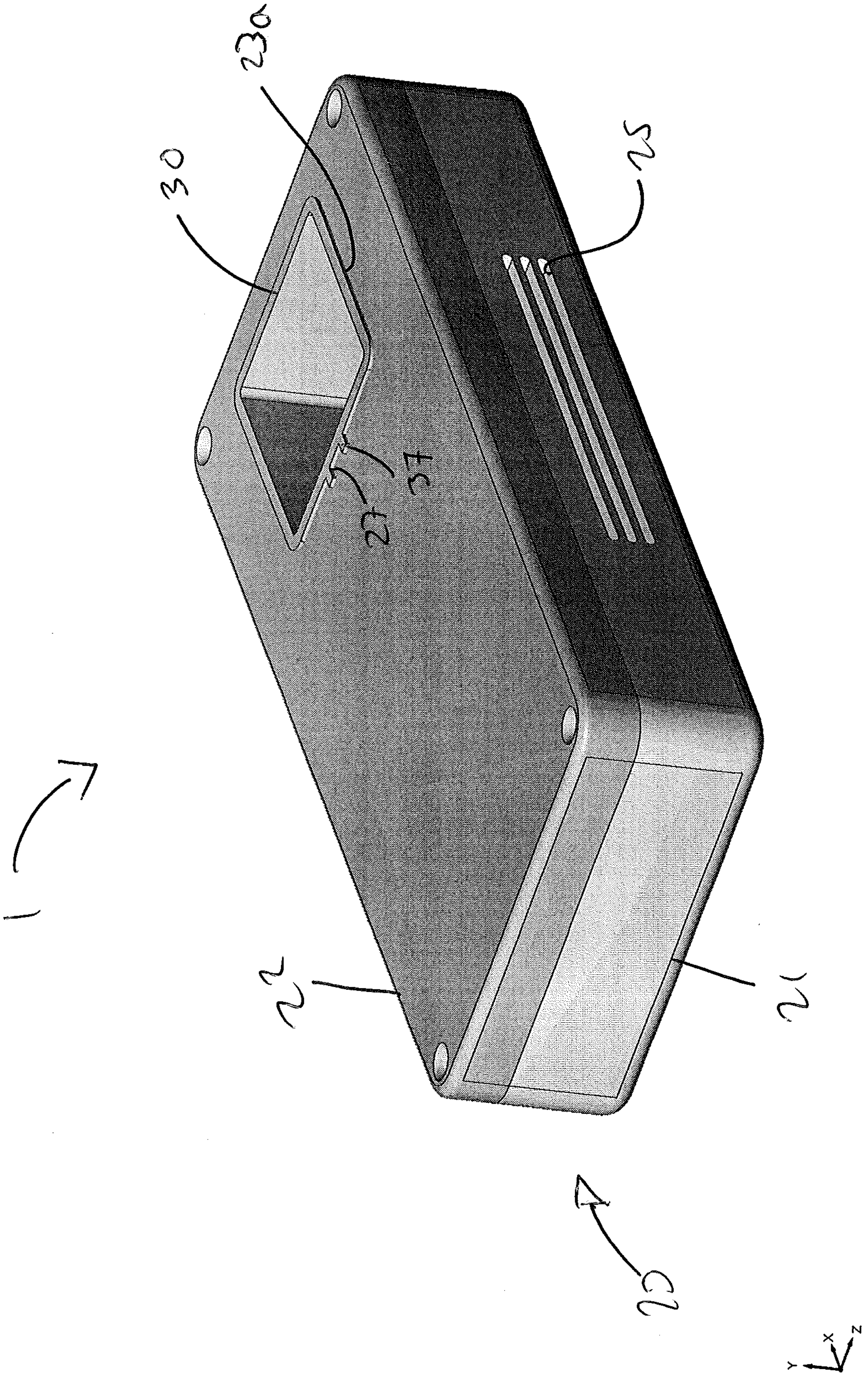

figure 3

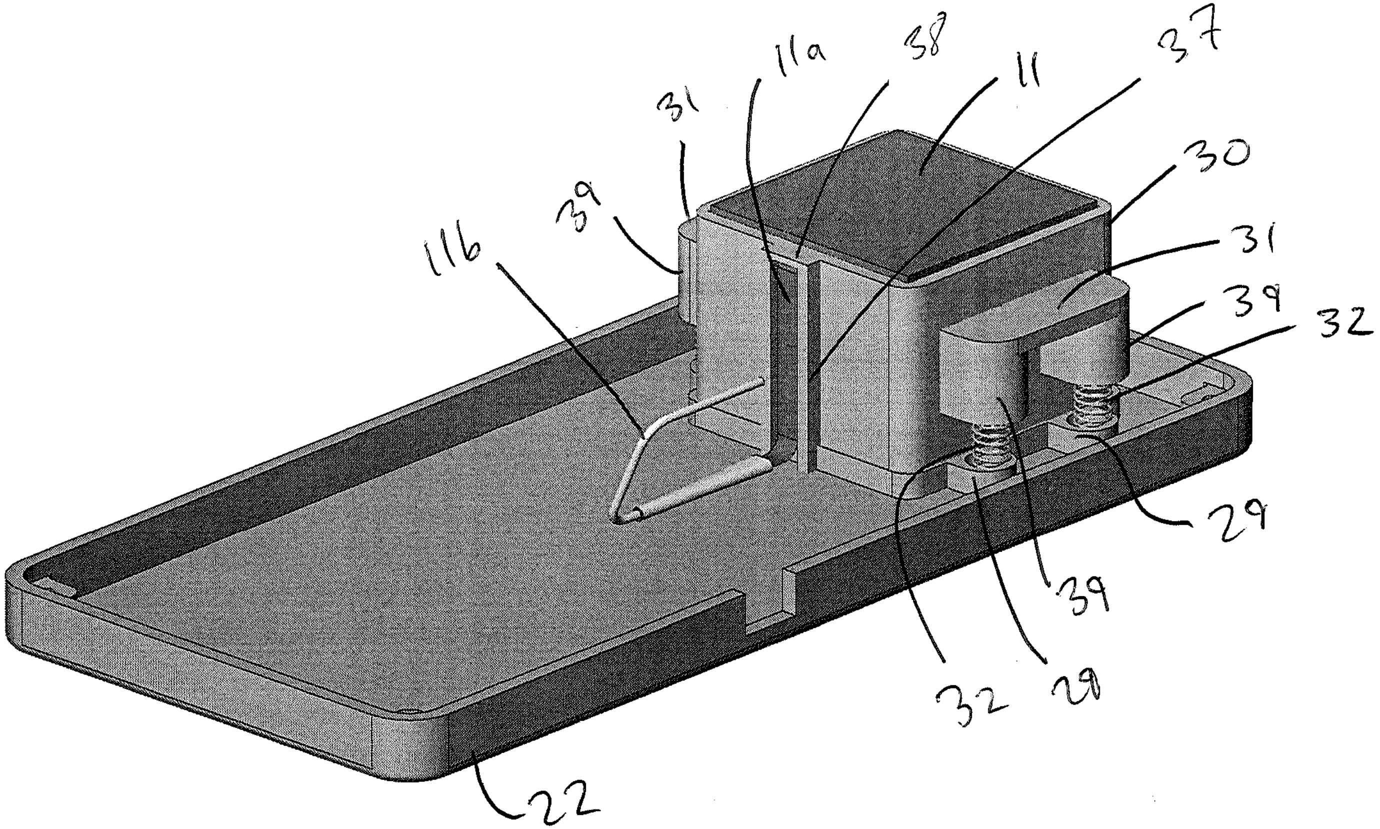

Figure 4

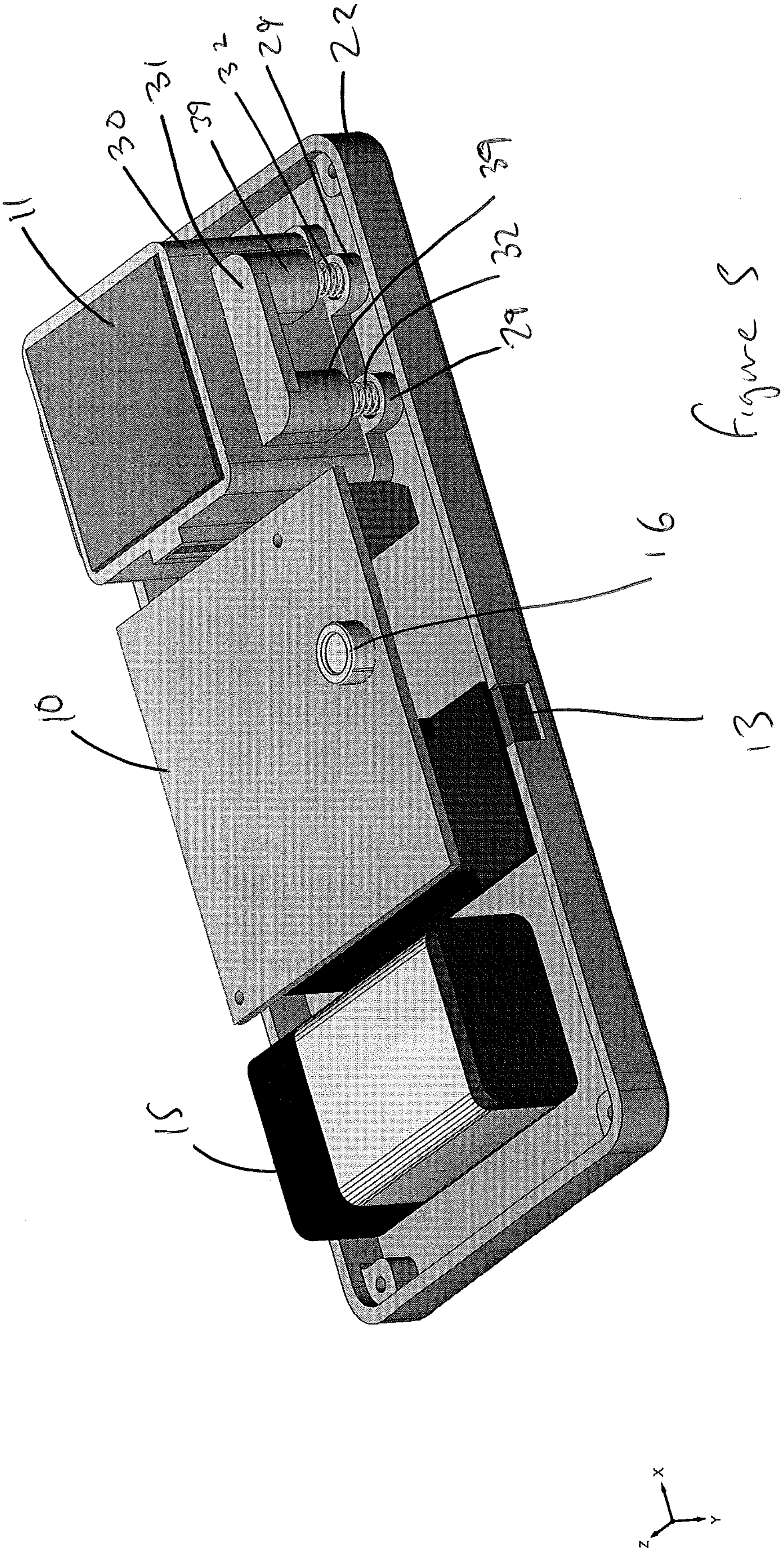

Figure 5

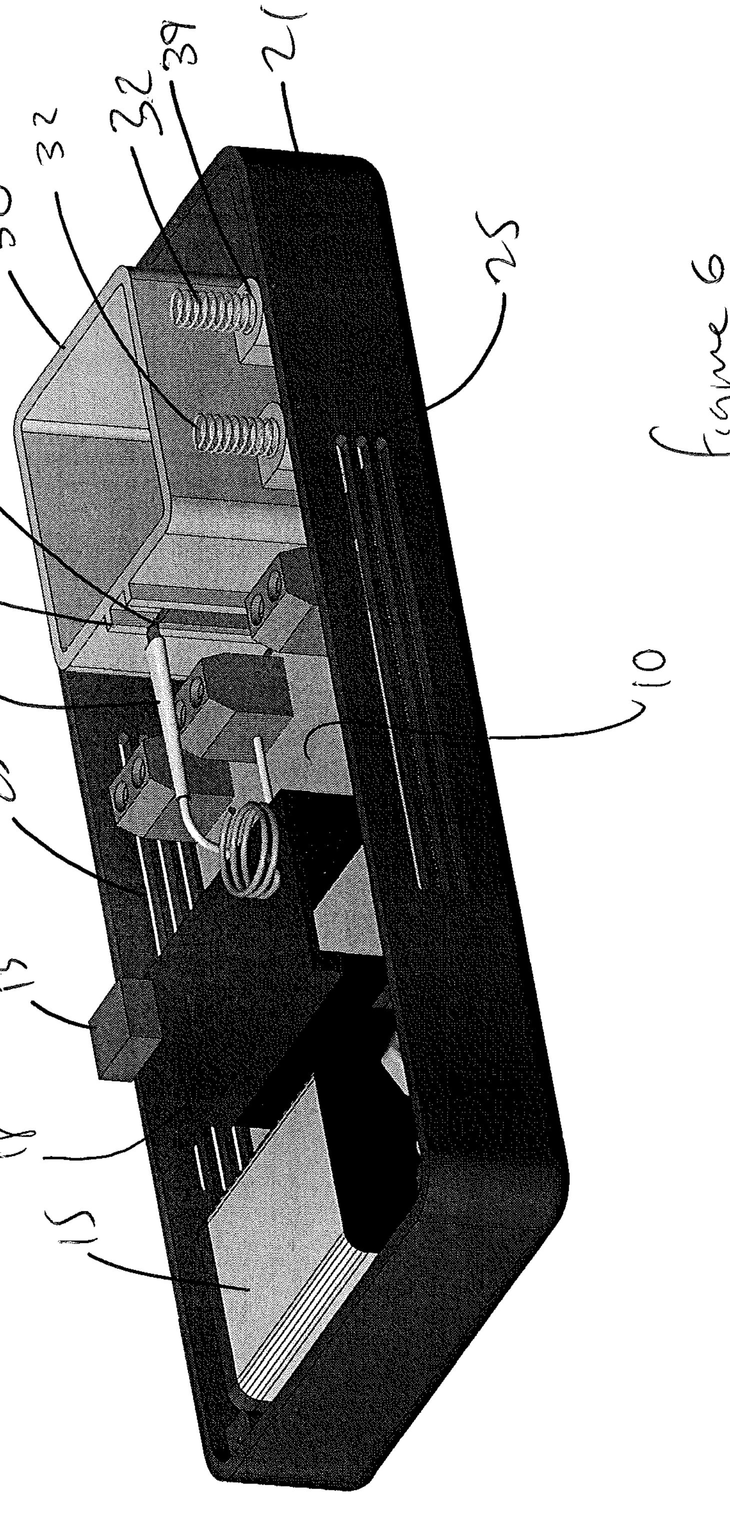

Figure 6

18 April 2016

“Performance gap” in domestic retrofits. Retrieved August 19, 2016

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ISURV

The Issue of the Performance Gap in Retrofits in Dwellings:

The energy efficient retrofit of the existing building stock has been identified as one potential pathway to a low carbon future. However, how do we know when we have been successful in reducing energy demand or not? The lack of evidence for some major retrofit projects in terms of monitoring data represents a missed opportunity in fully understanding what works and whether retrofit it achieving its objectives.

Topics

Introduction

1. Modeled Energy Performance vs. Actual Performance
2. When to Monitor and How
3. Energy Monitoring
4. Fabric Investigations
5. Conclusions, discussion and further reading.

Introduction:

Recent studies (Miles-Shenton, 2011) have found differences between the predicted and actual performance of domestic retrofits of up to 71% in terms of actual against modeled heat loss. Studies in the new build sector have identified this as a "performance gap", the gap between modeled and actual energy efficiency performance. Many of the issues that create this performance gap, such as workmanship, product substitution and design changes, are all applicable to retrofit (Zero Carbon Hub, 2014). The term performance gap is used to express the discrepancy in new buildings and retrofit, as well as commercial and domestic buildings. **This guidance will focus on only domestic retrofit.**

There are many reasons why a gap can exist between as built and the designed/modeled performance; insufficient modelling techniques, poor design, poor standards of materials and/or workmanship can all have an impact. Performance gap research identifies a number of opportunities for performance gap issues to be introduced throughout the design and construction life cycle. Design, information management and modeling have as strong a role to play as the physical delivery of the project.

Given we have this difference between the calculated and actual performance of energy efficient domestic retrofits, we can see a potential emerging role for the practitioner. There is a potential for both evaluation of a property in terms of understanding the components of its actual energy consumption, as well as tools that can better help us understand both issues and identify remedial actions that can be taken to close this performance gap. Here, we consider the models that are used to establish performance and the currently available tools and techniques that can be applied to better understand how buildings consume energy and how they may be improved.

Modeled Energy Consumption

In domestic housing in England and Wales, the usual method of predicting how much energy a building will use is the Standard Assessment Procedure (SAP). This is generally used in new build design assessments to validate compliance with the Building Regulations. A large number of variables are required, such as areas of building elements, materials, and heating systems.

SAP also has a variant called the Reduced Data Standard Assessment Procedure (RdSAP), which is used to carry out assessments of existing properties. It requires less data to be collected, relying on a greater number of assumptions, to inform its output. Both versions provide an estimate of predicted energy use of the property. This is known as "primary energy use" and is expressed in kWh/m^2.

SAP has been developed to allow designs to be checked and compared, rather than to create a detailed building physics model. In the same way, RdSAP was not designed to predict the future energy consumption of a building, rather it was intended to be used a preset package of assumptions to achieve a result that is broadly indicative of the potential energy usage.

When we model energy use to make predictions, discrepancies in modeling are almost inevitable. Errors such as recording the exact dimensions of the building, and correctly identifying that the materials that are installed that are different to those specified, can contribute to differences between what is modeled and what is built. The challenge for property professionals is to discover:

a) What causes these discrepancies, is it a problem with the model or the property?
b) How can we quantify the impact of these discrepancies?
c) What is the potential impact of the physical discrepancies? For example, poorly installed insulation may introduce defects into the building.
d) To capture these lessons and carry them forward to future projects.

Some Typical Causes of Performance Gap

As discussed previously, the performance gap can be introduced at any point through the design, construction and in-use life cycle. Some common examples from previous retrofit projects are,

- Underperforming cavity wall insulation due to inadequate fill/sagging,
- Poorly installed external wall insulation, such as around meter cupboards.
- Incomplete/missing airtightness membranes.
- Discrepancies between design of details and actual installation.
- Materials specified not matching with those installed.
- Modeled Energy Performance is incorrect due to data input issues or incorrectly measured areas.
- Poor commissioning of services such as heat pumps, or Mechanical Ventilation and Heat Recovery systems.

To quantify the performance gap, we need to understand the actual energy consumption of the property. To do this we need to undertake some form of monitoring of the property.

Data Collection and Analysis

There are two parts to effective monitoring studies: data collection and data analysis. Data collection can present a number of challenges and requires careful planning. We should first consider two questions:

- What do we want to know – what is the question we are trying to ask?
- And when do we need to know it – consider when we need the data to make decisions?

These two questions underpin any successful monitoring project. Firstly, we must establish our research question. We need to know what outcome is required from our investigation. Is it simply to find out if the insulation is working as expected, or is it to generate a detailed understanding of whole house performance? Monitoring can be very expensive and minimizing the costs for hardware is often required to meet the budgetary requirements a project. It is important not to forget that occupants are responsible for energy consumption in buildings, so human factors may also need to be considered, as occupants behaviour can often be responsible for adding to, or causing, the performance gap.

The Technology Strategy Board (now known as Innovate UK) published guidance, which aims to help practitioners, specify and carry out tests and monitoring on retrofit properties to address some of the issues around the performance gap. The Energy Saving Trust also developed similar guidance. Although some of the EST guidance is aimed at new build properties, it is directly relevant to retrofit scenarios. This guidance covers the selection of monitoring equipment, as well as guidance on how to set up equipment, addressing issues such as frequency of meter reads, accuracy and how to calibrate sensors. Monitoring energy and carbon performance in new homes (2008 edition)

The actual tests/measurements that are carried out on a building when examining retrofit performance are often driven by which retrofit products and systems were applied to the building. Many other factors will focus the available options for monitoring, such as cost of equipment, type of building, and the requirements of the client. However, when to measure these variables is crucial. In an ideal scenario the variables should be measured pre-retrofit and post-retrofit. This will allow for robust conclusions to be drawn as to whether the building is more energy efficient/ comfortable than it was previously. It allows the practitioner to identify what parts of the retrofit did and did not work as planned. Individual issues may be investigated in more detail if required.

Period	**Activity**
Pre start occupied	Performing baseline energy monitoring of the property, also understanding normal occupancy patterns. This should be carried out at least over an entire heating season. (in the UK this is generally taken as between the end of October and the beginning of April. Energy bills and Annual Energy Statements should be collected here if possible
Pre start unoccupied	Where more invasive testing is required this period should be used for tests such as: Coheating Test* Thermography studies* Air tightness testing U value testing of elements* *These tests can only be carried out to an accurate standard during the heating season.
Works Phase	All monitoring equipment and testing equipment to be removed, as it is extremely sensitive to dust and debris.
Post Construction Unoccupied	The same testing as took place in the pre start period should take place again. It is important that measurements/testing is carried out on the same elements under the same conditions to allow a robust comparison to be made: Coheating Test* Thermography studies* Air tightness testing U value testing of elements* *These tests can only be carried out to

	an accurate standard during the heating season.
Post Construction Occupied	Long term energy and indoor and external conditions should now take place, at least over 1 complete heating season, and preferably more than 12 months, if issues such as overheating are to be examined. This is also the period when some data will allow a comparison between modeled performance and as built performance.

Table 1. An example of when to carry out certain monitoring/testing as part of a complete retrofit cycle.

Data from monitoring projects can be extensive – when measuring for a long period, even a few metrics can generate many thousands of individual data points. A common issue with the development of a monitoring and evaluation programme, particularly if there is a multiple house project, is consideration of the quantity of data that may be generated. A single house monitored for a year for 6 different data streams every minute may generate more than 300,000 data points. This requires some strong analytical skills to extract information that may be acted upon. Some of the tools such as co-heating or in-situ U value measurement (see below) also require a detailed statistical knowledge. The important issue with monitoring data is that resource and skill needs to be applied to the tests to ensure value is extracted and decisions can be made.

Energy Bills

Before developing extensive monitoring programme, it is useful to consider what energy consumption data might already exist. Every energy customer is entitled to accurate billing data; this may be in the form of paper or electronic bills. This may be of limited use for a detailed evaluation, but they can help calculate annual energy demand and costs. Also, each consumer now receives an Annual Energy Statement, giving the consumption of gas and electricity over the year. This statement can also be compared against previous years, so this may be a useful source of historic consumption information.

It is important to note, when using statements in this way, to identify whether the data is based on a reading taken from the meter or on estimated consumption.

Gas Meters

Gas is the most challenging utility to monitor, due to the differing number of meter types and issues concerning safety. When using equipment that reads the meter constantly, which will give the profile of gas use, rather than just reading the meter at set periods, there are three main issues to be considered; ***safety, permission and communication.***

The gas meter and the surrounding area are considered as having a high risk of explosion. Devices used to read, or be placed next to gas meters, have to meet certain safety standards known as the ATEX standards HSE Guidance on ATEX standards. Only metering products that meet these requirements can be used to read gas meters in the UK.

There is also an issue of ownership: the gas meter is not owned by the homeowner; it is the property of the gas distribution company. Anything that interferes with, or disturbs, the meter, requires advice/permission from the meter owner. Some meters may have a socket on the bottom where devices can be plugged in to monitor the consumption, but these will often have tamperproof stickers to ensure that the device is not interfered with. It is generally better to use a propriety device, which simply sticks onto the meter to take readings. Most of these devices will also be ATEX compliant, but this should be checked with the supplier. These devices which allow meters to be read and data logged, in a way that does not interfere with the meter. These devices measure the dials on the gas meter turning around. When a complete pass is made the readers recognise this using one of two ways: an optical sensor that can "see" the needle turning round, or by measuring the magnetic field generated by the rotating dials. This in turn will be passed to a data logging device, which will record that one unit of gas has been consumed.

Figure 1. A meter, which has been fitted with an optical meter reader

A complete “unit” is dependent on the configuration of the gas meter, as older ones may measure in ft^3, whilst most modern ones will measure in m^3. The units will be a volumetric rate of how much gas is being consumed. This will generally not be in kWh. To convert the cubic measurements to kWh requires several inputs into a formula, including the calorific value and any correction factors attributed to the supply. When comparing gas consumption taken from logging equipment, the volumetric component of the bill should be compared and not the kWh figure. This figure can vary, due to the conversion process, which takes into account such things as calorific value of gas and correction factors attributed to the meter. There are online tools such as UK Power that will give a basic conversion from m^3 or ft^3 to kWh using a series of assumptions.

Figure 2. A selection of gas meters, each with different ways of viewing the same data, each requires differing monitoring equipment to log consumption.

Electricity:

In comparison with the other main utilities, gas and water, the logging of mains electricity is a relatively “easy” task. Researchers and engineers have been monitoring electricity usage in domestic property for a considerable period and there are many solutions to log electricity consumption. Most of them rely on clamp-based systems, which is fastened around one of the tails of the incoming electricity supply, usually between the mains fuse and the consumer unit, with the live or neutral cable. When electricity flows through the clamp, it generates a small electrical current, which is then converted into a figure that represents the instantaneous power consumption at that moment in Watts or Kilowatts. (W/kWh) This can then be used record consumption over a period in Kilowatt hours (kWh). The installation of these devices should be carried out in exact accordance with manufactures instructions, to avoid any health and safety risks. Where any concerns arise, a competent person should be asked to complete the installation. Care should also be taken to ensure that the clamp is placed perpendicular to the cable and away from any electrical interference to avoid measurement error.

Researchers have found the power levels and consumption of each individual circuit in a property is particularly useful in diagnosing issues with services, such as ventilation systems and electrical water heating. This can be done by adding monitoring devices to each circuit, rather than only monitoring the main incoming supply. This helps disaggregate energy usage, and can help better identify performance gap issues. However, this equipment can be expensive and also requires a competent person to carry out the installation.

Even more granularity can be gained by monitoring at the appliance level. Monitoring devices are available that allow appliances to be plugged directly into them so that the consumption of a specific appliance, such as a TV or fridge, can be identified. Systems exist where many sockets may be used in a wireless system, so each appliance can be monitored in a property individually.

Where deep retrofits are carried out, leading to major reductions in energy use of regulated emissions, then appliances may become a more significant component of the total electricity consumption for a household and, therefore, perhaps worthy of more detailed consideration.

Indoor and Outdoor Conditions

Outdoor conditions, and the desired indoor conditions established in response to these, drive a large proportion of our energy consumption for heating – some 60% of all energy consumption in the domestic sector. The amount of energy consumed by the heating system is directly influenced and proportional to these conditions. Both need to be clearly understood to establish a detailed understanding of heating energy use.

External Conditions

The climate in the UK is not only variable when considered on a macro scale but also variations around individual streets and buildings can be significant. It is for this reason that a localised the weather monitoring system will generate more accurate results. Some researchers do use internet weather station data which is gathered from Met Office weather stations. This data however identify localized weather on a particular building, which can have an effect on its energy performance. Wind, rain and solar gain on a building are all affected by local obstacles such as overshadowing of trees, while other structures may provide shelter from wind and driving rain. Generally, a locally fixed weather station fixed to the wall of the property at a high level will provide the required data. As a minimum, the weather station should record temperature, relative humidity, wind speed and direction, solar radiation and rain levels.

Indoor Conditions

Retrofitting domestic properties is not always carried out solely to save energy. The term energy efficiency implies keeping the same levels of comfort with less expenditure of energy – there is a clear relationship between input and output, which can sometimes be lost in the energy efficiency debate. When we retrofit we need to address the important issue of thermal comfort in domestic buildings.

To gain an accurate picture of pre and post indoor conditions a series of sensors can be deployed, to measure variables such as; relative humidity, carbon dioxide levels, and lighting levels. However, the main driver for energy transfer in buildings is the temperature of the indoor space driven by the heating system in relation to the external climate. As such, we need to monitor the internal temperatures both before and after retrofit. Many studies have observed a **"take-back effect" or "rebound effect"** (Hong, Oreszczyn, & Ridley, 2006). This is where a house has been retrofitted, but the energy consumption in the dwelling actually increases. This is often attributed to the fact that the occupants may have been under heating their property prior to the work. The post retrofit property requires less energy to attain a higher level of comfort, so the occupants often take advantage of this and the predicted savings are often not reached.

A study was carried out on 274 pre retrofit and 633 post retrofit dwellings. It was found that after energy savings measures had been put in place (heating system improvement or insulation measures) the average temperature in the living room rose by 1.6°C and a 2.8°C rise was found in the bedrooms. This is a clear example of **people reclaiming the anticipated savings as heat/comfort rather than money.** A further study (Hong, 2006) found that on average between 65-100% of the savings offered by the measures installed were "taken back" by the occupants through the raising of the internal temperatures of the living room and bedrooms.

If we are to correctly analyse and quantify effects such as "take back" then we must accurately monitor indoor conditions, both before and after retrofit. There are two main types of system to do this. The first are stand-alone loggers, which are simply left in the dwelling during the project and then collected and data downloaded at the end. A second, more sophisticated, system will consist of a series of individual devices or “nodes” which are placed in each room, they then communicate wirelessly with a central “hub” which in turn can then send the data to a central server where the practitioner can view the live and historic data. There is a significant difference in price between these systems, with stand-alone units costing around £60, compared to a wireless system, which has nodes that cost £100 and a hub, which can be around £300. The advantage of the wireless system is that the practitioner can watch for problems such as battery failure and peculiar readings remotely whereas the stand alone units can fail half way through a project and the practitioner would not be aware, losing a lot of valuable data.

All wireless units have to be connected to a central server to allow live viewing. This can be through a 3G data modem or using the broadband connection at the property. However, consideration should be paid to occupants if you are using their broadband connection.

It is important; if an accurate assessment of temperature is to be made, that that the sensors are well placed. If the practitioner wishes to draw conclusions that refer to thermal comfort and heating settings then a temperature sensor must be placed directly adjacent to the room thermostat that controls the heating in that room. It is important to ensure that temperature sensors are kept out if direct sunlight, at all times of the day. To allow a representative and accurate study the sensor should be placed as well as possible in a space that is representative part of the room. Where possible, internal conditions should be measured at the same point to all allow a direct comparison.

Levels of Occupancy

Occupancy is very difficult to measure accurately for both ethical and technical reasons. However, using some simplistic sensors and some careful analysis it is possible to identify approximate occupancy levels and room usage. The technology that most researchers employ is the passive infrared sensor (PIR). This is the same technology that is used in domestic burglar alarms. This sensor will produce a signal every time a source of infrared energy, such as a person, is detected in the room in which it is installed. What this gives the researcher is not the number of people present in each room at a given time, but shows that there is motion in that room. This system has its problems. For example, pets can be detected, or there may be periods when people in the room are stationary, and these periods will not be detected. However, the level of detail is good enough to examine occupancy levels in one period compared to another. A typical use of this is to validate if a room is now more comfortable and cheaper to heat, is it being used more? Additionally, if a room or building is found to have a higher occupancy figure than expected then it stands to reason that the energy consumption could be higher than expected

Humidity

Although not directly significant to energy consumption or performance gap issues, humidity can be an indirect contributor to both of them. As such, it is a useful variable to include in the monitoring dataset. The reason for this is that poor air quality can often be caused by unusual occupant behavior such as drying of washing indoors, higher than normal levels of occupancy, or reduced ventilation due to improved airtightness. Any one of these three factors is certainly worth considering when examining a retrofit and comparing pre and post data. As with temperature sensors, consideration should be given to placing them away from washers and dryers, cooking areas showers and baths.

Fabric Testing/Investigation

During a retrofit, even though the site may have been appropriately supervised and each stage of the work checked, there is a risk that the fabric may not perform to its designed standards. This is compounded by the fact that the original fabric may have been achieving different performance standards than reflected in the model. This indicates that investigating the fabric in situ, pre and post retrofit, may help us understand the fabric's contribution to the performance gap. This measuring of fabric performance levels allows accurate modeling values to be used at the start of a project, which in turn can be compared to measured values post retrofit.

Air Tightness Testing:

Currently, in England and Wales only new build dwellings and large extensions are required to have air tightness tests carried out. This is often referred to as "blower door testing". There is some level of use in domestic retrofit projects to prove the levels of air tightness. The test aims to identify unintended ventilation losses rather than ventilation losses that are intentional such as ventilation systems and vents. The procedure of the test is straightforward; a large fan is placed in the doorframe of an external door and creating either a negative or positive pressure differential in the property. Using this differential, an airtightness figure can be calculated, this is presented as the amount of air in m^3 that leaves the building in a given period, per m^2 of floor area.

In addition to providing a quantitative value for fabric permeability performance, when used in conjunction with a smoke machine or smoke pencil, it is possible to isolate where the air leakages are occurring. This can either be used for evidence or assist in the leak being addressed. It is for this reason that this test should be carried out at three stages; pre retrofit, during retrofit – particularly when the project is nearing completion. This allows for any issues to be fixed prior to practical completion. Some examples of unintended air infiltration paths are:

- Around service penetrations
- Poorly sealed doors and windows

- Gaps in construction materials such as floorboards
- Cracks in the building fabric
- Poorly fitting loft hatches
- Seals around light fittings

The current standard that air tightness test should carried out under is BS EN 13829:2001 by a member of a recognised accreditation scheme.

Thermal Imaging

Thermal imaging or thermography is an essential tool in performance gap studies, especially in schemes where the air tightness of the fabric has been improved. The thermal camera takes images, or movies, that measure the amount of infrared radiation emitted from a material. This is converted to a surface temperature picture, where different colours represent temperatures. With some careful analysis, it is then possible to interpret these images to inform how well insulated a building is or more likely where insulation may be missing in a building.

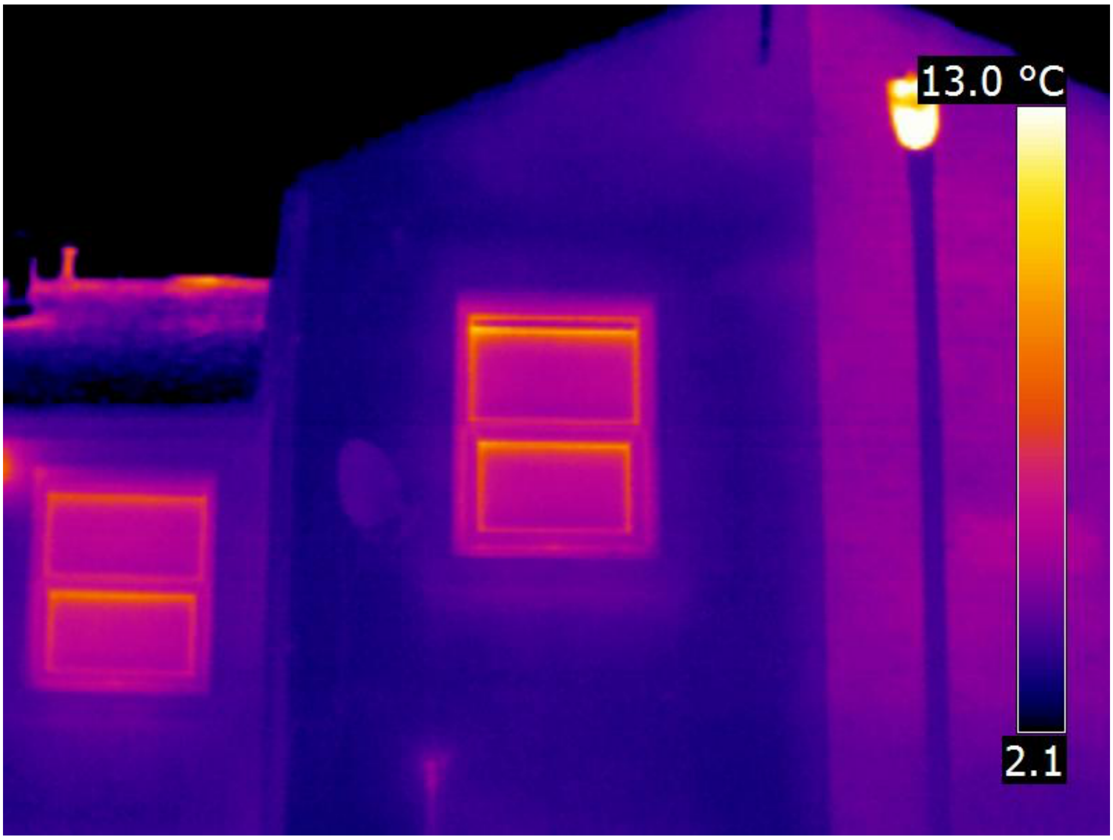

Figure 3. Here two parts of a rear extension can be seen in the image, the left half of the building has a lower surface temperature indicating that this part is better insulated (it has just been externally insulated).

When combined with an airtightness test, thermography can also identify air leakage pathways. Where a building is placed under negative pressure, and the air outside is cooler than inside then this air can be readily spotted by a thermal camera:

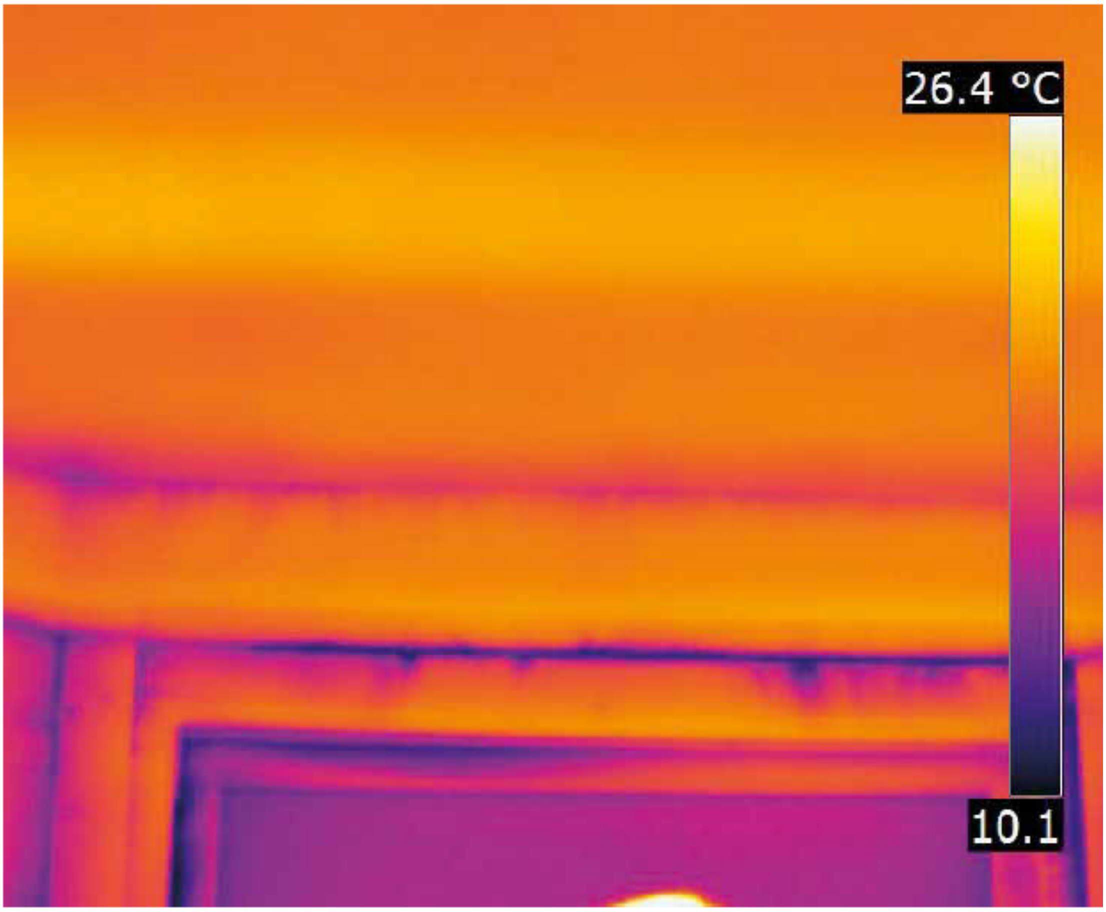

Figure 4. The cold air entering around the window edges is clearly visible using the thermal camera.

Thermography should be considered a qualitative tool, it cannot be used easily to quantify heat loss or energy efficiency. However, it is very useful for finding missing insulation, or poor installation. When coupled with air tightness testing, it is good for visualising air infiltration in the building. It also allows for large areas to be inspected in small amount of time and is a cost effective way of observing insulation defects instantly.

Although thermography is clearly a useful tool, it should be used with a great deal of caution. The images, although illustrative, need someone with a good understanding of building physics to interpret them. Clear protocols are needed to make sure that the images are accurate and to allow one image to be compared with another. There is a British Standard for thermographic surveys (BS EN 13187:1999) this provides formal guidance including setup of equipment and a suitable reporting standard.

U Value Monitoring

A U value is a measure of the coefficient of heat loss through a building element, generally walls, windows, doors and floors. Many practitioners will be familiar with U values, and may have specified or calculated U values. However, few in the property professions will have been involved in the measurement of these values. In recent years, U value measurement has become more popular with academic researchers in particular. They can help a great deal with the investigation of the performance gap. The procedure is relatively straightforward, usually an array of sensors is attached to the inside face of an element, most commonly a wall. A typical setup might consist of three heat flux sensors, which measure the rate at which heat energy is transferred through the wall, as well as internal and external temperature sensors. Whilst this appears relatively simple, it requires an expert to set this up. The sensors must be in a representative portion of the wall itself, and not near any thermal bridges. This is achieved using thermography to image the element beforehand. The sensors must also be fixed securely to the wall. When the data collection period is completed then the data must be analysed following a strictly defined protocol and only can be classed as a successful measurement if certain statistical criteria are met.

The measurement period is crucial. The minimum data collection time is 3 days, but is usually extended to at least 2 weeks. The internal temperature should be as stable as possible, with a difference in temperature of least 10°C between inside and outside of the property. This means that the investigation should be carried out in heated property during late autumn/winter/early spring.

The result of the testing period and data analysis will be a set of U values for each individual point of measurement, and in some cases an averaged value for the element measured. This should be accompanied by a figure, which will give a figure of uncertainty. This figure is important as it dictates the validity of the measurement and should always be quoted when results are published.

These criteria and more are all contained within an international standard (ISO 9869-1:2014). If a practitioner is ordering/specifying U value measurements then this standard should be used as a baseline/reference.

Co-Heating Test

This test is also known as the Whole House Heat Loss Test. It aims to provide an energy efficiency rating for the entire property. The methodology used by the majority of researchers is the latest version of a test methodology published by Leets Becket University. The idea of the test is quite simple: a set of electrical heaters and fans are used to elevate the temperature in each room of the house to 25°C. This artificially high temperature is designed to ensure that the heat is flowing out of the building rather than in. As with U value testing, the test should be carried out in the winter period, as a temperature difference between inside and outside of at least 10°C must be achieved. Another limiting factor is that the test period should be at least 14 days, and can often need to be extended further.

The energy consumed by the heating equipment required to keep this elevated temperature is recorded, as are the internal and external temperatures. This data is then analysed and normalised to allow for influencing factors such as wind and solar gain, which may be influencing the performance of the property.

The output of the test can be expressed as a single figure. This is expressed in Watts/Kelvin or Watts/°C . This figure is the amount of Watts taken to elevate the temperature in the dwelling by 1°C. Many researchers believe that this is an accurate and robust way to examine the fabric performance of a dwelling as it allows for all heat loss in the building to be covered in one measurement.

At the moment this testing regime is limited to only researchers in the field and a small number of consultants in the UK.

Conclusion

Understanding the performance of retrofit in terms of what measures do and do not work is an important issue for the UK. For example, homeowners need to understand what measures to choose for their properties, and policy makers need to understand what measures should be supported. The performance gap makes this a difficult issue. We need, as a sector, to be led by good data. The tools outlined above can be considered a developing series of approaches to help us understand and evaluate what does and does not work in retrofit. Designing effective monitoring programmes means we need to make more effort to understand the building pre and post retrofit, we need to ensure that the right questions are being asked and we are analyzing our data robustly.

While some of these tools can be considered as specialist, requiring a detailed understanding of building physics, there are tools we can use to gain an overall picture, which can provide us with some data to inform our decisions. Air permeability tests and thermography, while not without their risks of being applied incorrectly, when done correctly can provide good information at a relatively low cost. Approaches, such as engaging with occupants to understand their experience of the building can also provide valuable information at relatively low cost. However, if we are to develop a detailed understanding of a building more sophisticated approaches are available, but we need to recognize the skills and resources required to collect and analyse robust data.

In the last few years, prices for many of these approaches have been falling, tools are being developed to support the analysis of data and new, less time-consuming approaches are being developed. While many of the approaches, such as in situ U value monitoring or co-heating, require a great deal of time and skill, new developments in the field of in situ monitoring and building performance could see equivalent tools coming within reach of the practitioner. Additionally, should tests be developed that are less costly, it is possible that, as with the air permeability test, they could find their way into regulation.

Further Reading

U Value study carried out on historic walls, which have been retrofitted (Historic Scotland)
http://www.historic-scotland.gov.uk/technicalpaper10.pdf

Research Insights into Building Retrofit in the UK (Energy Savings Trust)
http://www.superhomes.org.uk/wp-content/uploads/2012/01/Retrofit_Challenge_2011.pdf

Retrofit Pattern Book: An open source directory of constriction details for domestic retrofit "The Retrofit Pattern Book allows designers and manufacturers to show their best practice details to others."
http://retrofit.support

Retrofit Reality Check (Building Magazine) – Coheating and U value measurement used to illustrate domestic performance gap issues.
http://www.building.co.uk/retrofit-reality-check/5038346.article
The full detailed report can be found at
http://www.leedsbeckett.ac.uk/as/cebe/projects/tap/

Books:

Retrofitting the Built Environment
http://eu.wiley.com/WileyCDA/WileyTitle/productCd-1118273508.html

Retrofit for Purpose
http://www.penoyreprasad.com/retrofit-for-purpose/

Academic Papers

Hong, S. H., Oreszczyn, T., & Ridley, I. (2006). The impact of energy efficient refurbishment on the space heating fuel consumption in English dwellings. *Energy and Buildings*, *38*(10), 1171–1181. doi:10.1016/j.enbuild.2006.01.007

Miles-Shenton, D. (2011). *Energy efficient renovation of an exisiting dwelling: Evaluation of design and construction and measurement of fabric performance*. Leeds: CEBE.

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Zero Carbon Hub. (2014). *Closing the gap between design and as built performance*. London. Retrieved from http://www.zerocarbonhub.org/sites/default/files/resources/reports/Design_vs_As_Built_Performance_Gap_End_of_Term_Report_0.pdf

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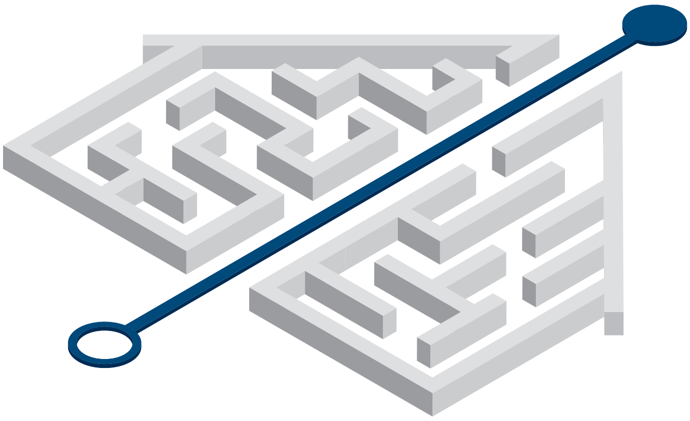

CLOSING THE GAP BETWEEN

DESIGN

&

AS-BUILT PERFORMANCE

END OF TERM REPORT

July 2014

ZERO CARBON HUB

The Zero Carbon Hub was established in 2008, as a non-profit organisation, to take day-to-day operational responsibility for achieving the government's target of delivering zero carbon homes in England from 2016. The Hub reports directly to the 2016 Taskforce.

To find out more, or if you would like to contribute to the work of the Zero Carbon Hub, please contact: info@zerocarbonhub.org.

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CONTENTS

The following appendices are available online at **www.zerocarbonhub.org**

EXECUTIVE SUMMARY

Context, Future Vision & Drivers for Change

For some time, the Government has had concerns about the potential gap between design and as-built energy performance, following research into this issue by several universities and specialist projects. Indeed, such was its concern that it invested £8 million into a research programme by the Technology Strategy Board to look into Build Performance. The Government subsequently undertook a consultation into a regulatory option to help close the Performance Gap as part of the Building Regulations Part L 2013 review, which led to the Zero Carbon Hub being commissioned to undertake a full and comprehensive review of possible causes of and solutions to the Performance Gap.

This is also in the context of a previous Zero Carbon Hub Task Group which in February 2011 made recommendations as to the level of on-site carbon reduction ('Carbon Compliance') required for Zero Carbon Homes, based on closing the Performance Gap and achievement of the ‘2020 Ambition’.

CLOSING THE PERFORMANCE GAP: THE 2020 AMBITION

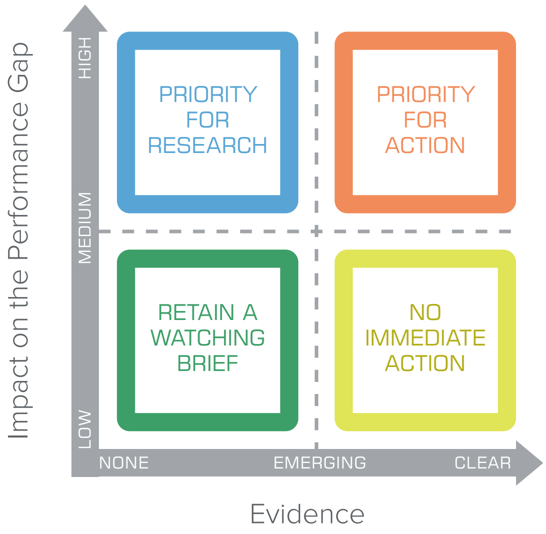
From 2020, to be able to demonstrate that at least 90% of all new homes meet or perform better than the designed energy / carbon performance.

This report draws together the findings of the Zero Carbon Hub project on Closing the Gap Between Design and As-Built Performance. It builds on two previous outputs; the ***Interim Progress Report*** (July 2013) and the ***Evidence Review Report*** (March 2014), together with subsequent work continuing the evidence gathering process and developing solutions to tackle various aspects of the Performance Gap.

The project, commenced in early 2013, aimed to: review evidence for the significance of the gap; explore potential reasons for it; set out proposals to address the issues identified; establish areas for further research; and to put forward potential methodologies to enable the industry to demonstrate progress in achieving the ‘2020 Ambition’. It has been a collaborative process that has brought together a wide range of participants from across industry, involving 160 experts who have worked enthusiastically to provide evidence and solutions to the many diverse areas of the Performance Gap.

From a government perspective, a gap in a building's energy and carbon performance undermines its vital role in delivering the national carbon reduction plan, as well as presenting reputational dangers to the industry and undermining consumer confidence if energy bills are higher than anticipated. Identifying the origin, size and extent of any gap between design and as-built performance is, therefore, seen as a high priority for not only government, but also industry.

A list of potential issues creating this gap was drawn up, spanning the entire design and delivery process, from site acquisition, through design, to statutory approvals, procurement, construction and commissioning. A detailed evidence gathering process was then carried out, including questionnaires, an analysis of SAP, a co-ordinated analysis of published and confidential literature, and the development of a ***Housebuilding Process Review*** method to gather primary evidence from 21 live housebuilding sites from 13 developers. The issues suspected of contributing to the Performance Gap were then categorised, based on the strength of evidence and the relative impact of each. From this, 15 were defined as ‘Priority for Action’, a further 17 as ‘Priority for Research’ and the remainder as ‘Retain a Watching Brief’.



The information reviewed and gathered revealed widespread evidence of a Performance Gap and that all stages of the process of providing new homes have the potential to contribute to it, either inadvertently, or as a consequence of conflicting drivers within the industry or through poor practice. Three cross-cutting themes were identified as primary contributors to the problem: lack of understanding, knowledge and skills; unclear allocation of responsibility; and inadequate communication of information.

A pan-industry shift in focus is required to create the necessary cultural change to address the issues identified. This will require a similarly systemic process to the embedding of health and safety within the industry consciousness and everyday quality processes.

The level of engagement in this project is a clear indication of the commitment by industry to close the Performance Gap, particularly from those companies seeking to deliver the highest quality low carbon homes but who are cautious about proactively marketing or guaranteeing as-built performance without being able to ensure consistent and demonstrable delivery in practice.

The scale of change in business practice envisaged within the tight timeframe of the '2020 Ambition' will only be possible if there are clear drivers to underpin it. In the context of pressures for increased housing supply and recent government efforts to reduce the regulatory burden, industry is also keen to embrace the opportunity to address the issue in a manner that is practically and commercially viable.

However, if a market advantage already existed for delivering high quality, low energy cost homes it would already be being exploited. Therefore it is believed that a clear regulatory commitment, appropriately designed, will help catalyse early action across the entire industry. A key aspect of any such regulatory driver must be the ability for industry to develop alternative approaches in a manner similar to the creation of Robust Details.

An example of industry developing innovative alternatives to regulation:
As a result of increasing occupant complaints, the Government announced in 2001 its plans to require post-completion acoustic testing under Part F of the Building Regulations. This galvanised industry to invest in innovative solutions to develop a more commercially viable method of demonstrating compliance. The resulting Robust Details scheme was launched in 2004 using a combination of type testing, process control and randomised end-of-line testing to ensure quality is maintained.

The success of such a period of rapid innovation is predicated on industry working together to demonstrate to government that it can improve and maintain quality outputs. Well targeted government funding for research and development, via bodies such as the Technology Strategy Board, is required to accelerate cross-sector innovations.

Areas for Change

A number of solutions, grouped into five key themes, have been proposed to address, in particular, the priority issues identified in the ***Evidence Review Report***. These are outlined below and are summarised at the end of the Executive Summary. While some may apply across the entire industry, others may only be relevant to certain sectors, professions or organisations.

Energy Literacy

Across the whole construction industry there is limited understanding of as-built energy performance and the existence of the Performance Gap. Consequently there is an urgent need to emphasise energy performance issues in training of new entrants and to provide additional training and Continuing Professional Development for existing members of the industry. This includes clients, planners, designers, architects, engineers, SAP assessors, energy modellers, developers, contractors, procurers, site managers, materials suppliers, operatives, commissioners, testers, verifiers, valuers and insurance bodies. An industry recognised card scheme should be developed to enable operatives and professionals to demonstrate that they have the necessary energy performance knowledge and skills.

Improving Quality Output

There must be strong actions to improve as-built energy performance by encouraging design continuity, identifying responsibility for championing energy performance, introducing 'gateways' and improving learning loops. There is a need to create a more robust industry-led approach to construction detailing, linked to improved quality control from design through to the construction and commissioning phase.

There is a clear need for manufacturers to address many areas of the Performance Gap, including via improved product labelling, design and installation instructions. Procurement teams need to prioritise energy performance when procuring materials and labour. Furthermore, improved quality control, from design through to the construction phase, is required together with rigorous independent commissioning of services.

National Compliance Method and Regime

The Standard Assessment Procedure (SAP) is a critical element within the assessment of a building's energy and carbon performance. Changes are required to increase the usefulness of the outputs for developers, designers, statutory bodies and occupants. A more comprehensive Product Specific Plain Language Compliance Report, signed by the housebuilder, should be implemented.

Conventions used for calculating key inputs related to both the fabric and building services need to be reviewed and in some cases linked to qualification schemes to ensure only those with sufficient knowledge provide this service. In a similar manner, the governance of SAP accreditation schemes, assessors and role of Building Control needs to be reviewed.

Demonstrating Performance

There is a clear need to refine existing diagnostic tests to make them more useful, usable and consistent, and to develop new techniques. In addition, manufacturers need to develop and adopt testing methods that better reflect the performance of their products as 'systems' within actual buildings. There remain conflicting views on the most commercially viable way to demonstrate a building's as-built performance, however the development of appropriate testing, measuring and assessment techniques is urgently required to enable the '2020 Ambition' to be demonstrated.

Continued Evidence Gathering

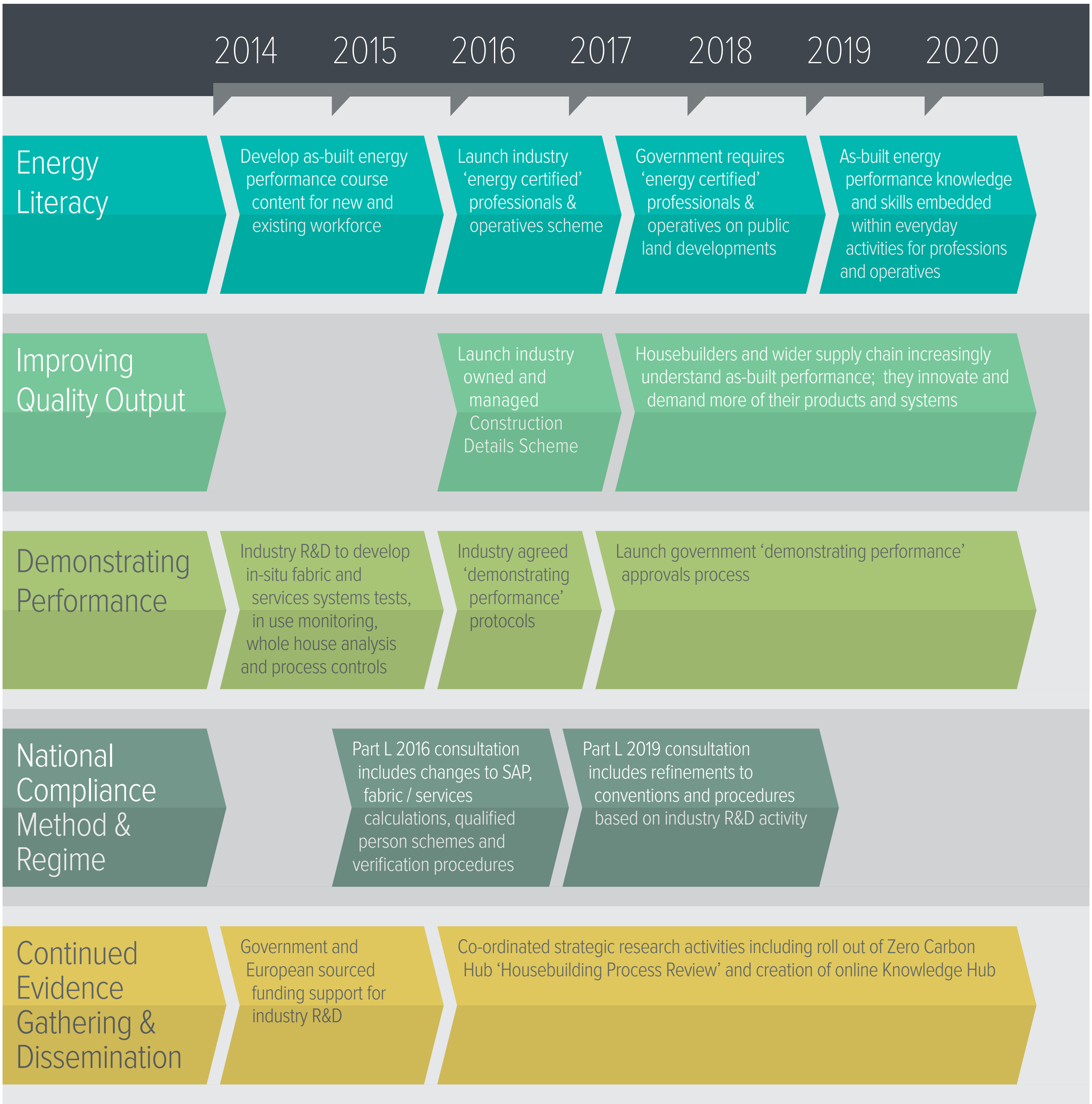
Expansion of the current evidence gathering process is required to increase understanding of the Performance Gap and disseminate findings and feedback to developers, industry and government. In order to drive the cultural change required, it will be necessary to ensure this communication is targeted specifically to the different audiences.

The initial ambition of the project was to undertake research and consider solutions that would, where possible, be cost neutral to industry. Whilst hugely ambitious, the project has indicated that although cost may be incurred in one area it is often offset in others. Certain improvements already undertaken by industry leaders have been undertaken at no cost but will have an immediate effect on the Performance Gap. These changes were instigated as a direct result of their involvement with the project's evidence gathering process.

Next Steps

As the construction industry develops products and processes capable of delivering homes with more predictable as-built energy and carbon performance, it will become essential that the research methods and tools used to assess them are continuously improved. Industry recognises the significant challenge the Performance Gap represents and the corresponding need to proactively address it. Rather than relying on ever more onerous regulatory interventions, industry is very capable of developing innovative, commercially viable methodologies to demonstrate their success.

This requires immediate co-ordinated pan-industry activity to trigger a cultural shift so that as-built performance becomes a core element of delivering high quality new housing. A strategically timed series of actions is therefore needed by industry and government between now and 2020, as set out in the summary Route Map that follows.


2014 2015 2016 2017 2018 2019 2020

Energy Literacy
- Develop as-built energy performance course content for new and existing workforce
- Launch industry 'energy certified' professionals & operatives scheme
- Government requires 'energy certified' professionals & operatives on public land developments
- As-built energy performance knowledge and skills embedded within everyday activities for professions and operatives

Improving Quality Output
- Launch industry owned and managed Construction Details Scheme
- Housebuilders and wider supply chain increasingly understand as-built performance; they innovate and demand more of their products and systems

Demonstrating Performance
- Industry R&D to develop in-situ fabric and services systems tests, in use monitoring, whole house analysis and process controls
- Industry agreed 'demonstrating performance' protocols
- Launch government 'demonstrating performance' approvals process

National Compliance Method & Regime
- Part L 2016 consultation includes changes to SAP, fabric / services calculations, qualified person schemes and verification procedures
- Part L 2019 consultation includes refinements to conventions and procedures based on industry R&D activity

Continued Evidence Gathering & Dissemination
- Government and European sourced funding support for industry R&D
- Co-ordinated strategic research activities including roll out of Zero Carbon Hub 'Housebuilding Process Review' and creation of online Knowledge Hub

Headline Recommendations

The ***Evidence Review Report*** identified key areas that needed ‘immediate action’ and those needing ‘further research’, but it is clear that actions are needed by both government and industry if we are to close the ‘Performance Gap’ in the short to medium term. Indeed, the 18 months of discussion with experts has highlighted many ‘cross cutting’ themes and the overarching recommendations below should not be assumed to be exclusive and should be read in the context of the full report.

Priority Actions for Industry

To commit to providing the investment for:

1. PERFORMANCE ASSESSMENT R&D

Undertake the research and development necessary to create innovative testing, measurement and assessment techniques to understand the Performance Gap and develop commercially viable methodologies acceptable across industry for 'demonstrating performance'.

2. SKILLS AND KNOWLEDGE DEVELOPMENT

Ensure that as-built energy performance knowledge, including learning from ongoing research and development, is embedded into training and up-skilling for professionals and operatives.

3. CONSTRUCTION DETAILS SCHEME

Develop an industry owned and maintained Construction Details Scheme providing ‘assured’ as-built energy performance for the most common major fabric junctions and systems.

4. CONTINUED EVIDENCE GATHERING

Support further evidence gathering processes and coordinated feedback to ensure accelerated continual improvement across all sectors of industry.

Priority Actions for Government

To accept the Zero Carbon Hub's recommendations to:

1. SIGNAL CLEAR DIRECTION

Clearly indicate that, in place of immediate additional regulation, it expects the construction industry to act now and have put in place a number of measures to ensure that the energy Performance Gap is being addressed and to demonstrate this by 2020.

2. STIMULATE INDUSTRY INVESTMENT

Signal their long term intent, by funding research and development into testing, measurement and assessment techniques with immediate effect, to support the industry in providing the information necessary to quantify the Performance Gap and create the learning loops required to drive continuous improvement. Additionally, provide pump prime funding to enable industry to develop a Construction Details Scheme.

3. STRENGTHEN COMPLIANCE REGIME

Take action by 2016 to ensure that the Zero Carbon Hub recommended revisions to energy modelling practices, SAP processes and verification procedures, together with a strong regime to ensure that only suitably qualified persons carry out energy modelling and assessment, can be put in place.

4. SUPPORT SKILLS & KNOWLEDGE DEVELOPMENT

Accelerate the demand for industry developed qualification schemes by requiring energy certified operatives and professionals for developments on public land from 2017.

This project has identified a number of key actions that government and industry are required to undertake. There is now a need for a concerted level of activity to implement the many detailed recommendations within this report in order to close the Performance Gap and demonstrate the '2020 Ambition'.

DETAILED RECOMMENDATIONS SUMMARY

A number of solutions, grouped into five key themes, have been proposed to address, in particular, the priority issues identified in the Evidence Review Report. While some may apply across the entire industry, others may only be relevant to certain sectors, professions or organisations.

Energy Literacy

- Training for all new entrants to the industry should emphasise energy performance issues, from site operatives through to planners, designers, procurement staff, assessors, testers and inspectors.
- Training for all current members of the industry is similarly needed in energy performance awareness, skills and knowledge.
- An industry recognised card scheme should be developed to enable operatives and professionals to demonstrate that they have the necessary energy performance knowledge and skills.
- Energy Performance Certificates should include a low / medium / high estimate of total energy consumption.

Improving Quality Output

- Encourage design continuity and feedback:
    - Appoint an 'energy champion' with the authority and responsibility to oversee the energy principles of the design from concept stage to completion.
    - Include 'gateways' within the design and construction process that define specific points at which energy performance requirements are checked.
    - Explore the potential for BIM to act as a 'golden thread' to monitor and control design, quality, change control and performance in respect of energy performance.
- Improve specification, design and procurement of materials and services:
    - Reduce inadvertent product substitution by improving labelling to aid product identification.
    - Improve product design to aid correct installation.
    - Improve manufacturer specifications and installation instructions to focus on correct installation of products and systems to achieve high levels of energy performance.
    - Procurement teams to assign very high levels of importance to ensuring that products and labour meet the necessary energy performance, specifications and competency.
- Responsibility for the provision of ‘standard’ construction design details should be moved to industry control. This industry owned and maintained Construction Details Scheme should provide 'assured' as-built energy performance for the most common major fabric junctions and systems.
- Improve quality control:
    - Greater importance needs to be placed on controls surrounding energy performance requirements, for example by clients and developers.
    - An increased focus on energy-related checks and assessments is needed across all areas of the building delivery chain, from the design stage to completion on site.
    - Improvements are needed to the commissioning process as a whole, and commissioning should be carried out by independent subcontractors.
- Improve learning and feedback loops so that lessons can be fed back effectively and appropriately to all relevant parties. As part of this, disseminate lessons learnt from the Zero Carbon Hub evidence gathering work, including from the ***Housebuilding Process Review*** (see also Continued Evidence Gathering & Dissemination section below).

National Compliance Method and Regime

- The SAP process needs to be refined to improve compliance reporting:
    - Introduce a more comprehensive Product Specific Plain Language Compliance Report, with a signed declaration of accuracy of the input information by the housebuilder, to be provided to Building Control at design stage as part of the controlled documents.
    - At the as-built stage, the updated Product Specific Plain Language Compliance Report, with signed declaration by the housebuilder, would be provided to the SAP assessor, Building Control and the occupant.
    - SAP assessors should only be allowed to issue the EPC on receipt of the as-built stage signed Product Specific Plain Language Compliance Report. Accreditation scheme disciplinary procedures must reflect the serious nature of any contraventions.
    - Building Control should only be allowed to issue a completion certificate on receipt of both the as-built stage signed Product Specific Plain Language Compliance Report and the EPC RRN from a full SAP.
- Governance of SAP accreditation schemes and SAP assessors needs to be reviewed:
    - Responsibilities of SAP assessor, housebuilder and Building Control need to be defined in a clear and coordinated manner.
    - The terms of reference of the SAP Conventions Group should be clarified and its membership expanded to ensure an appropriate focus on energy performance issues.
    - Government audits of SAP assessor accreditation schemes need to be tightened and have a strong technical standards focus, and assessor Continuing Professional Development expectations need to be refined.
- The accuracy of U-value and Psi-value calculations needs to be addressed:
    - Improve training and quality assurance for those undertaking U-value calculations.
    - Improve training and quality assurance for those undertaking Psi-value calculations.
    - Formally review BR443 and BR497 (which define the conventions for calculating U-values and Psi-values) with a view to better reflecting in-situ performance.
    - Establish an approval process for all U-value software.
- Undertake a systematic review of SAP methodology and assumptions, particularly focusing on those inputs which have significant impacts on the Performance Gap.
    - Confidence (or 'in-situ') factors should be considered for evaluation to reflect the real performance of the system or combined elements (i.e. the performance of a specific make up of completed walls or entire heating system, including its controls, etc.) implemented in such a way to allow competing systems to innovate and demonstrate their specific as-built performance.
    - SAP default values should be reviewed to ensure they are worst case to encourage product / system specific values to be entered.

- Make changes to SAP software:
    - Require the incorporation of a minimum level of input data validation to identify inconsistencies.
    - Provision must be made to include information to be fed into the Product Specific Plain Language Compliance Report and for the production of the report itself.
    - Establish an online document management and storage system for compliance documents to enable document transfers between clients and SAP assessors, accessible to occupants.
    - Software manufacturers should work with user groups to explore options to improve the usability of SAP software.

Demonstrating Performance

- Further development of diagnostic tests is urgently needed:
    - Refine and standardise protocols of existing tests to make them more useful, usable and consistent.
    - Develop new tests for fabric and services systems, for diagnostic use both in the laboratory and on-site.
- Develop new commercially viable testing, measurement and assessment techniques to demonstrate the '2020 Ambition'.
- Enhance testing skills, knowledge and practices through training and accreditation to ensure consistent interpretation and analysis of results (see Energy Literacy section).

Continued Evidence Gathering & Dissemination

- Continue and develop the current evidence gathering process and improve coordination with a view to providing better evidence of Performance Gap issues and to provide feedback to developers, industry and government.
- Collate and disseminate evidence of findings and examples of good practice, through an online 'Knowledge Hub', building on the work of the ***Evidence Review Report*** and linking to other communication channels targeted at specific stakeholders in the industry.

1. CONTEXT, FUTURE VISION & DRIVERS FOR CHANGE

In February 2011, a Zero Carbon Hub task group recommended that zero carbon homes policy should be linked to as-built performance.

This proposed future shift in the regulatory framework, known as the '2020 Ambition', influenced the task group's recommended levels for minimum on site carbon reduction levels as it recognised the significant challenge industry faces in delivering actual performance as opposed to simply designed performance.

From a government perspective, the Performance Gap would mean that new housing cannot be relied upon to play its expected, vital role in the national carbon reduction plan. For owners and occupants, energy bills may be higher than expected, undermining buyer confidence in new (low carbon) homes. For planners, designers, manufacturers and housebuilders the fall-out from underperforming new homes could impact on their reputation and business.

For these reasons, even though at the beginning of the Zero Carbon Hub Performance Gap project the origin, size and extent of the gap had not been identified, it was set as a high priority by government and by the wider construction industry.

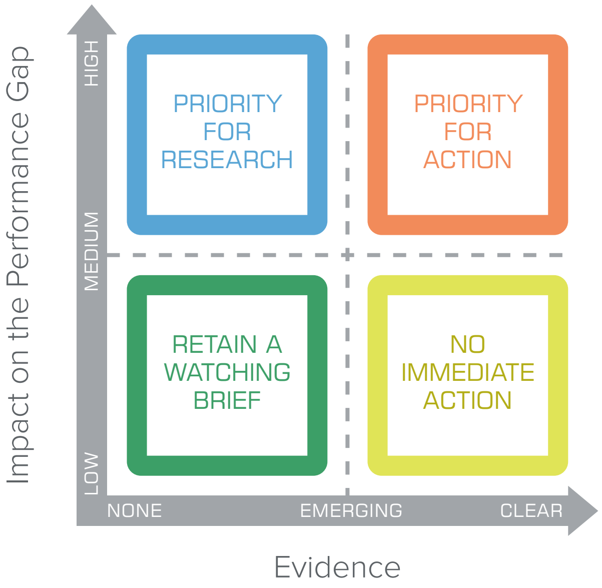
CLOSING THE PERFORMANCE GAP: THE 2020 AMBITION

From 2020, to be able to demonstrate that at least 90% of all new homes meet or perform better than the designed energy / carbon performance.

The Performance Gap project commenced at the start of 2013, since which time over 160 professionals from across the building industry have contributed to the project. Initial findings and activities are described in the ***Interim Progress Report***, published in July 2013. This identified a list of approximately 60 issues suspected of contributing to the Performance Gap.

There then followed an extensive process of evidence gathering, summarised in the ***Evidence Review Report***, published in March 2014. This provided industry and government with a structured review of how and where the Performance Gap occurs within the current housebuilding process. Evidence was gathered from a range of sources: an analysis of published literature and industry research; questionnaires, surveys and audits; and a ***Housebuilding Process Review*** that gathered evidence from delivery teams, including visits to 21 live construction sites.

Drawing on this evidence, issues contributing to the Performance Gap were categorised using a prioritisation matrix. This was based on the degree of evidence for each issue and the potential impact it may have on energy performance. Fifteen 'Priority for Action' issues were identified, with a strong supporting evidence base and medium to high potential impact on the Performance Gap when they do occur. These appeared across the delivery process from concept design and planning, through to construction and commissioning. There were also a number of issues around verification and testing activities.



A further 17 issues were identified as 'Priority for Research': it is suspected that these have a significant impact on the Performance Gap, but only emerging evidence is available. The remaining issues were categorised as 'Retain a Watching Brief'. A full list of issues is available in Appendix A of this report.

Since publication of the ***Evidence Review Report*** the industry experts involved in the project have been generating potential solutions, particularly focused on the 'Priority for Action' issues, as well as the cross-cutting themes of communication, responsibility and knowledge & skills. They were also tasked with identifying necessary research to enable activation of the suggested solutions. Alongside the original work groups, five specialist groups were formed with specific tasks:

- Speculative Housebuilder Delivery Approach and 'Design and Build' Delivery Approach Work Groups, considering which solutions had the greatest potential for success within their specific commercial environment.
- An Assured Performance Work Group considering what potential techniques could be used by industry to demonstrate the '2020 Ambition'.
- A Further Research Work Group considering where additional research is required and identifying potential funding routes.
- A Services Work Group considering services-related issues and solutions.

Future Vision

During this project it has become clear that the Performance Gap in new buildings is widespread. Many within industry, ranging from architects and manufacturers to site personnel and Building Control officers, now believe that significant change is needed.

The key recommendations presented in this report are intended to create a competitive environment where companies willing to invest in the R&D needed to rapidly and substantially close the Performance Gap are rewarded commercially, and able to gain significant market advantage within the regulatory environment.

A pan-industry shift in focus is required to create the necessary cultural change to address the issues identified. This will require a similarly systemic process to the embedding of health and safety within the industry consciousness and everyday quality processes.

Industry needs to make changes in a number of areas which have been identified and are detailed in the following Section 2 – Areas for Change. Many of these issues, which were highlighted in the ***Evidence Review Report***, are comparatively well known but to-date there have not been sufficient drivers to bring about change. The highly cost competitive nature of the industry means that in parallel with their efforts there is a role for limited and appropriate regulatory interventions to allow those delivering a better quality product / service to differentiate themselves, thereby increasing brand value and commercial advantage.

Making Change Happen

To engage the entire industry and catalyse change there needs to be a strong and certain business case for shareholders and executive boards of large organisations and the owners and directors of smaller businesses. Approval for the necessary investment to drive changes in their business practice typically requires the prospect of market advantage via strong consumer demand, increasing risks of consumer dissatisfaction, and / or a clear regulatory path.

Industry is committed to addressing the Performance Gap and would not want to be forced into action by negative consumer feedback or perceptions. Experience from similar periods of change indicate that industry is best placed to create innovate, commercially viable solutions.

However, if a market advantage already existed for delivering high quality, low carbon, low energy cost homes, industry would already be exploiting it. Therefore it is believed that a clear regulatory commitment, appropriately designed, will help catalyse early action across the entire industry. A key aspect of any regulatory driver must be the ability for industry to develop alternative approaches, in a similar manner to the creation of Robust Details.

INDUSTRY INNOVATIVE ALTERNATIVES TO REGULATION EXAMPLE:

As a result of increasing occupant complaints, the Government announced in 2001 its plans to require post-completion acoustic testing within Part E of the Building Regulations. This galvanized industry to invest and innovate in order to develop a more commercially viable method of demonstrating compliance. The resulting Robust Details scheme was launched in 2004 using a combination of type testing, process control and randomised end-of-line testing to ensure quality is maintained.

It is important to consider the challenge these issues represent within the context of the Government's growing demands for increased housing supply and recent actions to positively reduce regulatory burden. Industry is keen to embrace the opportunity to address the Performance Gap in a manner that is commercially viable.

> *The lesson from Robust Details is that if the regulatory pain is too great, industry will invest and create its own alternative.*
> –
> **Stephen Stone, Chief Executive, Crest Nicholson**

The success of such a period of rapid innovation is predicated on industry working together to demonstrate to government that it can improve and maintain quality outputs. Well targeted immediate government funding for R&D, via bodies such as the Technology Strategy Board, is required to accelerate cross-sector innovations.

Significant investment has been and is being made in designing and constructing low carbon homes. There are already sectors of the industry focused on delivering healthy and comfortable homes able to protect people from future fuel poverty. However the current lack of understanding of how to ensure consistent as-built performance means that only a small number of housebuilders are willing to proactively market or guarantee this element of their product.

The current inability to differentiate those companies seeking to deliver the highest quality low carbon homes is limiting industry's opportunity to take full advantage of the investments it is making in innovation. The housebuilding industry is complex, with multiple supply chains, often with varying incentives and therefore a coherent methodology is required to demonstrate current performance and future improvements. It is vital that the knowledge and skills developed during this time are disseminated across the construction industry via training courses and certification schemes. Industry is best placed to develop and deliver such schemes but requires support from government to accelerate early demand within the supply chain prior to 2020.

Building Control has an increasing role to play as buildings become more energy efficient and potentially more complicated. There are already some initiatives seeking to raise awareness of the importance of energy performance through the introduction of training schemes and this is expected to continue.

Those developers who have been involved in the evidence gathering exercise have already taken a huge interest in the findings and have instigated changes to their management processes and businesses, demonstrating that making change happen requires a 'nudge' rather than heavy regulatory control.

This combination of industry actions and careful deployment of appropriately targeted regulatory drivers will promote the learning loops essential to delivering the rapid innovation and improvements across industry, from designers, consultants and manufacturers, to site management, commissioning engineers and Building Control Bodies.

2. AREAS FOR CHANGE

A number of solutions to address the issues identified in the Evidence Review Report have been proposed.

It is important to note that they should not be considered as an exhaustive list and, while some may apply across the entire industry, others may only be relevant to certain sectors, professions or organisations. Icons can be found within each of the following sections that indicate which of the issues[1] are being targeted by the proposals. The solutions can be summarised into one of five key themes:

Energy Literacy

Across the whole construction industry there is limited understanding of as-built energy performance and the existence of the Performance Gap. Consequently there is an urgent need to emphasise energy performance issues in training of new entrants and to provide additional training and Continuing Professional Development for existing members of the industry. This includes clients, planners, designers, architects, engineers, SAP assessors, energy modellers, developers, contractors, procurers, site managers, materials suppliers, operatives, commissioners, testers, verifiers, valuers and insurance bodies.

Improving Quality Outputs

There must be strong actions to improve as-built energy performance by encouraging design continuity, identifying responsibility for championing energy performance, introducing 'gateways' and improving learning loops. There is a need to create a more robust industry-led approach to construction detailing, linked to improved quality control from design through to the construction and commissioning phase.

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[1] A full list of the issues identified in the Evidence Review Report can be found in Appendix A

National Compliance Method and Regime

The Standard Assessment Procedure (SAP) is a critical element within the assessment of a building's energy and carbon performance. Changes are required to increase the usefulness of the outputs for developers, designers, statutory bodies and occupants. Conventions used for calculating key inputs related to both the fabric and building services need to be reviewed and in some cases linked to qualification schemes to ensure only those with sufficient knowledge provide this service. In a similar manner the governance of SAP accreditation schemes, assessors and role of Building Control needs to be reviewed.

Demonstrating Performance

There is a clear need to refine existing diagnostic tests to make them more useful, usable and consistent, and to develop new techniques. In addition manufacturers need to develop and adopt testing methods that better reflect the performance of their products as 'systems' within actual buildings. There remain conflicting views on the most commercially viable way to demonstrate a building's as-built performance, however the development of appropriate testing, measuring and assessment techniques is urgently required to enable the '2020 Ambition' to be demonstrated.

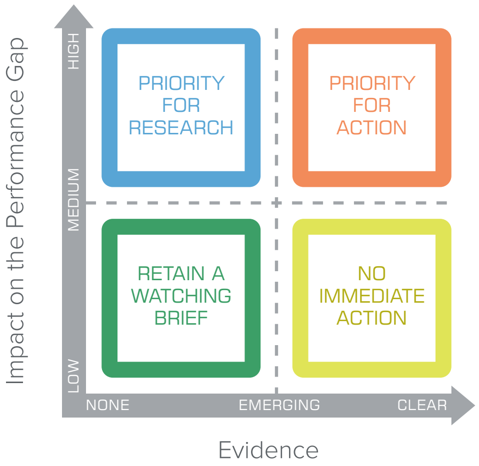
Continued Evidence Gathering and Dissemination

Expansion of the current evidence gathering process is required to increase understanding of the Performance Gap, disseminate findings and give feedback to developers, industry and government. In order to drive the cultural change required, it will be necessary to ensure this communication is targeted specifically to the different audiences.

Within this section of the report, each recommendation has alongside it a symbol, which indicates the issues being addressed. These directly relate to the list of issues presented in the ***Evidence Review Report***, the descriptions of which are in Appendix A. The symbols represent the cross-cutting themes of:

Knowledge & Skills ▲ **Responsibility** 💬 **Communication**

The symbol colour represents the quadrant of the prioritisation matrix within which a particular issue falls:



ENERGY LITERACY

Evidence clearly indicates that a lack of knowledge and skills on energy performance across the house-building industry is a significant contributor in causing a Performance Gap. A number of solutions are proposed to address this, including a requirement for new entrants to the construction industry to undertake **energy performance studies which are to be introduced / emphasised on all built environment and associated courses**. Those currently engaged in the industry are to attend **Continuing Professional Development, toolbox talks and other specific training** to enhance their knowledge and skills in areas that affect the energy performance of a building.

A **building performance and energy awareness scheme and qualification** for the whole industry is proposed, with qualification levels ranging from basic to more advanced, depending on responsibility level, potentially providing a means by which developers can help to ensure that their contractors and sub-contractors have the skills required. Professional bodies which accredit courses ranging from architecture to Building Control will need to revise their requirements, and academic institutions and training providers will need to update courses and may need to recruit new expertise. Ultimately, a **cultural shift in awareness of energy performance is needed**, similar to the changes in health and safety that have already occurred in the construction industry. Government could accelerate the demand for industry developed qualification schemes by requiring energy certified operatives and professionals for all developments on public land from 2017.

As well as tackling the energy literacy of those delivering the homes, it is also necessary for **all stakeholders to understand the benefits associated with closing the Performance Gap**. This includes those who commission buildings for construction and clients for the Design and Build sector, who stand to benefit from the Performance Gap being addressed.

To deliver these changes, **further research** will be required to develop an understanding of where improved energy literacy will make the biggest impact, and how challenges in achieving this can be addressed; and to test new ways of sharing knowledge in the field. Existing and ongoing research also needs to be communicated and coordinated more effectively. It is proposed that the *Evidence Review Report* for this project be updated with additional research and converted by the Zero Carbon Hub into an online resource for improving understanding of the Performance Gap. There is also a proposed Building Performance Evaluation network currently under formation by a leading university with which the Hub is working closely. In addition, the research community has a part to play in informing the key content which should be included in energy modules on built environment courses.

TRAINING NEW ENTRANTS

All new entrants to the housebuilding and construction products industry must be trained with the necessary energy skills to understand and reduce the Performance Gap. An appropriate level of energy knowledge needs to be specifically emphasised as part of all relevant courses. It should however be noted that changes to training will be relatively slow to make an impact: it takes time for courses to be updated and for the learning to filter through to change industry practice; other solutions will be needed for those already in the industry. It is also important the demand for this skills and knowledge is created.

I. SITE OPERATIVES

C13 C7

☑ What do we need to do?

There are different routes of entry into the job market for site operatives, so energy training must be designed to reflect this. It needs to form part of all training courses and apprenticeship schemes, requiring the involvement of professional bodies such as Summit Skills, CITB and BPEC to drive demand and set the requirements. Training centres will need to develop their curriculum and resources accordingly.

£ What kind of costs are involved?

The costs of updating existing training should be relatively low however the costs of building and setting up new training facilities would be considerable.

II. PROFESSIONALS

P2 D1 P1 PR4

☑ What do we need to do?

Training of planners, architects, surveyors, engineers, building control bodies, building performance assessors, testers and commissioners needs to include energy-related skills and energy modules that can impact on Performance Gap issues. This requires the involvement of the professional bodies that accredit courses, including *for example CIOB, Asset Skills, RIBA, RICS, CIBSE, CIAT and ARB, to encourage academic institutions and training providers to amend their courses, using input from the research community*.

£ What kind of costs are involved?

The costs of updating existing courses and training programmes should be low but new specialist staff may be needed where the required skills do not already exist within a particular education provider.

The recent UK Build Up Skills Roadmap (2013) made a range of recommendations to address workforce skills and knowledge gaps, including a call for an energy efficiency accreditation scheme which should be promoted to employers and clients. CITB and the Green Skills Alliance are working to address the recommendations of the Roadmap through a programme of work which will seek to establish energy literacy as an integral part of mainstream construction and building services engineering learning. As part of this programme, work is currently planned with industry-recognised card schemes, to provide a facility whereby individuals can demonstrate evidence of aligned energy efficiency learning and achieve recognition for energy literacy.

At Saint-Gobain we have seven dedicated training facilities, teaching site operatives to fit our products to optimise their energy performance.

–

Stacey Temprell, New-Build Sector Marketing Director, Saint Gobain

www.saint-gobain-technical-academy.co.uk

III. ENERGY MODELLERS

EM7 EM8

☑ What do we need to do?

More comprehensive training requirements should be developed for modellers of SAP, U-value and Psi-value calculations. This would be driven by changes to Part L and SAP to require the use of qualified U-value and Psi-value modellers (see section on 'National Compliance Method and Regime') and supported by CPD requirements. Training for all modellers needs to provide better awareness of the process and practicalities of construction and potential Performance Gap issues. This increase in technical requirements should be standardised across all accreditation bodies.

> *Zero Carbon Hub is running toolbox talks for SMEs and small builders over 2015-2016*
> –
> **Rob Pannell, Managing Director, Zero Carbon Hub**

★ What are the challenges and opportunities?

More training would, potentially, increase costs, making it more difficult for people to enter the market, and will require strong and positive interest from existing SAP assessors and assessor organisations. This may be addressed by closely involving SAP assessors in the process and clarifying the benefits of additional knowledge.

IV. THOSE CARRYING OUT TESTING

T3

☑ What do we need to do?

A programme is needed to address an expertise gap in the research and testing community, to improve its supporting infrastructure (*for example, the equipment used*), and to increase the value of tests that are undertaken. In addition, those that are interpreting and analysing test results also need training to avoid drawing incorrect conclusions from results of tests such as thermography. For the more established testing techniques, such as air pressure testing, this could be driven by a UKAS accredited Competent Persons Scheme (see section on 'Demonstrating Performance' for more detail).

★ What are the challenges and opportunities?

In the short term training can bring additional cost, which potentially can act as a barrier to those wishing to enter the market. However those involved in testing must have robust training schemes in place to manage these changes.

INCREASING SKILLS OF EXISTING WORKFORCE

In addition to educating new entrants to the housebuilding profession, much of the existing workforce needs to have a far better awareness of energy performance. For site operatives, it may be difficult to incentivise people to undertake this additional training, requiring an industry driver to encourage uptake of training. For other construction professionals, CPDs may provide a route for additional training.

I. SITE OPERATIVES

C13 C9 C15 C6 C1

☑ What do we need to do?

Educating site teams on energy performance skills should have an immediate impact on tackling the Performance Gap, to include specific topics such as: the importance of closely following the details within the drawings and specification feeding information back to the site management team where drawings are inadequate; sequencing the installation of specific materials into difficult areas such as complex roof construction and loft eaves; and helping individuals to understand their role in maintaining items such as the airtight barrier. A range of approaches are needed to try and reach all parts of the industry; this would include Toolbox Talks, directly relating to the Performance Gap, along with graphic examples of good workmanship to display on site. Manufacturers would have a role in training installers, which could be linked to the warranty on the product, which *for example is already the case with boiler manufacturers*.

★ What are the challenges and opportunities?

Existing site operatives need the time and incentive to undergo further training; they need to really engage with understanding the challenge. This may be helped by framing the issue in the right language and through carefully targeted campaigns. A cost may be incurred through the loss of working time, so employers would need to provide the suitable times and easy access to the training. Where there is a high turnover of site personnel, there is a risk that knowledge learnt is lost, both within and across different projects. Finally, training must highlight the importance of all operatives adhering to quality standards, emphasising the extent to which all parts of the build are vital in safeguarding the energy performance of the finished product.

II. OTHER CONSTRUCTION MANAGERS AND BUILDING PROFESSIONALS

P2 D1 C13 T3 V2
PR4 C7 P1 PR4 V1

☑ What do we need to do?

All stakeholders in the housebuilding industry need to improve their knowledge of low energy design and the Performance Gap, including construction managers, designers, planners, building control and engineers. This training will require to be delivered differently to the various stakeholders to ensure their critical part in the process is highlighted. *For example the procurement team could receive more detailed information on energy performance from suppliers; Building Control need to understand the relevant energy-related items to check on site; and commissioners have an important role in closing the gap.*

One way of delivering this training will be through CPD training, which could specifically address the Performance Gap, as well as broader issues of energy literacy.

It is clear that many issues arise between the design and construction team and specific collaborative planning sessions will be required at which designers and contractors can interact, to enhance one another's knowledge of detail, issues and construction methods and possible solutions. This training will be undertaken by professional associations and certified bodies such as Asset Skills.

★ What are the challenges and opportunities?

Some professionals may not be incentivised to carry out this training, though this could be addressed by changing the CPD requirements. *For example, attendees could be obliged to complete an assessment some time after training to demonstrate competency; or a certain number of important CPD topics could be made mandatory.*

Who needs to do what?

Professional institutions such as RIBA, CIBSE and RICS would need to change the emphasis, requirements and content of their CPD courses.

INDUSTRY RECOGNISED CARD SCHEME

C13 C15 C14

☑ What do we need to do?

An industry-supported scheme is recommended to demonstrate knowledge and skills of energy performance, with different levels of competence to suit different needs. As noted above, in response to recommendations arising from the recent UK Build Up Skills Roadmap, CITB and the Green Skills Alliance are currently planning a programme of work including investigating establishing an energy efficiency accreditation scheme.

What are the challenges and opportunities?

Procurers would need to start demanding that the workforce have the necessary certification, which would drive demand for site workers to undergo training and achieve the qualification. Operatives would need to invest time and money, for which they would need to receive some form of incentive and recompense. Investment would also be needed to set up the system, perhaps through a grant scheme.

Who needs to do what?

There is a need for a card scheme provider (or providers) to be identified. Once a scheme is introduced, procurers would be able specify a requirement for 'card-holders'; this would help to ensure that the necessary energy performance skills are employed on site and to encourage site operatives to undergo the necessary training to achieve the qualification. The scheme could be enabled by government, if they required all publicly funded developments to employ certified professionals and operatives as a pre-requisite within their tender for land sales and developments. This would aim to drive mainstream adoption of the new programmes.

WIDER AWARENESS OF THE PERFORMANCE GAP

What do we need to do?

The existence of the Performance Gap, the risks associated with it and the benefits of closing it need to be clearly communicated. Means of raising awareness within industry are outlined above, but it has been suggested that as a follow-on to this project, work also needs to be done to inform potential occupants who stand to benefit from the Performance Gap being addressed. Communication and marketing of the benefits of new low energy homes would raise awareness and increase demand for such homes by helping to differentiate them.

Registered Providers may also be able to ask for real performance as part of their Client's Requirements, as a means of driving change in the design and build sector.

Some of the organisations involved in this project suggested that EPCs should be updated to include estimates of unregulated energy use (low / medium / high), in order to make them more meaningful to householders.

IMPROVING QUALITY OUTPUT

Solutions to address the Performance Gap by improving quality output span from the earliest concept stage through design, construction and verification. Some of the solutions suggested here may not be appropriate for all businesses, but give an idea of what can and should be done. These fall into a number of themes:

The *Evidence Review Report* emphasised that unless there is **continuity of the original design and energy aspirations** through to the construction phase, unintended changes inevitably happen, which result in part of the Performance Gap occurring. It may therefore be important that an 'energy champion' be appointed who would be responsible for overseeing energy design and implementation through every stage of development. It is also recommended that 'gateways' could be introduced, requiring the design team to undertake certain key actions before progressing to the next work stage to ensure energy performance is not compromised. BIM may also be able to act as the 'golden thread' on which design, quality, change control and compliance are based.

Improvements need to be made to the specification, design and procurement of materials and services. Evidence clearly demonstrates that manufacturing changes could reduce the Performance Gap. *For example, a universal labelling system on difficult to differentiate materials*. Manufacturers should also include details in the specifications of the skills required for optimum installation. Those professionals who are responsible for the procurement of materials and sub contract services also have an important role: they should assign very high levels of importance to ensuring that products and labour meet the necessary energy performance, specifications and competency.

It is strongly recommended that an **industry-owned and maintained Construction Details Scheme be developed for the most common major fabric junctions and systems.** These need to be buildable, flexible, robust, cost effective and capable of being implemented at scale. Clear guidance on thermal bridging should also be provided for housebuilders and industry.

There is a need for an increased focus on **energy-related checks and assessments** across all areas of building delivery. Improvements to the **role of commissioning** are also required, and there may be a role for clients in driving a **greater emphasis on quality control in relation to energy performance**.

There is a clear lack of **continual improvement processes** in many parts of the industry. **Learning and feedback loops** are needed right across the housebuilding industry to ensure the necessary knowledge uptake. Clear methodologies need to be developed to make sure this takes place.

DESIGN CONTINUITY & FEEDBACK

I. APPOINT AN 'ENERGY CHAMPION'

P2 D2 PR2 C15

D3 D5 D6 D7 PR3 C11 C12

☑ What do we need to do?

Appoint an 'energy champion' with the authority and responsibility to oversee the energy principles and performance of the design and implementation, from concept stage to completion. Depending on the project, this could be a SAP assessor with good site experience or an architect with a high level of energy knowledge and awareness, it could be an external specialist, or it could be multiple people who share the role. Whoever takes this role must have sufficient authority and be involved from the earliest stage of the project.

★ What are the challenges and opportunities?

Clear limits would need to be set on exactly what the role entails – *for example, it would need to be built into the company business hierarchy to ensure that there is full accountability*. An unintended consequence could also occur, whereby the rest of the delivery team defer to the energy champion, rather than taking responsibility for their role in delivering the energy strategy. Some multi-disciplinary consultancies already offer this service, which is being driven by market demand. It is recognised that this idea is more difficult for SMEs.

£ What kind of costs are involved?

There would be an added cost to the client for filling this role, either from the increased time and responsibility for existing team members, or from the appointment of an external consultant. Initial estimates from Sweett Group indicate that the costs might be in the region of £100 - £300 per unit.

> *JRHT have developed a methodology over the years for trying to ensure designs & concepts are delivered effectively. Some might reply this is just good Project Management practice but it boils down to ensuring a collective understanding is arrived at by the key parties at the appropriate stage of a project. This is easy to say but often difficult to actually achieve, as who these key parties are, can be subject to debate - therefore this Performance Gap evidence is critical at it shines a light on who/what these key links in the construction chain are.*
>
> –
>
> **Nigel Ingram, Director of Development, Joseph Rowntree Housing Trust**

II. USE A WORK PLAN WITH GATEWAYS

P2 D2 D3 C4 C11 C10

What do we need to do?

Design continuity could be achieved through using a structure that limits progress beyond given ‘gateways’ unless certain requirements have been met. This would aim to improve sequencing, ensure better details and construction methodologies, clarify the handover process and define responsibilities. Specifics might include: requiring involvement of an M&E designer at concept stage, demonstrating sufficient handover from concept to detailed designer, fully disseminating the energy strategy or clarifying exactly which design team members need to input to a particular phase of work.

Who needs to do what?

For it to work, all stakeholders would need to familiarise themselves with a new plan and adopt it in full. Organisations such as RIBA clearly have a role in the Performance gap but little of their work applies to the house-building industry. However, the latest RIBA Plan of Work 2013 could help inform the underlying structure; the Construction Industry Council has already adopted it, and it has the potential to highlight Performance Gap issues as an ‘overlay’. Updates would be needed to the plan to better reflect Performance Gap issues and it would also need to be made applicable for projects that do not involve architects at all stages.

III. INCREASED USE OF BIM

P2 D2 D3 C4 C11 C10

What do we need to do?

Building Information Modelling and Management (BIM) could act as a ‘golden thread’ to achieving proper design continuity, helping to monitor and control design, quality, change control, performance and compliance. Used in full, it provides a collaborative exchange of information and is arranged around staged outputs, stretching from concept through design, delivery, handover and operation.

What are the challenges and opportunities?

Firstly, BIM needs to be fully adopted as part of the housebuilding process to be of benefit. There is also a perception that skills are lacking - an NHBC review found only 11% of major housebuilders using BIM - and that existing alliances and competitive procurement could be compromised. BIM would need to provide the necessary feedback loop to benefit skills development and cost optimisation. For small housebuilders, this could be a particular challenge. Some changes may be needed to the BIM process, such as data conformity standards and interoperability of software, and also to allow for the discrete nature of housebuilding workstages and uncertainty in the planning process. The potential role of BIM is explained further in Appendix G.

£ What kind of costs are involved?

Another major barrier is the additional up-front cost: the additional resources and skills required to adapt to using BIM. This may be reduced through a growing library of BIM-ready content: a platform has been developed by NBS which is being populated by manufacturers. Larger housebuilders constructing standard house-types may be better positioned to provide the necessary resources and skills. Savings should also be accrued through the use of BIM: the BIM Task Group[1] has found that it saves 8-18% on design fees and 8-10% on construction costs.

Who needs to do what?

There is already a clear signal from government that they wish the industry to make more use of BIM: they have committed to using it for central government building procurement contracts in the UK from 2016. Clients and contractors need to adapt, with clear requirements enshrined in the execution plan from the outset, stating the inputs needed from each project contributor. Project staff will need to undergo additional training and housebuilders may need to employ a BIM manager.

SPECIFICATION, DESIGN & PROCUREMENT OF MATERIALS & SERVICES

I. IMPROVED PRODUCT LABELLING

C9 C15 D6 C11 D7 C8

☑ What do we need to do?

The very simple suggestion has been made that where it is difficult to distinguish between two products, a universal labelling system be introduced. This would be a coding system particular to product families, such as mineral wool insulation, to ensure that once the packaging is removed, site operatives are still able to identify the materials and ensure they are fitted in the correct location. Material manufacturers are already coming forward with several effective solutions.

Who needs to do what?

This would need to be coordinated by organisations such as insulation trade associations, suppliers, installers and housebuilders. It would then be for the manufacturers to develop and adopt a finished scheme.

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[1] *www.bimtaskgroup.org*

II. PRODUCT DESIGN CHANGES

C9 C15 D6 C11 D7 C8

☑ What do we need to do?

There may be other opportunities for manufacturers to make small changes to their products, resulting in a positive impact on the Performance Gap. *For example, certain housebuilders have recently requested that their window manufacturers put a ‘stop’ on the windows to make certain that they are fitted at the right point in the window reveal and minimise thermal bridging*. This would address a problem repeatedly witnessed during the ***Housebuilding Process Review***.

> *After reading the Evidence Review Report, at Barratt Developments we are working with our suppliers to pilot providing window formers fitted with a stop, ensuring that windows are correctly located to reduce the risk of thermal bridging.*
>
> –
>
> **Michael Finn, Group Design & Technical Director, Barratt Developments**

III. SPECIFICATION CHANGES

PR2 C9 C15 PR1 PR4

☑ What do we need to do?

Improvements to manufacturers’ specifications could help their materials and products to be properly fitted, focusing on how to achieve performance and providing clear information on actual performance. This could link to the previous suggestion on product labelling, with individual codes on each component or material to confirm its performance.

★ What are the challenges and opportunities?

Manufacturers would need to be incentivised, and it would need to be adopted across the industry to avoid any commercial disadvantages. It may therefore require regulation to create a level playing-field.

£ What kind of costs are involved?

There should be negligible additional cost for improving specifications; however, if regulation was needed, it could become a more time consuming and costly process, requiring a full training programme and roll out.

IV. PROCUREMENT TO FOCUS ON PERFORMANCE

C5 PR3 C7 PR4

☑ What do we need to do?

A cultural shift is needed for procurement teams to prioritise actual material performance in their list of considerations. It is important that the labour resource procured has the necessary competence and that products meet the performance specification. *For example, using an elemental approach to material procurement often leads to a risk of a Performance Gap occurring which could be overcome by adopting a 'total cost' approach*.

★ What are the challenges and opportunities?

Further research is needed to understand how this fundamental change to procurement could be achieved. The limited knowledge of procurement teams in relation to the importance of specific product performance requirements is a barrier to change, however those companies involved in the ***Housebuilding Process Review*** are already taking positive steps to resolve this issue.

CONSTRUCTION DETAILS SCHEME

C15 V2 EM8 D6 EM1 EM3

What do we need to do?

Develop a set of up-to-date construction details, as envisaged in Part L1A of Building Regulations 2006, to provide best practice details covering the major fabric junctions and systems for current standard construction types (masonry, timber and concrete frame). These need to be buildable, flexible, robust, cost effective and capable of being implemented on a significant scale. These details should be developed by people who fully understand the technical challenges around air tightness, U-values, thermal bridging and the practicalities of construction. Once submitted, performance calculations need to be independently verified for robustness and accuracy.

The details can then be listed on a publicly available database, similar to the not-for-profit DataHolz database in Austria, although the priority should be to improve industry understanding, competency and consistency. It is expected that in addition to the technical drawings, additional guidance and other material would be provided to site operatives to enable them to build the details. The scheme structure could be further enhanced through a more robust auditing process based on actual site practice and quality. Alongside this, developers and manufacturers should continue to collaborate in reviewing best practice and publishing new details, so that advances in detailing are openly available.

Uptake of this may require an increased use of IT and BIM, as well as better guidance for thermal bridging in various parts of industry to address a gap in knowledge and skills.

There is an important link to recommendations made in the section on the 'National Compliance Method and Regime' for improving U-value and Psi-value calculations, to ensure that the details are based on robust inputs. This is with regard firstly to the technical aspects of reviewing BR443 and BR497, and secondly to the more comprehensive training required for modellers.

> *Robust Details has shown how the industry can deliver cost effective and demonstrably high levels of compliance and performance for sound in Part E. We believe we can do the same for Part L given a similar framework.*
>
> –
>
> **John Tebbit, Managing Director, Robust Details Limited**

What are the challenges and opportunities?

Identified problems include: the cost of developing the system, the lack of appropriate assessment process and the lack of skills to develop and understand the details. These would need to be overcome by demonstrating an appropriate balance of risk and reward. Consideration would be needed of verification processes to demonstrate the successful build of specified details, and of processes to ensure information flow from design to build stage and vice versa. Further information on these proposals can be found in Appendix E.

Who needs to do what?

Government needs to provide pump prime funding to enable industry to develop a Construction Details Scheme. Industry needs to commit to creating an industry owned and maintained Construction Details Scheme, match funding the investment from government, to provide 'assured' as-built energy performance for the most common major fabric junctions and systems.

Some modelling has already been undertaken by various manufacturers and developers, who also have experience of the buildability of such junctions, the findings of which could be contributed to the industry scheme. Once operational, the scheme would be run by industry through a not-for-profit organisation, which would oversee its running and maintenance. This would require extensive involvement of manufacturers and other industry experts. In addition, organisations such as CITB and RIBA should be engaged in the process of improving knowledge and understanding of construction details, *for example through inclusion in site work training courses and CPD*.

QUALITY CONTROL

I. THE ROLE OF CLIENTS & DEVELOPERS

C9 C15 C14 C8

☑ What do we need to do?

The construction industry already has many quality controls in place for the design and construction phases but there is a clear need for the ‘clients’ who commission a development or construction project and housebuilders/developers to place a greater importance on controls surrounding the energy requirements. Therefore, specifications, design guides and Employers Requirements should contain certain requirements – *for example, carrying out in line tests (such as air pressure), quality control checks and/or the introduction of 'gateways'.*

> *At Lend Lease, to ensure we are achieving the high quality we expect, we already do a staged process of audits on all our builds. This approach could be used on more developments throughout the industry.*
>
> –
>
> **Richard Cook, Head of Residential, Lend Lease**

★ What are the challenges and opportunities?

Barriers to adopting this practice include the additional time required of designers and site personnel to carry out these checks. If it were considered necessary, penalties (e.g. in SAP or by employers) could be introduced for failure to perform proper checks, though it should be noted that this approach did not receive consensus. It may be preferable to instead encourage best practice, *for example by identifying and rewarding individuals for good practice, perhaps in a similar format to NHBC Pride in the Job and LABC Excellence Awards*. This links to certain ‘Energy Literacy’ concepts, particularly around on-going training of designers and site personnel.

II. INCREASED ENERGY FOCUS FOR VERIFICATION AND QUALITY CONTROL

C9 C15 C14 C8

☑ What do we need to do?

There is a need for an increased focus on energy-related checks and assessments across all areas of building delivery including at the design stage and on site. This could be carried out either on all dwellings or on a proportionate basis. Reference should also be made to the 'Demonstrating Performance' section.

What are the challenges and opportunities?

There are various issues to be considered including who would carry out these energy performance related checks and assessments, how this would fit with existing responsibilities, and how to avoid conflicts of interest. Additional site visits would increase the time, resource and cost involved in the build process, particularly as multiple visits would probably be required, *for example in order to be able to see insulation when it has just been installed, particularly for smaller sites.* Additional costs would be involved in upskilling and good guidance would also be required (see 'Energy Literacy' section). However, the process could help to increase and share knowledge across industry and provide a quick win. It could also help to pick up on general quality issues, as well as improving the accuracy of the As-Built SAP calculation by highlighting where changes have taken place compared to the design.

Who needs to do what?

Industry and government need to further develop and appraise options for energy-performance focused site checks. There may be ways of including more rigorous energy performance checks as an element of Building Control assessments and inspections. Housebuilders and construction companies need to decide if their current business model fully addresses the management of energy performance.

What kind of costs are involved?

The costs are likely to be low after the initial investment of ‘change’.

III. THE ROLE OF COMMISSIONING

C9 V2

What do we need to do?

Commissioning is a vital process to ensure that the building's systems are fully functional at construction completion. In particular the commissioning of services, whilst already established, needs to be made more structured and delivery assured. It is also important that buildings are commissioned as a whole.

What are the challenges and opportunities?

Tick sheets are often an ineffective way of ensuring commissioning has been completed properly, if indeed at all, therefore other means need to be developed that are effective. There may be opportunities to link an enhanced commissioning process with information provided to the building occupant, *for example utilising the BSRIA Soft Landings approach*.

BSRIA work with the Construction Industry to ‘make buildings better’ by the provision of authoritative guidance on improving the performance of the building and its services. Soft Landings provides a process and a set of principles for the successful delivery of an operationally ready building. BSRIA looks forward to working with the house building industry to ensure all homes achieve a Soft Landing.

–

Ian Orme, Business Manager, Sustainable Construction Group, BSRIA

Who needs to do what?

Designers and suppliers need to ensure they provide full commissioning data; manufacturers need to supply appropriate commissioning approval protocols for complex systems, such as communal heating; and generally a more holistic approach needs to be taken to the commissioning process by all professions. It is strongly recommended that commissioners should be independent from the sub-contractors whose work they are commissioning.

What kind of costs are involved?

Extra cost should be off-set through the reduced scope of the sub-contractors works. However, some additional cost will be incurred initially whilst systems and procedures are put in place.

LEARNING & FEEDBACK LOOPS

D1 P2 V2

What do we need to do?

Feedback is needed right across the housebuilding industry throughout the supply chain to ensure the necessary learning. This could be aided by processes such as the RIBA Plan of Work 2013 Stage 7, which specifically schedules a feedback process. An increased role for developers and others in undertaking energy-performance related site checks should also help with feedback and communication. Feedback to government is also required to ensure that the '2020 ambition' is being met.

What are the challenges and opportunities?

The challenge is to ensure that feedback takes place at an appropriate time and level. Clear methodologies need to be developed to make sure this takes place. The opportunities are extensive as improved feedback loops would allow the processes linked to energy to also cross-fertilise other areas, strengthening the construction sector's resilience and the quality of the products produced.

Who needs to do what?

Businesses will need to change their processes by implanting new procedures and strengthening current ones. Building Control should also take the opportunity to review and improve their feedback processes.

NATIONAL COMPLIANCE METHOD & REGIME

The *Evidence Review Report* identified various issues relating to the current national compliance method and regime which contribute to the Performance Gap. Many of these related to the Standard Assessment Procedure (SAP), the methodology and tool which is used to check compliance with Building Regulations Part L1A, and the processes surrounding it. In particular, the evidence review found that As-Built SAP assessments are often not reflective of the actual built dwelling; that there are issues around the use of U-value and thermal bridging calculation procedures; and that verification procedures are not sufficiently robust when it comes to energy performance.

There is a need for **refinements to the existing SAP process** in the short term to help ensure that SAP assessments are accurate and that the inputs are easier for developers, Building Control and others to check. The adoption of a Product Specific Plain Language Compliance Report signed by the housebuilder is strongly recommended to help in this regard. **Improvements to the governance of SAP assessor accreditation schemes and assessors** are also recommended, to help clarify the responsibilities of those involved in the assessment process - including developers, assessors and Building Control Bodies as well as the governance bodies aiming to ensure high quality, consistent assessments, such as the SAP Conventions Group and those involved in accreditation scheme moderation.

Changes to U-value and thermal bridging calculation procedures are needed, including introducing new modeller competency requirements and changes to improve robustness and better reflect in-situ performance. More generally, a systematic **review and update of the SAP methodology and assumptions** has been suggested, particularly focusing on those areas which potentially have significant impacts on the Performance Gap. This review is likely to be informed by the testing proposals outlined in the 'Demonstrating Performance' section of this report which could potentially allow verification of the accuracy of SAP or of particular assumptions and inputs. It is recommended to include changes to **better reflect system-level performance**, as opposed to individual product performance, and amendments to how default input values are used. To deliver these changes, **further research and consultation may be required**, in particular to develop the evidence base for medium-term changes to the SAP methodology and to consider the potential implications for the regulatory regime. **Changes to software** are also proposed to improve data capture and validation and to provide approved U-value calculation software.

Some of these proposals will require changes to SAP and the management around it, and others may require changes to Building Regulations. As government has responsibility for both, it will need to be involved in all of these activities, including various teams across DECC and DCLG. **Government will need to take action by 2016 to ensure that the recommended revisions to energy modelling practices, SAP processes and verification procedures, together with a strong regime to ensure that only suitably qualified persons carry out energy modelling, can be put in place**. Stakeholders from across industry will also need to be strongly involved.

REFINE THE SAP PROCESS: IMPROVED COMPLIANCE REPORTING

EM4 V5 EM1 EM5

☑ What do we need to do?

A standardised, more comprehensive, Product Specific Plain Language Compliance Report is proposed to help ensure that the Design Stage and As-Built SAPs are accurate and that the inputs are easier for developers, Building Control Bodies (BCBs) and others to check. This should provide a comprehensive summary of the product-specific fabric and services specifications that have been inputted to SAP assessments. The compliance report should include appendices with U-value calculation data sheets, certificates or statements, and details of other calculations such as thermal mass.

Who needs to do what?

At the design stage, the Product Specific Plain Language Compliance Report would be signed by the housebuilder to declare its accuracy and would then be provided to BCBs as part of the controlled documents to use for checks during construction. At the As-Built SAP stage, the SAP assessor would confirm back to the developer all individual items that had changed since the Design Stage assessment. The updated Product Specific Plain Language Compliance Report would then be signed by the housebuilder and provided to the SAP assessor and to BCBs, as well as to occupants via lodgement on the EPC register to reinforce the importance of accuracy. BCBs must not be allowed to issue completion certificates before the signed compliance report had been lodged and received by them along with the EPC generated in full SAP. SAP assessors must also not be allowed to issue EPCs without it and should face disciplinary procedures if they did so.

Government would need to change the requirements in Building Regulations Part L and in SAP documentation and would need to instruct the SAP assessor accreditation organisations and software providers. Regulatory powers should be reviewed to ensure that BCBs have the power to require the information. SAP assessors, assessor accreditation organisations and BCBs will need to be aware of the changes and update their processes. As part of their audit processes, SAP assessor accreditation organisations should include sample checks that valid developer signed declarations have been provided.

It is believed that this recommendation should be acted on in the short-term. Note also that it links to the 'Improved Quality' theme suggestion of increased focus on energy-performance related checks on site, which might be undertaken by SAP assessors, BCBs or others.

> *If we are to address any performance shortfall then it is critical that the SAP Assessment tool and the SAP verification process is both robust & auditable. Those undertaking U-value & Psi-value calculations need to be subject to improved training & rigorous accreditation to ensure accuracy & consistency of those details. We strongly endorse the Report's recommendations in this regard and for the development of robust Construction Details to underpin such improvements in performance.*
>
> –
>
> **Michael Black, Group Development Director, Bovis Homes Ltd**

GOVERNANCE OF SAP ASSESSOR ACCREDITATION SCHEMES AND SAP ASSESSORS

I. DEFINITION OF SAP ASSESSOR RESPONSIBILITIES

EM7 EM1

There needs to be a clear definition of SAP assessor responsibilities set out and publicised by government in SAP documentation, along with a summary of the responsibilities of housebuilders and BCBs, so that assessors understand what they are and are not responsible for.

II. DEFINITION OF SAP CONVENTIONS GROUP RESPONSIBILITIES

EM3

The SAP Conventions Group has a key role in bringing consistency to the decisions made by SAP assessors. The Group's Terms of Reference need to be updated and the membership expanded to ensure an appropriate focus on energy performance.

III. CROSS-SCHEME MODERATION AND SCHEME AUDITS

EM7 EM6

Government moderation of the SAP assessor accreditation schemes needs to be tightened, ensuring different schemes apply SAP consistently. Government audits of the accreditation schemes need to be improved to have a strong technical standards focus - ensuring schemes are adhering to their operating requirements, are consistently applying the SAP conventions, have consistent CPD requirements, and are auditing their assessors properly.

IMPROVE U-VALUE AND PSI-VALUE CALCULATIONS

I. IMPROVED TRAINING AND QUALITY ASSURANCE FOR U-VALUE MODELLERS

EM8 EM1

☑ What do we need to do?

Improved training for those undertaking U-value calculations is required to drive up standards. Current training is usually limited to a short module in the SAP assessor (DOCEA) qualification. Some form of competency scheme could also help to drive up quality. Whilst BBA already provides such a scheme, clear incentives or requirements are needed to motivate modellers to undertake additional training or join a scheme.

Training needs to be made more rigorous and should aim to provide a strong understanding of building physics, good construction practice and likely Performance Gap issues. Ongoing CPD requirements should be set, and regular audits of the calculations should be undertaken, with ongoing support for modellers. Guidance on ensuring calculations are robust will need to be agreed (see the ‘Review of calculation procedures’ recommendation below).

Who needs to do what?

The U-value training could continue to be provided as part of the SAP assessor qualification, but could also be delivered separately as it will need to be available to those who are not SAP assessors. Government needs to support the implementation of the recommendation to only allow assessors to accept calculations from appropriately qualified modellers, which is likely to require changes to Part L and SAP.

When do we need to do it?

Improved training is required in the short term and government needs to amend regulations around the competency of U-value modellers at the next Building Regulations Part L review.

II. IMPROVED TRAINING AND QUALITY ASSURANCE FOR PSI-VALUE MODELLERS

EM8 EM1

What do we need to do?

A qualification or scheme for Psi-value modellers is needed to address the current variability between results and to drive up standards. Current training courses are generally fairly limited and often only provide teaching in how to use modelling tools and do not sufficiently cover the building physics behind the calculations, good construction practice, and likely Performance Gap issues.

A Psi-value competency/accreditation scheme is strongly recommended to provide ongoing quality assurance of calculations, ensure consistent and effective CPD, and to provide a forum for modellers and a vehicle for agreeing guidance on ensuring calculations are robust. A similar approach to the BFRC scheme for windows could be used, balancing technical rigour with cost.

There is a vital link between the requirements on improved competency of those undertaking U-value and Psi-value calculations and the recommendation to develop a set of robust Construction Details in order for such a scheme to be successful (see the ‘Improving Quality Outputs’ section of this report).

Who needs to do what?

Training might be added to the SAP assessor qualification, but it is likely that a separate qualification will be needed due to the extent and complexity of training required. Therefore a competency scheme provider needs to be identified and funding may be needed to help with up-front development costs. Government needs to support the implementation of the recommendation to only allow SAP assessors to accept calculations from appropriately qualified modellers, which is likely to require changes to Part L and SAP.

When do we need to do it?

Improved training and scheme setup is required in the short term and government needs to amend regulations around the competency of Psi-value modellers at the next Building Regulations Part L review.

> *BBA already provides a U-value competency scheme aiming to raise standards in this important area, but clear incentives are needed for modellers to join such schemes. We are also exploring providing a similar scheme for Psi-value modellers, and would be able to set this up fairly quickly should funding be provided to get the project underway.*
>
> –
>
> **Fanoula Ziouzia, BBA**

III. REVIEW OF CALCULATION PROCEDURES & THEIR OWNERSHIP

What do we need to do?

It is recommended that BR443 and BR497, the documents setting out the conventions that govern U-value and Psi-value calculations, should be reviewed through a formal process. This should be either by implementing a formal standard or through full Building Regulations consultation, to reflect the fact that any change to the treatment of different products can have significant impacts. The review should consider how the calculations could be changed to better reflect in-situ performance at scale, as well as 'systems-level' performance based on entire elements, such as a wall. This would be informed by in-situ testing, though some changes surrounding in-situ system level performance may be best made in SAP itself.

It is also felt that the calculation procedures should have a wider ownership than at present; *for example government with industry input (such as through the use of an advisory group like the Building Regulations Advisory Committee*) or another body that represents all of industry.

These recommendations are also strongly linked to the proposal to develop robust Construction Details (see section on 'Improving Quality Output') because it is these recognised calculation procedures which the scheme would need to use. There is also a link to proposals to develop testing methods, which are outlined in the 'Demonstrating Performance' section.

Appendix A to the ***Interim Progress Report*** of this project contains a summary of recommended changes to BR443 in aid of closing the Performance Gap.

What are the challenges and opportunities?

Challenges include the costs of developing BR443 and BR497 or transferring their ownership; the need for evidence to support calculations of real system performance; and the commercially sensitive nature of changes. However, there appear to be significant potential benefits to the Performance Gap from improving U-value and Psi-value calculations by ensuring that calculated figures are more closely aligned with in-situ performance.

Who needs to do what?

Government needs to support an industry-led review of the standards for calculating U-values, and the conventions for using those standards, with a view to updating the requirements of the approved document for Part L. It is understood that BRE are currently reviewing BR497, but wider industry involvement is required. Manufacturers and testing and research experts will need to be involved to input into changes which affect product performance assumptions, to ensure changes are equitable and to evolve products as needed. U-value and Psi-value modellers will need to keep up-to-date with any changes made. As the data may not be available at present to provide the evidence required to change calculations to better reflect in-situ performance, there is a need for more research into in-situ U-values and Psi-values and how to measure these (see also the 'Demonstrating Performance' section). Research processes should be formalised so that outputs are comparable, generating robust information to improve the reliability of calculations.

When do we need to do it?

It is important that these recommendations are acted on in the short term.

IV. APPROVED U-VALUE CALCULATION SOFTWARE

EM8

An approval process needs to be established for all U-value software to ensure consistency and quality.

REVIEW OF SAP METHODOLOGY AND ASSUMPTIONS

EM2 EM3

What do we need to do?

A systematic review and update of the SAP methodology and assumptions is recommended, particularly focusing on an analysis of those which potentially have significant impacts on the Performance Gap.

The review should include changes to SAP to better reflect system-level performance and interactions (e.g. performance of a completed wall or entire heating system), as opposed to individual product performance, and potentially reflecting this in SAP's Product Characteristics Database to also help provide designers and specifiers the information they need to make more informed choices. The introduction of confidence (or in-situ) factors should be considered more widely in SAP. If implemented, a robust, equitable process would be needed for determining and updating the factors which have the confidence of developers, manufacturers and the wider industry and would allow competing manufacturers to innovate and demonstrate the as-built performance of their systems. The need for the use of confidence factors will depend to a large degree on the scope and ability to make appropriate amendments to U-value and Psi-value calculation procedures described above.

The review should also include amendments to how default values are used, making these worst case to encourage the use of product/system-specific information. The SAP Conventions should be changed to require defaults to be used when no documentary evidence is provided.

The review is likely to be informed by the testing proposals outlined in the 'Demonstrating Performance' section of this report, which could potentially allow verification of the accuracy of SAP or of particular SAP assumptions and calculation procedures.

Who needs to do what?

Government will need to be involved as the owners of SAP and BRE will need to be involved as the current government contractor delivering SAP. Industry and research experts will need to be engaged in and consulted on changes, as well as providing evidence to support the review, and ensuring that changes which affect product performance assumptions are fair.

When do we need to do it?

These recommendations need to be acted upon immediately such that any proposed changes to SAP methodology can be consulted upon at the next available opportunity and implemented as soon as possible.

CHANGES TO SAP SOFTWARE

Changes are required to SAP software in the short term to improve the quality of SAP assessments:

I. DATA VALIDATION

EM7

Government and software providers should ensure that all SAP software has a standard minimum level of data validation on inputs into the software to identify any inconsistent data and improve the quality of SAP assessments. *For example, increased validation could pick up errors such as incompatible components*.

II. SPECIFICATIONS MORE CLOSELY LINKED TO DATA INPUTS

EM4 EM1 EM5

Software providers need to make provision for including information to go into the Product Specific Plain Language Compliance Report, and for the production of the report itself. This would help deliver the requirements set out in ADL1a 2013 Appendix C Section 4 which states that 'an important part of demonstrating compliance is to make a clear connection between the product specifications and the data inputs required by the compliance software'. Government needs to ensure these changes happen.

III. DOCUMENT MANAGEMENT

EM4 EM1 EM5

It is recommended that all compliance documents, including the proposed new signed Product Specific Plain Language Compliance Report, should be made accessible through an online document management and storage system which enables document transfers between clients and SAP assessors and is accessible by occupants.

IV. SOFTWARE INTERFACES

EM4 EM7

Various suggestions have been made for improving the usability of SAP software, *for example some supported the creation of a 'SAP app' to allow the impact of specification changes to be tested by developer teams, and some wanted SAP software to be able to interface with other software such as 3D modelling packages to improve its accuracy*. Software manufacturers should work with user groups to explore these possibilities.

Further detail on all these recommendations, including an illustrative example Product Specific Plain Language Compliance Report, can be found in Appendix C.

DEMONSTRATING PERFORMANCE

Some of the issues that contribute to the Performance Gap are obvious and actions can be taken to address these immediately. Other issues are more complex or may not yet be apparent. The full significance of the various issues, and the Performance Gap as a whole, requires further investigation. However, the existing techniques to measure and assess as-built performance are not fully developed and tend to be expensive, and in-situ tests are often disruptive of the build process.

Therefore **in order to close the Performance Gap it is critical that real performance can be assessed, measured, tested and demonstrated.** This information is vital to inform robust designs; products and systems that deliver 'what they say on the tin'; accurate construction; and good commissioning. Without the ability to measure and assess energy performance, sufficient action to address the Performance Gap and sustain that improvement is unlikely to happen.

Diagnostic tests are needed to investigate why a finished home, system or element does not meet the design intent. **Existing diagnostic tests need to be more useful, useable and consistent,** through standardising the application of tests and the interpretation of results. In addition, research organisations and commercial groups need to **develop new and emerging diagnostic test methods for both services and fabric, particularly at system level** and to improve industry's ability to assess in-situ performance.

It is vitally important that an approach be developed to demonstrate the '2020 Ambition', to enable industry as a whole to firstly ascertain the baseline position and then be able to show progress towards closing the Performance Gap. Good process control and quality assurance checks can also provide some of the feedback required but some form of testing is needed to demonstrate whether these measures are working effectively. Approaches used to demonstrate as-built performance would help to provide feedback on the capability of the housebuilding process (design, product and systems manufacture, construction, commissioning and verification) to produce homes that perform. If the results are worse than expected, questions can be asked as to what may be going wrong with the process.[1]

Government needs to signal their long term intent to support the industry in providing the information necessary to quantify the Performance Gap and create the learning loops required to drive continuous improvement, by funding research and development into testing, measurement and assessment techniques with immediate effect.

Industry needs to commit to undertaking the research and development necessary to create innovative testing, measurement and assessment techniques to understand the Performance Gap and develop commercially viable methodologies acceptable across industry for 'demonstrating performance'.

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[1] *It is important to note that for an individual building, this type of as-built performance analysis would not form part of Building Regulations 'compliance' checks.*

FURTHER DEVELOPMENT OF DIAGNOSTIC TESTS

T3 T1 T2 T6 T5 EM9 T7

☑ What do we need to do?

Diagnostic tests are needed by industry to understand why a finished house, system or element might not be achieving the designed performance. These are particularly beneficial for housebuilders wanting to investigate where problems may be occurring and feed back to manufacturers, suppliers and contractors when problems are indicated; and for manufacturers wanting to analyse the in-situ performance of their products and systems.

The ***Evidence Review Report*** and feedback from industry during this project has identified a lack of consistency in the application of existing diagnostic tests and interpretation of results, as well as limitations to the fabric and services tests currently available. To address this, it is suggested that protocols of existing tests be refined and standardised to be more useful, useable and consistent in assessing the energy and carbon performance of homes. New and emerging test methods also need to be developed by research organisations and commercial groups, for both services and fabric, both in the laboratory and in-situ. A better understanding is needed of inconsistencies in results and the impact that building methods and different combinations of products have on test results. To help with this, data informing and arising from tests should be made available at a suitable scale for analysis.

Fabric tests cover a range of techniques to evaluate the thermal performance of the building fabric. Existing assessment methods, such as thermography, heat flux testing and elemental laboratory tests, need refining and standardisation of protocols to improve consistency and robustness of results is urgently needed. The air pressure test is well established, but some refinements are needed to make it more robust and consistent, and it could also be used more commonly as a diagnostic tool in combination with other test methods such as smoke tests and thermography. Other less well developed fabric tests need to be progressed: *for example, improved in-situ testing (e.g. using environmental chambers) would help industry to understand site specific impacts on the performance of products and systems, perhaps supplemented with better testing and recording of the impact of site tolerances and practices in laboratory conditions, and the ability to test whole system U-values and thermal bridging.* These tests could help reduce the risk of an associated Performance Gap occurring.

The majority of currently available tests on building services are laboratory based, and focus on individual components rather than the entire system. In-situ tests need to be developed, as do system-level services tests, both laboratory and in-situ, and more systems-level field trials need to be undertaken. For installed services, simple checks and tests and better commissioning guidance could make a significant impact. This would require a collaborative effort from stakeholders including suppliers,

> *Willmott Dixon has been evaluating the performance of the zero carbon housing development Greenways Drive, working in collaboration with our client Catalyst Housing. We undertook a detailed energy specific design review, regular site visits by energy performance specialists, and various forms of testing on a sample of dwellings together with on-going in-use monitoring. This understanding is feeding into future design choices and influencing construction practices to help narrow the Performance Gap.*
>
> –
>
> **David Adams, Technical Director, Willmott Dixon**

> *National compliance methods need to be adjusted if we are to address the performance gap in the UK. Appropriate measurement is vital in determining performance and requires further research. We need to move our thinking away from simply assessing efficiencies of individual components and towards system performance; we should be looking at in-situ measurements next to lab-based measurements – but how will these new tests work? More practical research into this is needed and government support is crucial.*
>
> –
>
> **Marieke Beckmann, Research Lead, National Physical Laboratory Centre for Carbon Measurement**

manufacturers and commissioning experts. Commissioning requirements may also need to change to include better checks on the performance of the system as a whole.

An analysis of the strengths and weaknesses of current test and assessment methods has been carried out and details can be found in Appendix D.

Whole house or whole system tests are unable to pinpoint exactly where a problem is occurring, but can provide an indication that something is wrong and of the broad area(s) where further investigation is needed. They may therefore have a place alongside the use of diagnostic tests described above.

Process control and testing skills and practices within the industry need to be improved through additional training, and quality assured through accreditation. This recommendation is discussed in more detail in the section on 'Energy Literacy'.

What are the challenges and opportunities?

The development of specific tests comes with specific challenges. These might be technical, *for example complications of testing apartments rather than individual houses, or limits to the times of year at which tests can be undertaken; or strategic, for example, attributing fault when testing a combined services system*. There may also be resistance from certain parts of industry to introducing new tests or changing existing test methods and protocols.

Broadly speaking, industry needs a range of approaches to diagnostic testing to provide effective options for understanding performance. These need to be able to be consistently carried out at scale and available for a reasonable cost. This will require significant investment in research and development. Supply chain issues need to be addressed, including the limited availability of testers and testing equipment, such as environmental chambers and hot boxes. If mechanisms are put in place to motivate industry to address the Performance Gap on a mass scale, then it could be expected that the supply chain would respond.

> *Knauf recognise that there is a competitive advantage of being able to guarantee the robustness of our product performance in use. Our challenge is to make enough commercial benefit to reward early innovators so that the sceptics do not win out.*
> *We are at the limits of our current testing capabilities, which is a challenge for the entire supply chain.*
>
> –
>
> **John Sinfield, Managing Director – Northern Europe, Knauf Insulation**

Who needs to do what?

Testing experts and research organisations will need to be involved in developing existing and new tests and assessment methods, working with developers to ensure commercial viability. Academia, manufacturers and industry bodies will need to be involved. Funding will be required from a range of sources including Government, developers, manufacturers, and research programmes such as Horizon 2020 and those run by EPSRC and TSB. As new and existing tests are developed, there may be potential implications for the national compliance method and regime which need to be considered by government and industry.

When do we need to do it?

It is crucial that tests are developed in the short term, to enable industry to better understand the extent and magnitude of where Performance Gap issues are occurring, such that the necessary action can then be taken. Real progress needs to take place prior to 2017.

DEVELOPING APPROACHES TO DEMONSTRATING PERFORMANCE

ALL ISSUES

Understanding real performance of completed homes provides the impetus for continuous improvement. It drives designers to ask searching questions beyond the standard system and product performance data sheets, as well as to consider specifying systems that are more robust to install. Product and system manufacturers are motivated to test their products in real life (not just under EU standard laboratory conditions) because otherwise their products may not be selected. Construction teams are driven to follow the correct installation processes and to pay attention to detail, because eventual performance will be demonstrated in some form.

While the market currently delivers products that comply with regulations, there is an increasing awareness of the need to deliver based on performance, with competitive pressures brought to bear on delivering this real performance (of products, systems and buildings) at the lowest cost. This will provide occupants with a home that performs and housebuilders with the confidence to actively market their homes as low energy.

CLOSING THE PERFORMANCE GAP: THE 2020 AMBITION

From 2020, to be able to demonstrate that at least 90% of all new homes meet or perform better than the designed energy / carbon performance.

☑ What do we need to do?

We need to be able to measure as-built performance at an industry level in order to determine the size of the Performance Gap, understand the effectiveness of solutions, and demonstrate progress in achieving the '2020 Ambition'. At present, on an industry-wide level, the size of the Performance Gap is unknown and the existing techniques to measure as-built performance are not fully developed and tend to be expensive and disruptive of the build process. Currently the only as-built test routinely undertaken is the air pressure test, and there is currently a lack of a suitable 'in-line' or 'end-of-line' test which covers fabric and services energy performance (in contrast to the test that can be undertaken to demonstrate acoustic performance, *for example*).

Furthermore, whilst the ***Evidence Review Report*** identified a significant range of issues causing the Performance Gap, these are only the known issues; there are likely to also be unknown issues that may be significant. At both an individual housebuilder level and at an industry level as-built performance feedback is needed to determine where further effort is required and where performance is good.

Approaches discussed as part of this project that could be used to demonstrate the '2020 Ambition' include:

- Extrapolating data from type testing and process control;
- Sample construction completion assessments;
- Deriving as-built performance from smart meter gathered metadata; and
- Deriving as-built performance from statistically significant sample in-use measurement.

Type testing and process control involves undertaking detailed diagnostic tests on a particular dwelling type (i.e. a house with a particular combination of fabric and services systems), and using this to inform design changes and process control measures for other dwellings of the same type, with quality control processes put in place to ensure that improvements are maintained. ‘Process drift’ can occur so there is likely to still be a need for some ongoing testing. Data could be extrapolated from this process and collated to provide an industry-wide measure of the Performance Gap.

Sample construction completion assessments may include in-line / end-of-line performance tests which could be used to directly demonstrate the Performance Gap. Looking at populations of whole house or whole systems tests can identify patterns of better or worse performing combinations, *for example correlations based on particular systems or build techniques may become apparent*. Whilst at a certain level this statistical data is useful for developers, it is also likely to be of interest to suppliers, designers, researchers and government.

Deriving indications of as-built performance from smart meter metadata gives less detailed data and so is less useful for identifying causes of a Performance Gap (and hence less useful for individual developers). However, it could be useful at a larger scale to demonstrate the '2020 Ambition'. Sample in-use monitoring provides a step between construction completion assessments and smart metering metadata, as more specific data can be measured at an individual dwelling level making it easier to derive 'normalised' building performance information.

More research is required to develop each of the approaches, including development of suitable construction completion assessment techniques, and ways of ‘normalising’ in-use monitoring data or smart meter metadata gathered at scale to enable the impact of individual occupant behaviour to be removed from the data.

> *We are concerned that proposed pre- occupation testing might have unintended consequences, for example as a Registered Provider and Developer , if we are developing for sale on public land we may find that consent to sell may be withheld if acceptable results data is not provided.*
>
> –
>
> **Hazel Warwick, Asset Management Director and Deputy Chief Executive, First Wessex**

> *At Kingerlee Homes, we market our homes for sale based on real energy performance, rather than just designed values, as evidenced by our preparedness to monitor the performance of our completed and occupied new homes. In use monitoring should be supported by industry as the essential means of understanding the performance of the completed new home, for the designer, the builder and the occupant alike.*
>
> –
>
> **Tony Woodward, Managing Director, Kingerlee Homes**

Who needs to do what?

Work will be needed to gain cross-industry agreement on the suite of testing, measuring and assessment protocols considered acceptable to demonstrate performance, resulting in proven methodologies that are robust and commercially viable at scale. Government needs to signal their intent to support the industry in doing this.

What are the challenges and opportunities?

The approaches outlined above, to varying levels of granularity, can be used to show how well a population of homes ‘perform’. The different approaches have different levels of cost, levels of time required, delay to the handover process, associated data privacy issues, and further research requirements. The strengths and weaknesses of the different approaches are explored in more detail in Appendix F.

When do we need to do it?

It is crucial that approaches to demonstrating performance are agreed in the short term, to enable industry as a whole to firstly ascertain the baseline position and then be able to show progress towards closing the Performance Gap. Industry agreement on the suite of testing, measurement and assessment protocols considered acceptable to demonstrate performance is required prior 2017.

CONTINUED EVIDENCE GATHERING & DISSEMINATION

The *Evidence Review Report* published in March presented the results of the evidence gathering process undertaken in the first phase of the current project which aimed to understand issues that contribute to creating the Performance Gap. It identified 15 'Priority for Action' issues, 17 'Priority for Research' issues and 23 'Retain a Watching Brief' issues, all of which to varying degrees will require further evidence to be collected.

Whilst a number of the 'Priority for action' issues have been quantified it is, at this time, difficult to assess the size of the impact they will individually have on the Performance Gap. Therefore a **coordinated programme of ongoing work to collect and evaluate more evidence** is now required. This will provide data to fully understand the scale and nature of the issues' impact on the Performance Gap, in particular focusing on the less well evidenced 'Priority for Research' and 'Retain a Watching Brief' issues. This programme will need to take place in the short term to ensure that industry and government are aware of and understand the different issues which need to be tackled.

Improved communication of the findings of existing and ongoing evidence gathering will also be vital to ensure that the housebuilding industry learns from and responds to these. A regularly updated online resource is proposed, to bring together a range of evidence sources, allowing the issues identified as part of the current project to be monitored. This resource could also be further developed to communicate potential solutions to the various issues. Alongside this, it is proposed that regular symposiums and events be held to disseminate the evidence gathered by the current project, particularly from the *Housebuilding Process Review*. It is recognised that these should be in the context of the journey to Zero Carbon Homes and specifically the importance of addressing the Performance Gap in the context of 'Carbon Compliance'.

This programme of evidence gathering will need to involve stakeholders from all parts of the industry, including academics and researchers, developers, manufacturers and other participants, as well as government. Funding will be needed from both national and international governments and from other organisations, and some potential sources have already been identified.

The Zero Carbon Hub has been collecting further evidence from a variety of sources since the *Evidence Review Report* was published in March 2014, which has reinforced the findings contained therein. A summary of findings is provided in Appendix B.

EVIDENCE GATHERING PROGRAMME

What do we need to do?

Current evidence gathering processes need to be developed and continued, and coordination needs to be improved. An evidence 'mapping' process is proposed which would help to understand what research is currently existing, ongoing and planned. Building on this, the development of a route map to forward-plan research is recommended.

This research should include the further implementation of the current project's ***Housebuilding Process Review*** as a formalised method, rolled out to a broader range of housebuilders, and reporting on a regular (bi-annual) basis. Although this would aim to better evidence some of the Performance Gap issues, it should also specifically aim to provide feed-back to developers, industry and government to help develop and implement ways of continually improving housebuilding and reducing the Performance Gap. It is intended that different versions of the ***Housebuilding Process Review*** be developed by the Zero Carbon Hub, tailored separately for particular audiences, *for example Registered Providers commissioning new developments; Building Control officers inspecting sites; and speculative housebuilders seeking to embed best practice within their design and procurement teams*.

The programme should also include regular reviews of newly available literature and collate and analyse research external to that presented in the ***Evidence Review Report***. This will draw on other streams of the continued evidence gathering programme: *for example new desk studies, field trials, manufacturer research and site visit / assessment projects*. It will also include other evidence gathering tools used as part of the current project, such as surveys of practitioners and SAP audits to gather evidence on, and gauge the state of practice in, different parts of the industry.

This evidence gathering should help to determine the scale and potential impact of the 'Priority for Research' and 'Retain a Watching Brief' issues, common underlying causes of these issues, and potentially also other issues that have not previously been identified. The evidence gathering process is likely to be informed by developments in testing, measurement and assessment methods which are discussed separately in the 'Demonstrating Performance' section of this report.

It is also important that more evidence is gathered to further strengthen our understanding of the 'Priority for Action' issues; however it is suggested that the primary focus for these should be on developing solutions and on the research to inform these.

The Housebulding Process Review and site walk throughs carried out for this project have helped inform NHBC's vision of how verification might work in the future and have provided valuable input to further research being carried out into the causation of defects in new homes.

–

Mark Jones, Head of House-Building Standards, NHBC

Suggestions for this research are presented in the other themed sections of this report, and include:

–

research to support the development of testing, measurement and assessment techniques to demonstrate the 2020 ambition

–

to develop protocols, methods and measurement techniques to ensure that evaluation takes place in a consistent manner

–

to address the need for a business case for tackling the Performance Gap to be made for different housebuilding models

–

to test solutions

–

and to embed learning from research and development into training and up-skilling industry to enable the Performance Gap to be tackled.

What are the challenges and opportunities?

Evidence gathering needs to be better coordinated and planned across the industry. The proposals outlined below on improving dissemination of evidence would help better understand where research is most needed and what research has already been undertaken.

When do we need to do it?

Evidence needs to be gathered in the short term to support the identification of issues and development of solutions, but also continuing to 2020 and beyond.

£ What kind of costs are involved?

The scale of the costs will depend on the extent of the research programmes. EU funding streams such as Horizon 2020 may be used (Horizon 2020 has a specific call for projects developing methodologies and tools to reduce the Performance Gap and to monitor and assess actual building energy performance), along with industry funding, Technology Strategy Board and government funding. However individual companies and those Institutes and Associations representing the different sectors of the industry will also need to step up to the challenge and invest in energy performance research themselves.

COMMUNICATION OF EVIDENCE FINDINGS

ALL ISSUES

What do we need to do?

It is recognised that the biggest challenge to reducing the Performance Gap will be informing large sections of the industry, firstly that it exists and secondly that it is part of the Zero Carbon policy and must be addressed by 2020. It is therefore intended to hold a major campaign of dissemination with a series of seminars and events targeted at manufacturers, consultants, developers and local government together with Building Control to raise the profile of the Performance Gap.

> *This work has proven to be really valuable and should benefit both the industry and homebuyers. The engagement process delivered a raft of suggestions, directly from the industry, for reducing the Performance Gap. Importantly it also identified some very achievable savings can be achieved now by looking at procurement and site practice. These savings are very cost effective and will help reduce the cost of owning a new home.*
>
> –
>
> **Adam Mactavish.**
> **Operations Director,**
> **Sweett Group**

It has been identified that research is not always well communicated and so improved dissemination of evidence findings is required. The development of an online resource or 'knowledge hub' is proposed. This will directly help those involved in the housebuilding industry to understand and address key issues contributing to the Performance Gap. It would perform two key functions: firstly, pooling and communicating findings from the growing body of Performance Gap research and helping to review the less well-evidenced issues; and secondly, providing practical resources to help industry address the Performance Gap, including a portfolio of good practice, exemplar projects and solutions. It would include a full update of the evidence gathered by Zero Carbon Hub since the publication of the ***Evidence Review Report*** (a summary of which is included in Appendix B).

More widely, improved dissemination is also needed through various channels such as knowledge transfer networks, seminars and publications. The Zero Carbon Hub will be holding a symposium later in 2014 to communicate the detailed findings from the evidence gathering that has been ongoing since the publication of the ***Evidence Review Report***. Other organisations are already developing dissemination strategies for their research in this area, *for example the results of the TSB Building Performance Evaluation programme.*

What are the challenges and opportunities?

There is now a massive opportunity to provide more consistent and targeted messages to industry, which can help to inform solutions to address the Performance Gap and also contribute to improving knowledge across the industry. However, ongoing management and communication of data will be a significant task. There will be a need to ensure that data is held securely and consistently, making it available to future research projects.

Often research is kept secret due to confidentiality and efforts need to be made to encourage appropriate sharing of anonymised data, *for example through review and dissemination by a trusted body (the role performed by the Zero Carbon Hub in the current project*). Cross-industry groups and organisations can help to improve coordination.

Various presentational formats and styles are likely to be required for the communication of evidence as the information will need to be targeted at a range of audiences, including housebuilders, Design and Build clients, architects and design teams, SAP assessors, energy consultants, site managers and operatives, Building Control Bodies, researchers and policymakers. It is recognised that this is a major task and will require 'continuous' effort for all sectors of the industry including those institutes, associations and training bodies whose members will need to be upskilled (*for example CPA, HBF, FMB, RICS, RIBA, CITB, Summit Skills and Asset Skills*). The success will be down to the commitment of these organisations in meeting this challenge.

> *A group of experts in building performance is being established, to share knowledge and further improve the vital work being done in this area to provide evidence on the Performance Gap and to help identify solutions. The group will include leading and upcoming academics and practitioners, as well as the companies who rely on their information.*
>
> –
>
> **Dr Will Swan, School of Built Environment, University of Salford**

When do we need to do it?

Communication of evidence needs to be an immediate priority, but will also need to continue to 2020 and beyond. The development of an online resource or 'knowledge hub' would be created during 2014-2015 and regularly updated over the period to 2020.

What kind of costs are involved?

The Zero Carbon Hub has already started to scope out in more detail what work would be needed to develop a useful online resource. Funding will be sought from the TSB, the European Horizon 2020 platform together with applications to all Institutes and Associations. The CITB has indicated that it would support applications to enhance the knowledge and skills of those sectors it represents.

3. NEXT STEPS

As the construction industry develops products and processes capable of delivering homes with more predictable as-built energy and carbon performance, it will become essential that the research methods and tools used to assess them are continuously improved.

Industry recognises the significant challenge the Performance Gap represents and the corresponding need to proactively address it. Rather than relying on ever more onerous regulatory interventions, industry is very capable of developing innovative, commercially viable methodologies to demonstrate their success.

This requires immediate co-ordinated, pan-industry activity, to trigger a cultural shift so that as-built performance becomes a core element of delivering high quality new housing. A strategically timed series of actions is therefore needed by industry and government between now and 2020, as set out in the Route Map that follows.

Priority Actions for Industry

To commit to providing the investment for:

1. PERFORMANCE ASSESSMENT R&D

Undertake the research and development necessary to create innovative testing, measurement and assessment techniques to understand the Performance Gap and develop commercially viable methodologies acceptable across industry for 'demonstrating performance'.

2. SKILLS AND KNOWLEDGE DEVELOPMENT

Ensure that as-built energy performance knowledge, including learning from ongoing research and development, is embedded into training and up-skilling for professionals and operatives.

3. CONSTRUCTION DETAILS SCHEME

Develop an industry owned and maintained Construction Details Scheme providing ‘assured’ as-built energy performance for the most common major fabric junctions and systems.

4. CONTINUED EVIDENCE GATHERING

Support further evidence gathering processes and coordinated feedback to ensure accelerated continual improvement across all sectors of industry.

Priority Actions for Government

To accept the Zero Carbon Hub’s recommendations to:

1. SIGNAL CLEAR DIRECTION

Clearly indicate that, in place of immediate additional regulation, it expects the construction industry to act now and have put in place a number of measures to ensure that the energy Performance Gap is being addressed and to demonstrate this by 2020.

2. STIMULATE INDUSTRY INVESTMENT

Signal their long term intent, by funding research and development into testing, measurement and assessment techniques with immediate effect, to support the industry in providing the information necessary to quantify the Performance Gap and create the learning loops required to drive continuous improvement. Additionally provide pump prime funding to enable industry to develop a Construction Details Scheme.

3. STRENGTHEN COMPLIANCE REGIME

Take action by 2016 to ensure that the Zero Carbon Hub recommended revisions to energy modelling practices, SAP processes and verification procedures, together with a strong regime to ensure that only suitably qualified persons carry out energy modelling and assessment, can be put in place.

4. SUPPORT SKILLS & KNOWLEDGE DEVELOPMENT

Accelerate the demand for industry developed qualification schemes by requiring energy certified operatives and professionals for developments on public land from 2017.

Route Map to 2020

The priority actions are designed to stimulate an intense period of R&D significantly increasing industry's understanding of how to assess, test, model and monitor as-built energy performance. These innovations will raise awareness of the Performance Gap across the industry, so that by 2016, housebuilders will be able to work with a more informed supply chain.

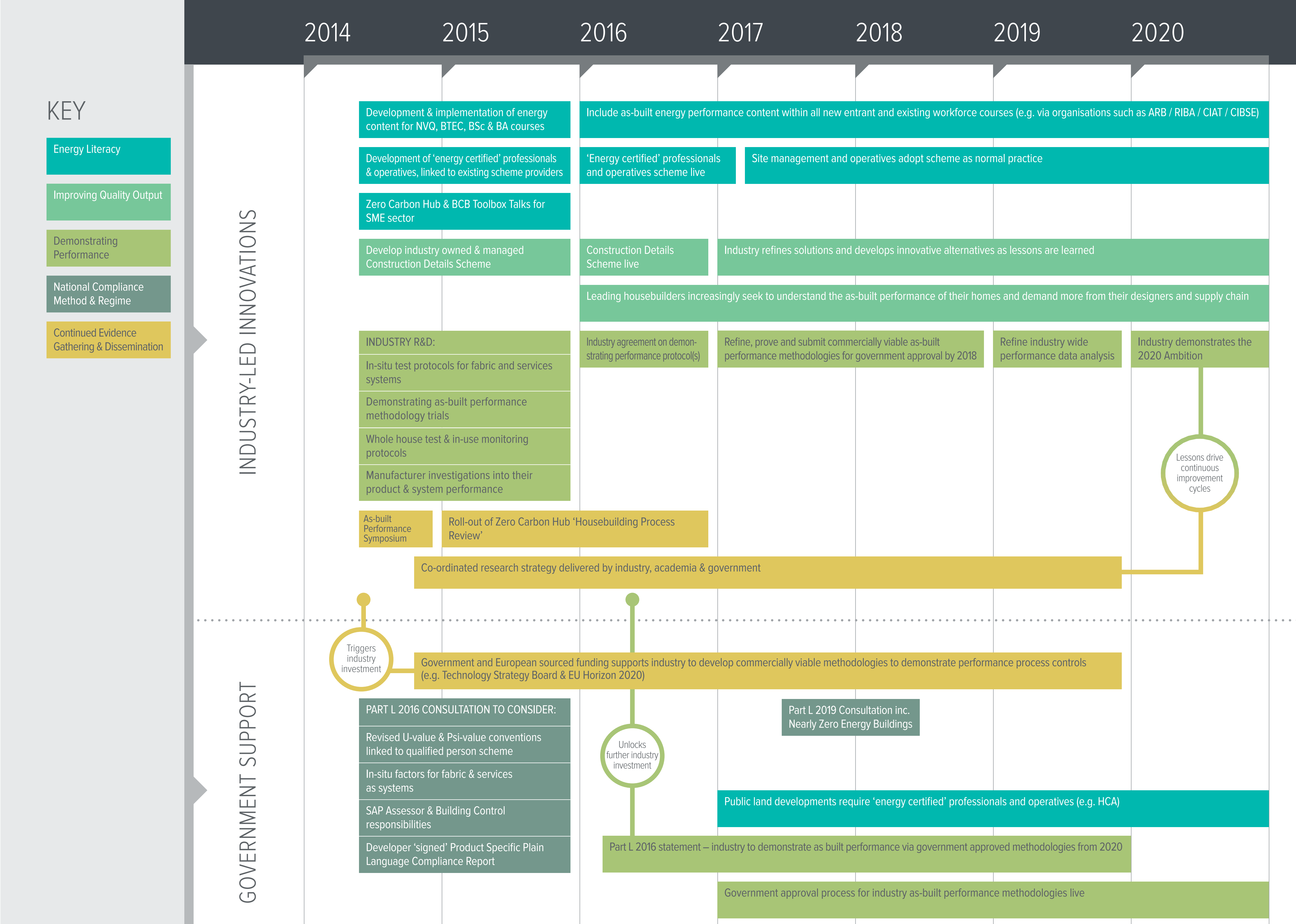
It is within this emerging industry mind set, and a climate of government support for industry-led R&D, that an early statement regarding the '2020 Ambition' should be included within the Building Regulations Part L 2016 announcements. This should include a commitment from government to have in place, by 2018, an approval process by which industry can submit their methodologies for 'demonstrating performance'. If, by 2018, government considers proposals by industry are unlikely to meet the '2020 Ambition', they may need to explore additional regulatory interventions within the 2019 Part L consultation process.

The reporting by industry on progress in relation to the '2020 Ambition' is only intended to be used to gauge performance across the industry and provide confidence that regulations are delivering the intended energy performance and carbon emission reductions. It would not be used as a method of deciding whether a particular building complies with Building Regulations Part L.

From 2019 onwards it is envisaged that the methodologies being used at scale by industry to demonstrate performance will provide knowledge to drive a further phase of rapid innovation, responding to the realities of as-built performance in a variety of development scales and construction types. Information gathered in subsequent years would inform continuous improvement cycles.

The following diagram presents a 'Route Map to 2020' summarising the key industry and government activities considered critical over the next six years.

This project has identified a number of key actions that government and industry are required to undertake. There is now a need for a concerted level of activity to implement the many detailed recommendations within this report in order to close the Performance Gap and demonstrate the '2020 Ambition'.



KEY

- Energy Literacy
- Improving Quality Output
- Demonstrating Performance
- National Compliance Method & Regime
- Continued Evidence Gathering & Dissemination

2014 2015 2016 2017 2018 2019 2020

INDUSTRY-LED INNOVATIONS

Development & implementation of energy content for NVQ, BTEC, BSc & BA courses

Include as-built energy performance content within all new entrant and existing workforce courses (e.g. via organisations such as ARB / RIBA / CIAT / CIBSE)

Development of 'energy certified' professionals & operatives, linked to existing scheme providers

'Energy certified' professionals and operatives scheme live

Site management and operatives adopt scheme as normal practice

Zero Carbon Hub & BCB Toolbox Talks for SME sector

Develop industry owned & managed Construction Details Scheme

Construction Details Scheme live

Industry refines solutions and develops innovative alternatives as lessons are learned

Leading housebuilders increasingly seek to understand the as-built performance of their homes and demand more from their designers and supply chain

INDUSTRY R&D:

- In-situ test protocols for fabric and services systems
- Demonstrating as-built performance methodology trials
- Whole house test & in-use monitoring protocols
- Manufacturer investigations into their product & system performance

Industry agreement on demonstrating performance protocol(s)

Refine, prove and submit commercially viable as-built performance methodologies for government approval by 2018

Refine industry wide performance data analysis

Industry demonstrates the 2020 Ambition

Lessons drive continuous improvement cycles

As-built Performance Symposium

Roll-out of Zero Carbon Hub 'Housebuilding Process Review'

Co-ordinated research strategy delivered by industry, academia & government

GOVERNMENT SUPPORT

Triggers industry investment

Government and European sourced funding supports industry to develop commercially viable methodologies to demonstrate performance process controls (e.g. Technology Strategy Board & EU Horizon 2020)

PART L 2016 CONSULTATION TO CONSIDER:

- Revised U-value & Psi-value conventions linked to qualified person scheme
- In-situ factors for fabric & services as systems
- SAP Assessor & Building Control responsibilities
- Developer 'signed' Product Specific Plain Language Compliance Report

Unlocks further industry investment

Part L 2019 Consultation inc. Nearly Zero Energy Buildings

Public land developments require 'energy certified' professionals and operatives (e.g. HCA)

Part L 2016 statement – industry to demonstrate as built performance via government approved methodologies from 2020

Government approval process for industry as-built performance methodologies live

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Abbreviations & Glossary

ACD	Accredited Construction Detail
ARB	Architects Registration Board
BBA	British Board of Agrément
BCB	Building Control Body
BFRC	British Fenestration Ratings Council
BIM	Building Information Modelling/Management
BPE	Building Performance Evaluation
BPEC	British Plumbing Employers Council
BR443	The document setting out the conventions that govern U-value calculations
BR497	The document setting out the conventions that govern Psi-value calculations
BRE	Building Research Establishment
CIAT	Chartered Institute of Architectural Technologists
CIBSE	Chartered Institution of Building Services Engineers
CIOB	Chartered Institute of Building
CITB	Construction Industry Training Board
CPA	Construction Products Association
CPD	Continuing Professional Development
DCLG	Department of Communities and Local Government
DECC	Department of Energy and Climate Change
DER	Dwelling Emission Rate
DOCEA	Domestic On Construction Energy Assessor (SAP assessor)
DPC	Damp Proof Course
EPC	Energy Performance Certificate, required when a home is sold or leased
EPSRC	Engineering and Physical Sciences Research Council
FETA	Federation of Environmental Trade Associations
HBF	Home Builders Federation
HCA	Homes and Communities Agency
HHIC	Heating & Hotwater Industry Council
Horizon 2020	EU research and innovation funding programme
LABC	Local Authority Building Control
M&E	Mechanical and electrical
MCS	Microgeneration Certification Scheme
NBS	National Building Specification
NHBC	National House Building Council
Operatives	The term operatives has been used throughout this report to refer to trades and those individuals involved in technical applications of construction elements, such as groundworkers etc.
Part L	In the context of this report, this refers to Part L1a of the Building Regulations, which deals with the energy efficiency requirements for new dwellings
Psi-value	A measure of heat loss associated with non-repeating thermal bridges at junctions between different element types (measured in W/mK)
QA	Quality Assurance
R&D	Research and development
RIBA	Royal Institute of British Architects
RICS	Royal Institution of Chartered Surveyors
Robust Details	A scheme offering an alternative to pre-completion sound testing for meeting Part E requirements
SAP	Standard Assessment Procedure, the methodology and tool which is used to check compliance with Building Regulations Part L1A
SMEs	Small and Medium Enterprises
TSB	Technology Strategy Board
UKAS	United Kingdom Accreditation Service
U-value	A measure of heat loss through a building element (measured in $W/m^2/K$)

APPENDIX A: ISSUES LIST

REF	WHAT MIGHT BE HAPPENING TO CREATE THE PERFORMANCE GAP?
LAND ACQUISITION, CONCEPT DESIGN & PLANNING	
P1	Limited understanding by planners or funders of the impact of phasing or aesthetic requirements on performance and energy related targets, e.g. form, house type variations, roof shapes, orientation, materials and finishes.
P2	Limited understanding by concept design team of impact of early design decisions on performance and energy related targets (aesthetics - form, house type variations, roof shapes, orientation materials and finishes, phasing).
P3	Inconsistent setting of standards and targets between local authorities (methodology and/or level) leading to increased complexity of solutions.
P4	Limited guidance, modelling tools and standards available to evaluate and review issues associated with energy performance at early design stages, including overheating.
DETAILED DESIGN	
D1	Inadequate understanding and knowledge within design team e.g. buildability, thermal detailing, tolerances, construction systems and materials, site conditions, SAP and energy issues, performance.
D2	Lack of integrated design between fabric, services, renewables and other requirements, e.g. due to lack of specialist input.
D3	Lack of communication of design intent through work stages, e.g. due to discontinuities in design team, specialist involvement or general work contract structure.
D4	Lack of suitable design tool that incorporates compliance check.
D5	Design team not communicating sufficient information regarding critical energy performance criteria of components to procurement team.
D6	Insufficient design information provided for building fabric, potentially leading to critical decisions being left to contractor/sub-contractor at construction phase.
D7	Insufficient design information provided for building services, potentially leading to critical decisions being left to contractor/sub-contractor at construction phase.
D8	Product and system design issues, e.g. concerns about robustness of product design, systems design issues.

REF	WHAT MIGHT BE HAPPENING TO CREATE THE PERFORMANCE GAP?
PROCUREMENT	
PR1	Manufacturer information lacking critical energy performance detail, relating to either building fabric or services.
PR2	Inadequate consideration of skills and competency requirements at labour procurement (fabric & services).
PR3	Product substitution at procurement without due regard for performance criteria.
PR4	Procurement team lack of understanding of critical energy-performance related criteria.
PR5	Tender documentation not containing up-to-date requirements or trade specifications.
CONSTRUCTION AND COMMISSIONING	
C1	Lack of designer input available to site if issues arise, e.g. due to type of contract.
C2	Sales or year-end/interim build targets driving programme delivery - putting labour out of sequence and potentially compromising construction quality.
C3	Frequently changing site labour limiting ability for lessons to be shared or learnt.
C4	Construction responsibilities for energy performance unclear, lack of collaborative working, e.g. services penetrating air barrier.
C5	Product substitution on site without due regard for impact on energy performance.
C6	Lack of adequate quality assurance on site and responsibility for QA, e.g. due to site managers being overly reliant on sub contractors' QA processes, variability in processes, lack of supervision, reliance on Building Control.
C7	Lack of understanding in sales team of impact of changes, e.g. customer add-ons which affect SAP.
C8	Lack of ability to identify some products on site/in situ, e.g. by operatives or for QA or audit purposes.
C9	Poor installation or commissioning of services, e.g. due to installation guidance or design drawings not followed, lack of manufacturer installation and/or commissioning guidance.

REF	WHAT MIGHT BE HAPPENING TO CREATE THE PERFORMANCE GAP?
C10	Short term fixes and improvisations on site without understanding of long-term impact, e.g. mastic for achieving required air pressure test result.
C11	Full design information or installation guidance produced but not available on site.
C12	Site management - inadequate consideration of sequence of trades and activities on site, later phase work undermining previous works.
C13	Lack of site team energy performance related knowledge and skills and / or care.
C14	Accredited Construction Details 'tick box' culture, i.e. recorded in SAP but not built on site.
C15	Poor installation of fabric, e.g. due to installation guidance or design drawings not followed.
VERIFICATION	
V1	Lack of robust verification of planning requirements and standards at completion.
V2	Lack of robust energy-performance related verification, reliance on third-party information (e.g. by Building Control or warranty providers).
V3	Commoditised third-party schemes not independent or checks not adequate (including Competent Persons Schemes).
V4	Lack of Building Control enforcement ability relating to Part L issues.
V5	Lack of clarity over documentary evidence required or acceptable for Part L and Part F compliance.
TESTING	
T1	Limited tests and agreed protocols available for in-situ fabric performance measurement.
T2	Limited tests and agreed protocols available for in situ services performance measurements, including for system performance.
T3	Concern over consistency of some test methodologies and interpretation of data and guidelines.
T4	Limitations of air-pressure testing methodology (QA, robustness of third party certification, protocols).

REF	WHAT MIGHT BE HAPPENING TO CREATE THE PERFORMANCE GAP?
T5	Lack of suitable end-of-line overall performance test to validate energy calculation models, products and building fabric.
T6	Tests not replicating or accurately taking into account dynamic effects, e.g. solar gain, microclimate, wind speed, weather effects.
T7	Limited tests and agreed protocols for innovative/less mainstream products and services.
ENERGY MODELLING TOOLS AND CONVENTIONS	
EM1	Commercial pressures leading to optimistic SAP input assumptions.
EM2	Concerns about accuracy of aspects of the SAP calculation model and assumptions, e.g. thermal mass, hot water, ventilation, overheating, cooling, lighting, thermal bridging, weather, solar shading, community heating, particular technologies.
EM3	SAP conventions not adequate, comprehensive or reflective of site conditions.
EM4	As-Built SAP not reflective of actual build.
EM5	Lack of transparency and clear outputs for verifiers to check modelling assumptions (including designers to verify material performance assumptions, BC and others).
EM6	Infrequent or insufficient audits of SAP assessors by licensing organisations.
EM7	Concern over competency of SAP assessors (accuracy of data input, following of conventions, validation of assumptions, provision of design and specification advice).
EM8	Issues surrounding use of calculation procedures in BR443 (U-values) and BR497 (Psi-values) or associated Standards.
EM9	Limited as-built test data used in SAP calculations (only air-pressure testing).
EM10	Limited ability to include new technologies in SAP calculations.
EM11	Concerns about the robustness or lack of overheating checks outside SAP.

APPENDIX B: EVIDENCE UPDATE

Since the publication of the Evidence Review Report in March 2014, further evidence has been gathered and analysed.

This Appendix summarises the findings, with a full update planned later in 2014. The new evidence includes:

- A continuation of the ***Housebuilding Process Review*** presented in the ***Evidence Review Report***, with an additional 12 sites reviewed, taking the total to 21 sites. The focus of this update is on the findings from the additional sites. It also includes further assessment of some of the sites in the form of:
  - Further SAP Audits of 18 plots across 10 of the sites, taking the total to 26 plots audited across 14 sites. Updated findings are presented, covering results from all of the sites.
  - Costing analysis undertaken to estimate the impact of correcting some common errors observed on site, based on SAP modelling estimates of the potential energy savings.
  - Testing: 'forensic' airtightness testing undertaken in combination with thermal imaging and smoke tests on 20 plots across 10 of the sites to assess the impact of variability in air pressure testing methods. Along with further thermal imaging undertaken on 10 plots across five sites, this also provided supporting evidence for some of the ***Housebuilding Process Review*** findings. A 'round robin' airtightness testing assessment was undertaken on six plots across two sites, with tests being carried out by up to five companies on each plot to investigate the impact of variability between testers.
- A SAP Sensitivity Analysis investigating the impact of potential variation in SAP inputs. The summary presented here updates and provides more detail on the initial results presented in the ***Evidence Review Report***.
- Further analysis of eight of the TSB Building Performance Evaluation Domestic Phase 1 projects, which were included in the Literature Review in the ***Evidence Review Report***.

Housebuilding Process Review Update

A '***Housebuilding Process Review***' has been undertaken to identify and gather evidence on issues occurring on housebuilder development sites that may contribute to the Performance Gap.

In total 21 sites have been reviewed, with approximately 200 plots assessed. Evidence from the first nine sites reviewed was presented in the ***Evidence Review Report*** and supporting appendices.[1] This Appendix includes the results from the additional 12 sites which have been reviewed since. These additional sites include a wider range of construction methods, with concrete and steel frame construction, as well as timber and masonry. In addition there was also an increase in the variety of insulation types used, with rigid board insulation used less commonly on the additional sites and both blown insulation and mineral wool batts being used. More smaller-sized sites were included than in the initial review. The additional sites also included greater use of bespoke designs. All sites were built under 2010 Building Regulations, some with additional planning requirements.

Evidence was collected by a review team in three stages: interviews with design teams, SAP assessor, procurement team and construction team; a design review to provide an understanding of the design and construction methodology; and finally a site visit to review plots at each stage of the build process where possible. The review team recorded their findings in pre-prepared assessment sheets covering key assessment items that could contribute to the Performance Gap.

It is important to note that the findings given below are based on preliminary analysis and that a more detailed assessment will be carried out and disseminated at a later stage. The findings have been presented in the same format as that used in the ***Evidence Review Report*** to allow easy comparison with findings from the initial sites.[2]

Summary Update of Housebuilding Process Review Interview Findings

Planning and Concept Design

All of the issues observed in the ***Evidence Review Report*** at this stage were supported by findings on the additional sites. This included a lack of feedback to concept design teams on the potential impacts of their decisions on the detailed design stage and on buildability. However, confusion about energy targets was not mentioned to the same extent as on earlier sites. On sites using bespoke designs, the lack of specialist and site team involvement at this stage and lack of effective handover also generally seemed to be slightly less problematic as there was often more focus on maintaining continuity, *for example through use of the same team at concept and detailed design, concept design teams being given a 'watching brief' role, and involvement of specialists and site teams at an earlier stage*. However, further analysis needs to be carried out to investigate the impact of this.

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1. Zero Carbon Hub, Closing the Gap Between Design & As-Built Performance: Evidence Review Report, March 2014.

2. For more information on the findings for the initial nine sites and on the methodology used please see the Evidence Review Report appendices.

Detailed Design

Many of the issues that were noted in the ***Evidence Review Report*** have been substantiated by the interviews for the additional sites reviewed. *For example, interviewees commented on SAP assessors not being informed of changes to the design, lack of feedback from site teams, timescales for the design process being too short, and a lack of consideration of overheating*. Some issues that were flagged up in the ***Evidence Review Report*** were felt to be less of an issue on the additional sites, although it is important to note that there were more bespoke sites visited and the differences were found primarily on these sites. In common with concept design teams, on several sites interviewees reported less problems with handover though some still noted significant issues; and several of the bespoke sites had more SAP assessor involvement and some had site team involvement at the design stage, though again further analysis needs to be carried out to investigate the impact of this.

SAP Assessment

The ***Evidence Review Report*** noted potential issues with how assessors were verifying the information used to calculate the As-Built SAPs, with many assessors accepting a sign-off from a technical manager or member of the design team rather than a site manager or equivalent. This theme was also found on the additional sites visited with some assessors suggesting that changes made on site would generally not be fed back to the technical team and on to them, and that not enough time is given to correctly update the SAP inputs at the As-Built stage. On the additional sites it was also found that most assessors used default values for window g-values, corroborating the findings in the ***Evidence Review Report***. The ***Evidence Review Report*** also identified the competency of some assessors as a potential issue contributing to the Performance Gap - *for example, their ability to recommend compatible components and their rigour in checking assumptions*. It was found that the checking of information relating to both U-values and Psi-values remained an issue on the additional sites although lack of information provision may have also contributed to this.

Procurement Review

Overall the findings on the additional sites visited correlated quite closely with the findings in the ***Evidence Review Report***. One of the most prevalent issues was the g-value not being used by the purchasing team to procure the windows. Possible causes might include a lack of full information from design teams, or the procurement team not understanding the importance of the value and so disregarding it when making purchasing decisions. Other issues noted in the ***Evidence Review Report*** were further substantiated to varying degrees on the additional sites, including some instances of unclear or limited communication and handover, and evidence of limited consideration of energy-related skills. As on previous sites, there was a lack of awareness of schemes such as BPEC and MCS. Most procurement teams again said that they would always report product substitution proposals - either directly to the technical team or at meetings.

Construction

The findings for the additional sites reviewed quite closely reflect the findings outlined in the ***Evidence Review Report***. Issues commonly raised included site teams not being involved in signing off specifications for As-Built SAPs, site managers feeling that their job was to overcome problems on site rather than to refer them to the technical team, and design information missing on site or not fully complete before the start on site. Potential issues were noted during the interviews relating to a lack of energy-related knowledge, varied levels of understanding of the 'air barrier' and a lack of feedback and interaction with the design team, as was found on the previous sites. However on two of the additional sites where bespoke designs were used the site managers were involved early in the design process, though more work needs to be done to investigate the impact of this. Interviewees provided fewer comments on the QA process than in previous interviews though it was found that a few sites did not have a written log book on site.

Summary Update of Housebuilding Process Review Site Visit Findings

Build Stage 1: Sub-Structure

The additional sites reviewed further substantiated all the issues highlighted in the ***Evidence Review Report***, including trench block substitution, insulation missing below the DPC and door thresholds bridging cavities. The types of issues occurring tended to be consistent across sites and build types; with some new examples including a timber frame not fitting correctly on top of the foundation block work, creating an overhang to the cavity.

Build Stage 2: Oversite

Very few differences were found on the additional sites when compared to the findings of the ***Evidence Review Report***. The sealing around services at this stage was again generally fairly good at this stage. Proprietary insulated floors were generally found to be poorly installed (*for example with gaps at the perimeter and between blocks of insulation*), perimeter insulation was often the incorrect material and/or was poorly installed, and screed was often noted to 'bleed over' the perimeter insulation as well as in several cases bridging the cavity. The installation quality of horizontal floor insulation was also a more prevalent issue than found on previous sites. These findings were supported by the thermal imaging carried out as part of this project, where heat loss was indicated around the perimeter of the ground floor.

Build Stages 3 and 4: Oversite to Joist, Joist to Roof

On all the sites where timber frame construction was used, the findings again supported those found previously. *For example, it was found that the incorrect timber fraction was used in U-value calculations on all the sites where this could be checked, with the default being assumed but significantly more timber being used on site*. In some cases poorly installed or missing sole plate insulation and damaged low-emissivity breather membranes were also observed.

On the sites where masonry construction was used, the issues observed also tended to be similar to the sites included in the ***Evidence Review Report***, including dirty cavities and cavity closers not fitting tightly (often as a result of inconsistent cavity widths). As on previous sites, it was found that where joists were not on hangers they were often not fully pointed up; and thermal imaging testing indicated heat loss around joists which is likely to be due to air leakage.

Some of the additional sites reviewed included blocks of flats which used different construction methods than those on the sites included in the ***Evidence Review Report***: concrete frame and steel frame. The cavity wall issues noted above for masonry sites were also observed on some of these sites, but additional issues were also found. Often these related to the U-value and Psi-value calculations. In particular, it was observed that the use of Metsec was not reflected well in the U-value calculations – *for example, double sheets of Metsec were used on site but not included in the calculations, or the amount of concrete observed on site was not accounted for*. On one site, Accredited Construction Detail (ACD) Psi-values were assumed for a concrete frame and Metsec construction, although ACDs do not exist for this construction method. Steel beams creating unaccounted for thermal bridges were also commonly observed on these sites, and in one case a thermal bridge was noted where floor slabs were continued through walls to create balconies.

Whilst the majority of the previous sites used rigid insulation, this was used less commonly on the additional sites – where it was used, there were examples of good practice but also some issues with gaps between boards and around openings, as seen on previous sites. A different issue was observed on the additional sites where blown insulation was used: it was observed that drill patterns were not always consistent or likely to allow insulation to be installed around difficult to access areas such as cavity closers and meter boxes. This was also observed at later build stages.

For all types of construction, issues were observed on the majority of the sites relating to party walls: in particular the insulation was often not tightly packed in the cavity and edge seals were often of the wrong type or incorrectly installed. During thermal imaging testing heat loss was indicated through the edges of party walls. As found on previous sites, substitution of lintels was common, and problems with delivering bay window and internal garage detailing were also observed. Heat loss at complex details was also indicated by the thermal imaging testing.

Build Stage 5: Roof to Weathertight

The three main issues highlighted in the ***Evidence Review Report*** for this build stage have been well supported on the additional sites reviewed: windows and doors being installed forward from their design position resulting in insufficient overlaps with cavity closers leading to greater heat loss from thermal bridging, the tolerances around windows and doors being considerably out which would lead to increased heat loss from thermal bridging, and installed doors and windows varying from the design (most commonly, window g-values varied, but window or door U-values also commonly varied). Where thermal imaging testing was undertaken it also highlighted heat loss around windows and doors.

Build Stage 6: First Fix

Generally all the issues found in the ***Evidence Review Report*** at this build stage were found on the additional sites reviewed: service penetration sealing was often not done well and staircase strings were not always packed out and sealed. Thermal imaging testing also showed heat loss around some external services, indicating air leakage.

Build Stage 7: Drylining

At this build stage again there were few differences noted on the additional sites compared to those included in the ***Evidence Review Report***, with instances of plane ceiling insulation not being correctly fitted or matching the design, insulated boards on the soffits of openings missing and external penetrations not being fully sealed. A continuous ribbon of adhesive was not generally being achieved around plasterboards, with gaps commonly occurring at internal corners and around openings – this was also found on previous sites. The air tightness 'forensic' testing also indicated significant air leakage from behind the plasterboard on the majority of sites where testing was carried out. The thermal imaging also indicated heat loss which is likely to be associated with the poor installation of the roof insulation that has been observed on several sites.

Build Stage 8: Second Fix

The additional sites reviewed further substantiated the issues described in the ***Evidence Review Report***, in particular missing skirting and inconsistent sealing behind kitchen and bathroom units were observed and these were also highlighted as areas with a high degree of air leakage during the air tightness 'forensic' testing. Analysis of the air tightness forensic testing results suggested that the second fix installation may be disturbing the air barrier. As on the earlier sites, on some of the additional sites it was found that there were differences between the mechanical and electrical system designs and the installed systems, including changes to ducting layouts (with excessive bends and length and supply inlets and extract outlets installed too close together) and different or missing heating controls.

Build Stage 9 and 10: Finals and Build Complete, Testing and Commissioning

As was found on earlier sites, plane roof insulation was commonly observed to have been disturbed post-installation leaving some gaps, and the insulation was also not always properly cross-lapped. Other issues further supported by the additional sites included doors not being trimmed to match the ventilation design requirements, Domestic Ventilation Compliance Guide checklists not being available on site, the misuse or poor application of mastic, and customer extras not being accounted for in As-Built SAP calculations.

Summary of SAP Audit Findings

For 26 plots across 14 of the sites visited as part of the ***Housebuilding Process Review***, the SAP assessment has been reviewed, based on design information and observations recorded during the site visits. The draft results from four of the sites were included in the ***Evidence Review Report***. The updated findings including results from all of the 14 sites audited are described here.

It was not possible to undertake audits for all the sites visited as part of the ***Housebuilding Process Review***, as some sites were not sufficiently far progressed at the time of the site visits – this has meant that the majority of the sites for which SAP Audits were undertaken are larger developments where plots close to completion could be seen. Most of the plots audited were semi-detached or detached houses, with some mid-terraced houses and flats. In addition, most were of traditional masonry construction, but some timber and concrete frame plots were included. Seven of the plots included photovoltaic panels; 17 were naturally ventilated, seven had mechanical extract ventilation (MEV) and two had mechanical ventilation with heat recovery (MVHR). All plots had a gas heating system, the majority with regular condensing boilers and hot water cylinders.

Two stages of audits were undertaken for each plot:

- **Stage 1:** A review of the original SAP assessment done by the developer's SAP assessor.
- **Stage 2:** A SAP assessment based on site visit observations, compared to the corrected audit from Stage 1.

Differences found during both stages of the audit were evaluated in terms of the change to the DER in absolute percentage terms (i.e. no matter whether the change was positive or negative). Where available, original As Built SAPs were used (12 plots) but construction on some of the sites was not complete, so in these cases (14 plots) Design Stage SAPs were used instead. The ***Evidence Review Report*** should be referred to for more detail on the methodology used and the assumptions made.

Stage 1 of the SAP audit found errors in the original SAP assessments in all cases. The errors found are summarised below. On average across all the plots audited, an absolute DER deviation of 14% was found.

SAP ENTRY AREA	FREQUENCY OF DEVIATION (% OF PLOTS)*	AVERAGE ABSOLUTE DER DEVIATION (%)	ERROR EXAMPLES
Orientation	15%	0.7	Orientation incorrect by 45°
Sheltered Sides	38%	0.8	Incorrect by 1 sheltered side (usually 1 too many)
Measurements	92%	6.1	Storey height and wall areas; wall, floor, roof type, window/glazed door identification; total floor area
U-values	100%	1.6	Wall, floor, roof type, window/glazed door identification errors; corrections not applied
g-values	42%	1.0	Use of SAP defaults instead of specified values; specification missing g-values; use of incorrect sources for values
Thermal Mass	88%	1.6	Incorrect calculated values; use of incorrect default; differences between default and calculated values (thermal mass usually higher when calculated than default 'low' value assumed). Note that defaults are allowed by SAP Conventions so this latter finding is not an 'error' as such, but perhaps highlights an area where Conventions could be updated.
Linear Thermal Bridging	88%	2.7	Not accounting for different constructions for a particular junction; errors in treatment of dormers and bay windows; inappropriate use of sets of Psi-values for constructions they do not apply to.
Ventilation	38%	1.1	Incorrect number of extract fans
Heating System	58%	2.9	Incorrect boiler size/type/efficiency; incorrect cylinder type; incorrect controls; omission of secondary heating
Low and Zero Carbon Technologies	14%	1.2	Incorrect PV pitch

** Note: the percentage of plots is out of the total 26 plots in all cases except for low and zero carbon technologies present where it is out of the total plots with these technologies present (seven).*

Stage 2 of the SAP Audit found that in all instances changes were occurring in constructed dwellings that were not reflected in the SAP assessments. The discrepancies found are summarised in the table below. On average across all the plots audited, an absolute DER deviation of 14% was again found. It should be noted that given various constraints of the project, it was not possible to check all parts of the SAP assessment when on site.

SAP ENTRY AREA	FREQUENCY OF DEVIATION (% OF PLOTS)*	AVERAGE ABSOLUTE DER DEVIATION (%)	ERROR EXAMPLES
Measurements	27%	1.5	Storey height and wall area errors; door/window identification errors
U-values	92%	3.8	Incorrect opening U-values; window/door errors; corrections not applied; incorrect timber frame fraction; reduced roof insulation found on site; party walls not correctly fully filled / sealed (biggest impact); floor block substitutions
g-values	96%	1.3	Incorrect g-values (usually default used but value lower on site, i.e. worse)
Thermal Mass	19%	0.4	Substitution of dense block in party wall increasing thermal mass
Linear Thermal Bridging	92%	7.1	Lintel substitution; lack of continuity of insulation at eaves/wall junction and between joist and gable walls; inner leaf block substitution and insulation missing/bridged at wall/ground floor junction; change in opening overlap with cavity closer; missing cavity closers
Ventilation	4%	2.3	Additional flue for secondary heating found on site
Lighting	19%	4.0	Incorrect low energy lighting percentage (e.g. 100% assumed but 75% found on site)
Heating System	35%	1.7	Weather compensator missing on site; incorrect cylinder heat loss; primary pipework not insulated; secondary heating added
Low and Zero Carbon Technologies	14%	9.9	Incorrect PV overshading (none assumed but overshading found on site)

When the combined errors from Stage 1 and Stage 2 are taken into account (i.e. Stage 2 findings are compared to the original uncorrected SAP assessment), the deviation becomes even more significant: on average an absolute DER deviation of 26% was found.

Summary of Costing Assessment

Information from the site visits and SAP audits was used to identify some common examples of errors and differences observed between designed and as built dwellings which could be modelled in SAP. This modelling was undertaken to provide a rough indication of the relative impact of each item on energy performance, as assessed by SAP.

This was used to inform an assessment of the estimated financial, energy and carbon savings that might be expected if these differences or errors were corrected. The results from the modelling are presented in the table below.

ERROR/DIFFERENCE	SAP VARIABLE	FUEL	ENERGY SAVING (KWH/YR)	CARBON SAVING (KGCO$_2$)	FINANCIAL SAVING (NPV £)	ANNUAL SAVING (£/YR)
Block substitution in inner leaf of wall at ground floor (dense block instead of aircrete)	Ground floor/wall junction Psi-value	Gas	110	440	80	5
Window overlap	Window/wall junction Psi-values	Gas	65	260	50	3
Lintel substitution (continuous perforated instead of split)	Lintel/wall junction Psi-value	Gas	140	550	100	6
Weather compensator	Excluded / included	Gas	120	470	85	5
Lighting substitution (high energy instead of low energy)	75% instead of 100% low energy	Electricity	100	1025	225	14
		Gas	-20	-80	-15	-1
Window substitution	g-value	Gas	210	835	155	10
Timber frame fraction (36% instead of 12%)	U-value	Gas	520	2055	375	23
Party walls not fully filled and sealed	U-value (0.2 assumed)	Gas	660	2620	480	30
Partial fill insulation poorly installed	U-value (air-gap correction level only)	Gas	325	1275	235	15
Roof insulation specification change (100mm less insulation)	U-value	Gas	285	1135	210	13
PV overshading	Overshading level 'modest' not 'none/very little'	Electricity	155	1625	350	22

It is important to note:

- The energy saving estimates are based on the estimated impact in SAP and a 'typical' scenario based on the site visit findings.
- The energy saving modelling was constrained by data availability, and the variables that could be changed in SAP or in U-value calculations were limited without undertaking detailed analysis to assess the impact of changes – so it is unlikely that the full impact of the changes are reflected in the modelling carried out.
- The base case model used was the Zero Carbon Hub's standard semi-detached house type, 2010 compliant with a gas boiler and natural ventilation.
- A 20 year timefame and a discount factor of 3.5% have been used for the financial assessment. The discount factor was chosen as this is the standard value used by government to conduct financial analysis.
- Energy savings and carbon factors are assumed constant over time.
- Future energy price predictions were based on DECC central projections.
- No changes to capital or labour costs have been assumed. Though some of the changes modelled may have capital or labour cost implications, *for example where one product is substituted by another or omitted entirely, it was considered that the costing of the development should be assumed to have allowed for what was included in the design specification.*
- Figures have been rounded to avoid a false impression of accuracy.

Summary of Testing Findings

‘Forensic’ Air Pressure Testing

‘Forensic’ air pressure testing was undertaken to investigate the potential impact on results when the air pressure test is conducted in different ways. 10 sites were included in the analysis with two dwellings tested per site.

Air pressure tests were undertaken for each dwelling with four variables examined to determine their impact on the test results: closing / opening of trickle vents, sealing / unsealing of ventilation systems (trickle vents and extract fans), front/back door positioning of equipment, and use of pressurisation / depressurisation method. The current approved test procedure for Building Regulations requires trickle vents and other controlled ventilation systems to be closed and sealed, but allows either option to be chosen for the other variables.

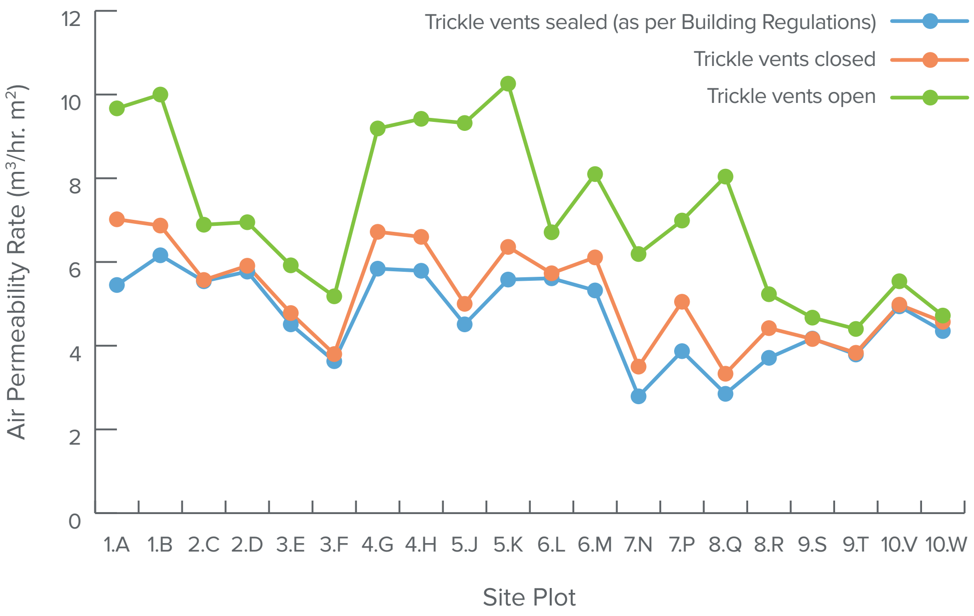
In addition, air leakage paths in the test dwellings were investigated using thermographic surveys, smoke pencil tests and full dwelling smoke tests – some of the findings from these tests are included under the ‘Site Visit’ section.

The design air permeability rates of the sites under assessment ranged from 4.5 to 6.0 $m^3/hr.m^2$@50 Pa (with one site with a target of 7 when including provision for the plus 2 penalty for not testing all units). The results of the forensic testing showed that nearly all units were below their design air permeability rate, with results between 2.8 and 6.2 $m^3/hr.m^2$@50Pa and with only one instance of a test result above the design rate. However, there were a number of instances where dwelling test results were significantly lower than their target, *for example with one site achieving a result of 2*.9 against a target of 5.5. The test dwellings were all naturally ventilated and units with air permeability rates below 3.0 $m^3/hr.m^2$@50 Pa with significantly higher design targets may be at risk of being under-ventilated.

The study found that the biggest variance from the standard Building Regulations test procedure was with trickle vents open, with 75% of the dwellings seeing an increase of over 1 $m^3/hr.m^2$ air permeability rate – as shown in the graph below. At the extreme end three of the properties recorded an air permeability rate that was double the rate recorded under the standard test procedure, with increases of around 4 $m^3/hr.\ m^2$@50Pa. It should be noted that leakage associated with trickle vents and other forms of controlled ventilation is not included in the Building Regulations approved procedure as they are not considered background ventilation. SAP calculations do include trickle vents in the form of a default effective ventilation rate, which is based on typical user behaviour. If tests were undertaken with the trickle vents open, in contravention of the approved procedure, it would have a significant impact on results.

The effect of unsealing the ventilation system and unsealing closed trickle vents was considered to be less significant, with increases in air permeability rates for each case generally below 0.5 $m^3/hr.m^2$. The differences between measuring from the front and back door were, as a percentage, less than 10%, and generally less than 5%. This would indicate that the choice of test doorway does not have a significant effect on the result obtained. The results also indicated that for the dwellings tested the choice of using a de-pressurisation or a pressurisation method was also not significant. However, it should be noted that at higher or lower air permeability rates than those of the sample the impact may be more pronounced.

Figure 1. **Air permeability rates for Trickle vents open, closed and sealed**



Note that Site/ Plot designation does not relate to notation used in other sections of this Appendix.

'Round Robin' Air Pressure Testing

A 'round robin' assessment was undertaken to investigate potential variation in Building Regulations air pressure test results, undertaken at the same stage on the same dwelling by different companies. Two development sites each provided three plots to test, with up to five companies performing a Building Regulations air pressure test for each plot. The assessment replicated a standard air test as the developers' organised the tests in the usual way – the only instruction was to complete a test for Building Regulations compliance. The testing companies were not aware that the plots had been tested by other companies and the results were compared to the original air pressure tests for each site which had actually been used for Building Regulations compliance. All the 'round robin' tests on the same units were carried out when the dwelling was at the same stage of completion/finish and within the space of eight days on one site, and 15 days on the other.

The round robin assessment recorded significant differences in air permeability values measured on the same test unit. The largest variation recorded was between 4.7 and 7.1 $m^3/hr.m^2$@50 Pa; another plot (on the other site) had a similar magnitude of variation, ranging from 3.7 to 5.6 $m^3/hr.m^2$@50Pa. Whilst some variation in results is to be expected it is felt that these differences are outside acceptable limits. Due to the nature of this exercise it is not possible to ascertain which of the results is closest to the actual air permeability. However, the fact that there are such large differences in the recorded results is concerning.

The tests were undertaken in close succession and so it is felt that the differences due to ageing effects are unlikely to be significant. External conditions can impact on results, and the level of information provided by the testers on this varied considerably and would not account for all effects, making it difficult to draw conclusions. It is noted that testing companies are no longer required to record the wind speed experienced during air pressure tests. Equipment error is another possibility and whilst testing companies are required to calibrate their equipment each year in order for it to be compliant, not all companies provided the full information on equipment calibration. A more probable cause of the differences in results observed could be the assumptions made by the testers: *for example one company in particular recorded significantly different measurement assumptions from the others*. The information provided by the testers on measurements necessary to calculate the air permeability ranged from the floor area, surface area and volume all being provided to no measurements provided at all. The majority of testers reported the total surface area only.

In relation the choice of testing under either depressurisation or pressurisation, the favoured approach of the testers in the 'Round Robin' assessment was to test under depressurisation, with all companies who provided testing methodologies choosing this method. Whilst the 'Forensic' testing showed relatively small differences in the air permeability between these methods (less than 0.3 m^3/hr. m^2) the rates were generally lower under depressurisation than pressurisation in the sample. This might suggest that commercial testers may prefer the depressurisation approach as it is more likely to give a 'favourable' result.

A summary of some of the key results from the testing is included in the tables below.

Site A

PLOT	COMPANY	AIR PERMEABILITY (M^3/HR.M^2@50PA)	ENVELOPE AREA (M^2)
1	1	4.4	330
1	2	6.0	348
1	3	4.2	Not Supplied
1	4	6.0	347
2	1	4.6	330
2	2	5.0	348
2	3	4.0	Not Supplied
2	4	6.1	347
3	1	4.7	292
3	2	7.1	305
3	3	4.9	Not Supplied
3	4	6.9	291

Site B

PLOT	COMPANY	AIR PERMEABILITY (M^3/HR.M^2@50PA)	ENVELOPE AREA (M^2)
A	A	5.2	378
A	B	4.7	384
A	C	5.1	375
A	D	3.9	526
A	E	5.3	370
B	A	4.1	315
B	B	3.7	306
B	C	3.9	303
B	D	5.6	313
B	E	4.1	301
C	A	6.0	197
C	B	5.5	197
C	C	5.3	199
C	D	5.5	210
C	E	5.4	204

Thermal Imaging

Thermal imaging surveys were undertaken on 10 plots across five sites. It is important to note that thermal imaging is not a quantitative assessment method. However, by analysing the thermal imaging surveys in the context of the observations made on the site visits and findings from the air leakage path investigation undertaken as part of the forensic airtightness testing, confidence can be gained as to where problems are occurring.

Issues corroborated by the thermal imaging surveys included:

- Lack of continuity of insulation, in particular when fitting loft insulation and when insulation has not been well installed at the junction between walls and ceilings. These issues are compounded as they allow cool air to flow over the uninsulated areas;
- Air leakage around joist ends and at service penetrations such as boiler flues and pipes;
- Thermal bridging around lintels and other window details and at the perimeters of ground floors;
- Party wall heat loss potentially indicating an opportunity to improve party wall detailing including air tightness.

Similar issues have been identified in many other projects where building performance evaluation has been undertaken, indicating that specific design and construction improvements need to be identified for these common details.

The Sensitivity of SAP to Input Discrepancies

Description of analysis

Analysis has been undertaken to consider the impact on the Dwelling CO_2 Emission Rate (DER) when a SAP input is used that does not match what is built. Several important limitations of this study should be noted:

- Not every possible input discrepancy could be considered, so some may be under-represented or omitted completely.
- Certain discrepancies will affect a larger proportion of new homes, so are of more importance at a national level. This proportion was based on the expert opinion of the Design & Assessment Tools Work Group, but universal agreement was not reached.
- An 'importance score' was calculated for each discrepancy (DER impact multiplied by proportion of new homes affected).
- Individual results depend on specific assumptions which in practice may vary greatly, so this analysis should be treated as a series of examples.

Key Findings

The three most important SAP input discrepancies appear to be:

1. **Community Heating Distribution Losses:** Tabulated values and default assumptions were considered to be too generous, providing little incentive for assessors use a more carefully derived figure. The impact on DER of a discrepancy can be huge; with documented cases where well over half of the heat from boilers is lost en-route to homes.[3]
2. **Wall U-Values:** DER is very sensitive to wall U-value and there was judged to be a high chance of a discrepancy between the wall U-value input and the as-built value. If there are gaps large enough to allow cold air to circulate behind insulation, a nominally insulated wall could perform similarly to an uninsulated one, potentially resulting in a rate of heat loss several times worse than calculated.
3. **Thermal bridges:** Thermal bridge input discrepancies are likely to be both multiple and very common; *for example, accredited values may tend to be used where in fact default values should be*. In combination, these can make a significant difference to the DER and therefore this is seen as another important area of potential discrepancy.

Other areas found to be important were inputs relating to window performance, overshading, roof U-values, proportion of low energy lights, air permeability and photovoltaic power rating. It is also clear that discrepancies relating to dimensions, especially those which affect floor area, can have a large impact on DER. In combination, the input discrepancies identified have the potential to approximately double the DER of a dwelling. In attempting to close the performance gap it is therefore critical to ensure these SAP inputs match what is actually built.

More detail on this work can be found in Appendix H.

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[3] *E.g. www.pam.ealing.gov.uk/PlanNet/documentstore%5CDC11123716-107-1_AF_A.PDF*

Summary of TSB Building Performance Evaluation Project Analysis

The *Evidence Review Report* included a Literature Review which, alongside other publications, covered all the available reports from the first phase of the Technology Strategy Board's (TSB) domestic Building Performance Evaluation (BPE) programme. Since the *Evidence Review Report* was published, the Zero Carbon Hub has been further analysing eight of the TSB BPE Phase 1 projects, to better understand the issues which contribute to creating a Performance Gap.

The findings from the reports have been assessed against the issues identified in the *Evidence Review Report*, which include problems potentially arising at all stages of the development process. This approach has provided a structure for comparison across the projects that could also be used for future building performance evaluation, both for informing evidence-gathering, and for evidence analysis by providing a means of identifying and categorising common themes.

Analysis is still underway and initial findings demonstrate examples of both good and bad practice, providing very useful current information on Performance Gap issues. Some initial findings included:

- **Planning** - Most projects had specific environmental performance targets set for them at the initial planning stages and these were dealt with at a preliminary stage by the initial design team. Their successful translation was significantly dependent on the continuity of this team into detailed design stages.
- **SAP assessment** - The role of the SAP assessor and the degree of their influence and involvement varied significantly across the projects.
- **Detailed design** - The contract type for projects significantly determined the cohesion with which the design team members worked. Where several sub-contractors were appointed there was a greater need to identify a designated person with responsibility for ensuring that the energy requirements were not undermined due to changes in design and specification. There were examples of good understanding of the specialist knowledge and skills needed to incorporate innovative processes and systems.
- **Procurement** - Several anomalies were observed between the specific systems designed and those procured. This was due to a combination of lack of adequate ownership of ensuring the energy efficiency of the product and a lack of familiarity within the team to meet the design intent.
- **Construction and site coordination** - Projects where the initial environmental targets were tied in with a critical control over the construction processes, like those targeting Passivhaus standards, were the ones where there was more effective site management. These also generally tended to be smaller scale projects.
- **Modelling and testing** - There was significant variation between tested and monitored energy performance indicators and modelled performance.

The detailed information from these developments will contribute to the full evidence review update later in 2014.

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Comparison of whole house heat loss test methods under controlled conditions in six distinct retrofit scenarios

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Comparison of whole house heat loss test methods under controlled conditions in six distinct retrofit scenarios

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Abstract

The difference between the expected thermal performance of buildings and the measured values is a significant phenomenon in new and existing buildings. This ‘performance gap’ can be substantial and impacts building owners and users, with building potentially failing to meet emissions or performance goals. One of the main drivers for measuring the energy performance of buildings is to identify and understand this performance gap.

Total heat loss from a building is the sum of losses transmitted through the building fabric and those caused by ventilation and infiltration. The Heat Loss Coefficient (HLC) is the *rate* of heat loss from the thermal envelope of the building and is used to quantify thermal performance at the whole building level. Two techniques to measure the HLC are the Coheating and the Quick U-Value of Buildings (QUB) methods.

This paper presents a comparison of these two alternative methods within the context of an assessment of fabric retrofit conducted in a test house situated within an environmental chamber. While coheating is shown to be an accurate method, the QUB method produces acceptable accuracy in less time. This has potential implications for the testing of existing and new build domestic properties in the field.

Keywords: Coheating, Building Thermal Performance, Performance gap, thermal performance methods, HLC, QUB, retrofit.

1.0 Introduction

The *performance gap* describes the difference between the predicted and actual thermal performance of buildings. Whole building heat loss tests show that dwellings can experience 60 percent or greater heat loss than designed [1,2]. This can be attributed to a wide variety of reasons ranging from the design and construction of a building to its use by occupants [3].

The final energy consumption in the domestic sector is 27% of total UK final energy use [4]. This has major implications for policy, such as energy efficiency and fuel poverty targets. An understanding of the actual performance of buildings, taking into account the identified performance gap issues, is essential if we are to deliver policy targets and positive outcomes for occupants.

The drivers for energy consumption are manifold. Consumption of energy use in the EU is largely driven by demands for space heating, with an average figure across the EU member states of 68 % of final energy consumption in the household sector [5]. Interactions between the fabric, systems, controls and occupants form complex relationships to determine overall energy use.

The performance gap is compounded by the difficulties of monitoring domestic properties in the field, with many tests proving intrusive and difficult to implement, particularly in occupied properties [6].

Fabric is a major contributor to the overall efficiency of a property when considering heating loads [7]. In retrofit, where existing buildings are raised to higher standards of energy efficiency, in particular, a fabric first approach is recommended [8]. Understanding the building fabric can be approached through qualitative methods such as thermography, or quantitative methods, such as in situ U-values measurements. However, there are also a number of approaches that are used to investigate the whole building performance.

The heat loss from an entire building envelope can be quantified using the Heat Loss Coefficient (HLC). The HLC is the rate of heat loss in Watts from the entire thermal envelope of a building per Kelvin of temperature differential between the internal and external environments (ΔT) and is expressed in units of W/K. The HLC is an aggregate of the total fabric transmission and background ventilation heat losses from the thermal envelope.

This paper compares two methods of measuring the HLC of a dwelling in a unique testing facility at the University of Salford. Using the Salford Energy House allowed the HLC to be measured by both methods at six stages of retrofit under exactly the same conditions. The first method is one of the current leading approaches, the Coheating Test, which can take 1-3 weeks [9]. The second method, which is currently under development is the QUB test, which takes 1-2 days [10]. This has the potential to take the HLC methodology from a research focused tool to wider practical applications. The coheating and QUB methods are not the only whole house approaches, Bauwens and Roels (2014) identify a number of alternative approaches such as PRISM and PSTAR [11].

1.1 Measuring the HLC using coheating

The coheating test is a quasi-steady state method that can be used to obtain an in-situ estimate of the HLC of a building. Bauwens and Roels [11] provides a comprehensive overview of the coheating test. Coheating has existed in various forms since the late 1970’s [12,13,14,15] however, there is presently no international standard. Currently, most coheating tests in the UK have been undertaken using the Leeds Beckett University (formerly Leeds Metropolitan University) Whole House Heat Loss Test Method [16].

A coheating test involves heating the internal environment of a building to an elevated, homogenous, and constant temperature with electric resistance heaters and maintaining that temperature over a period of time, usually 1-3 weeks. Air circulation fans are used to increase the consistency of the internal air temperature. The power input to the building, as well as the internal and external environmental conditions, is monitored throughout the test. The coheating test assumes the following whole house energy balance [17]:

$$\mathrm{Q} + \mathrm{R.S} = (\Sigma\mathrm{U.A} + \mathrm{Cv}).\Delta\mathrm{T}$$

Equation 1

Where:

$\mathbf{Q}$ = Total measured power input from space heating (W)

$\mathbf{R}$ = Solar aperture of the house (m^2)

$\mathbf{S}$ = Solar irradiance (W/m^2)

$\Sigma\mathbf{U.A}$ = Total fabric transmission heat loss (W)

$\mathbf{Cv}$ = Background ventilation heat loss (W)

$\Delta\mathbf{T}$ = Temperature difference between the internal and external environment (K)

In this study the test house is not subject to solar radiation, so the terms **R** and **S** can be removed from the whole house energy balance, and the equation rearranged to show that:

$$\mathrm{HLC} = \frac{\mathrm{Q}}{\Delta\mathrm{T}}$$

Equation 2

1.2 Measuring the HLC using the QUB method

The QUB method is a means of assessing the HLC of a building in 1-2 days. This method was developed by Saint-Gobain [10,18,19,20] and consists of heating the building with constant power during an initial phase and then letting it cool down with almost no power during a second phase. The QUB method involves describing the building as a simple resistor-capacitor (RC) model as shown in Figure 1.

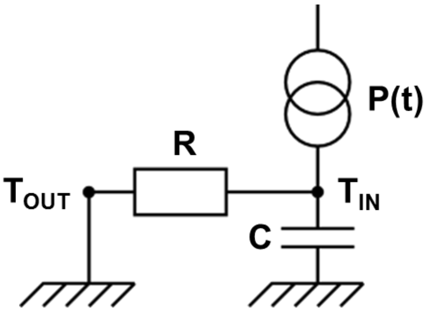

Figure 1. The Resistor-Capacitor (RC) model used in the QUB method for assessing the HLC of buildings.

Two homogeneous temperature nodes, inside and outside the building, are separated by a resistance (R) representing the global thermal resistance of the building. This describes heat losses by transmission and infiltration through the envelope. The inside temperature node is connected to a capacitor (C) which represents the thermal mass inside the building. In field tests it is usually more convenient to measure the power applied to the building so the HLC measurement is usually performed during the night to avoid solar radiation and without occupancy.

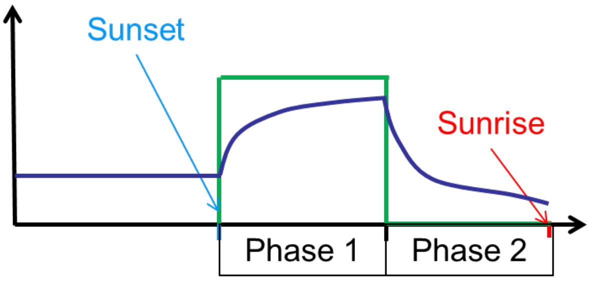

Figure 2. Schematic of temperature development during the two phases.

Figure 2. shows the temperature development through the two phases of the test. At sunset the building is heated with constant power in Phase 1 for a period of a few hours. Phase 2 involves letting the building cool down with almost zero power input for the same duration. In this model the power applied to the building is compensated by the heat loss through the envelope and the heat stored in the building fabric as described in equation 3.

$$P = HLC \times (T_{in} - T_{out}) + C \times dT_{in} / dt$$

Equation 3

Where:

P is the total power applied to the building in Watts, T_{in} and T_{out} are the inside and outside temperatures respectively in Kelvin. HLC in W/K is the inverse of the whole building resistance R introduced previously and C is the thermal mass in J/K.

It is assumed that the temperature response is a single decaying exponential and that its time constant is the product of the thermal resistance and the thermal capacity of the building. In reality the thermal response is more complex and is the superposition of a large number of decaying exponentials but by performing an experiment of an adequate length, after some time only the largest time constant plays a role and the previously described model becomes valid.

Using the two successive thermal loads the static HLC and the thermal capacity can be determined with the following QUB formula:

$$HLC = (P_1 \times a_2 - P_2 \times a_1) / (\Delta T_1 \times a_2 - \Delta T_2 \times a_1)$$

Equation 4

Where P_i is the total power in Watts used in phase i, ΔT_i is the inside-outside temperature difference at the end of phase i and a_i is the slope of the inside temperature variation at the end of phase i.

There are some experimental conditions that may be used to reduce the duration of the testing procedure [21]. The HLC measured with a QUB experiment is the product of the static HLC and a corrective factor. This is a result of the superposition of large time constants which still play a role in short experiments. The duration of the experiment can be increased or the heating power can be optimized in order to perform measurement of the HLC by the QUB method. The following criterion has been identified:

$$P_1 \sim 2 \times HLC \times (T_{in,0} - T_{out})$$

Equation 5

Where $T_{in,0}$ is the initial inside temperature and T_{out} the average outside temperature during the experiment.

1.3 The Salford Energy House

The Salford Energy House is a full scale pre-1919 solid-wall Victorian end-terrace house constructed inside an environmentally controlled chamber at the University of Salford [22]. The construction of the Salford Energy House Test Facility was achieved by using reclaimed materials and methods of the time. An adjacent house is also present so that the effects of a neighbouring property can be explored during experiments.

1.3.1 Energy House construction

The Energy House Reference case had the following construction:

- Solid brick walls 225.5 mm thick arranged in English bond (with every fifth course being a header row), with 9 mm mortar joints 12.5 mm hard wall plaster to inside face of wall with 2 mm skim as finishing coat. Magnolia paint to internal face of wall.
- The house is built off a reinforced concrete raft with no insulation added. A 200 mm gap exists between the house and this raft; this forms a ventilated floorspace and allows for a constant airflow beneath the house. The floor is suspended on 200 mm timbers and is finished off with 22 m floor boards (non-interlocking and non-sealed).
- The windows are double glazed units of a type found circa 2000. The doors are UPVC of amid range type, in terms of thermal performance.
- The roof is a timber rafter and purlin roof with 100 mm insulation at the time of the initial tests. A layer of mineral wool insulation. There is a small amount of eaves ventilation, sarking felt is installed.
- The party wall is a solid wall construction to match the external walls, and remained unplastered on the neighbouring side.

The construction of the neighbouring building is as follows:

- This building has a layer (60 mm) of closed cell foil backed insulation, to the external facing walls only, and not the party wall.
- The external facing walls are solid brick as above.
- The gable of this building is concrete block (2 skins of 100 mm with a 20 mm air gap).
- The loft has 200 mm of insulation.
- The doors are single skinned timber panel doors; the rear door is half glazed with single glazing.

- The floors are constructed in the same manner as the other building.

1.3.2 Environmental Chamber

The environmental chamber is a large reinforced concrete structure. The dimensions are 11.1 m wide, 9.3 m deep and 7.4 m high. This gives a chamber volume of 763 m^3. The chamber walls are insulated with 100 mm PIR foam insulation to the walls and ceiling and 35mm expanded polystyrene insulation to the floor element (reinforced concrete slab on short bored piles). This helps to isolate the chamber from external influences such as wind, rain and solar gain.

The chamber has the ability to maintain a constant temperature between the range -12°C and +30°C with an accuracy of +/-0.5°C at a 5°C setpoint. The chamber is cooled by an air handling unit that is supplied with cooling by 4 No. condenser units, with a total of 60 kW of cooling (15 kW per unit). This is supplied to the chamber via a ducted HVAC system. This system reacts to the heat load of the house in the chamber and maintains a setpoint of ± 0.5°C.

Figure 3. The Salford Energy House within its environmental chamber

1.4 Retrofit

Retrofit, or sustainable retrofit, can be defined as improvements made to the fabric, systems or controls of a property to specifically improve the energy performance of a building [23,24]. Retrofit is a response to reducing energy consumption in the built environment, considering that some 60-80% of buildings standing in 2050 have already been built. Retrofit is as subject to performance gap issues as new buildings [25].

The HLC measurements took place during a series of measures to improve the thermal performance of the Energy House. The retrofit programme provided the opportunity to measure the HLC of the test house at each retrofit stage using both the coheating and QUB test methods. The staged nature of the test programme meant that the test house HLC was measured under a range of HLCs which included differing rates of fabric and ventilation thermal transmission from the building envelope, as well as differing thermal mass characteristics.

1.5 Uncertainty

Uncertainty for the coheating method in measuring the HLC obtained was calculated by error propagation of the uncertainty associated with the measured variables Q and $\Delta\mathrm{T}$ in equation 2.

Uncertainty for the QUB method was calculated by error propagation in the equation 4. For each parameter entering this equation we calculate the uncertainty associated to it. This reflects the uncertainty linked to the quality of the temperature measurements (temperature homogeneity, sensors accuracy, etc.) and so the uncertainty due to the experimental apparatus (heating system and sensors) used. It does not integrate the uncertainty linked to the choice of the model which could lead to a systematic bias. This work is still on-going and will be published in a separate paper.

2.0 Methodology

Two sets of tests were carried out at each stage of the retrofit over the same testing period. The coheating tests were carried out by a team from Leeds Beckett University and the QUB measurements were conducted by a team from Saint-Gobain Recherche.

2.1 Retrofit programme

The thermal upgrade measures that were applied to the test house during the test programme are set out in Table 1.

Table 1. The thermal upgrade measures applied to the test house.

Solid wall insulation (SWI)	Internal Wall Insulation (IWI) on the front wall: A thermal laminate board “British Gypsum ThermaLine” comprising 80 mm PIR rigid insulation board (λ = 0.022 W/mK) with vapour control barriers bonded to 12.5 mm Gyproc WallBoard formed the main insulating layer of the IWI system.
	External Wall Insulation (EWI) on the gable and rear walls: Weber Therm EWI system comprising 90 mm EPS boards (λ = 0.037 W/mK) were mechanically fixed to the external walls. A glass fabric mesh was applied over the first render coat then a render coat finish.
Suspended timber floor insulation	200 mm Isover Renovation Roll Thermal mineral wool insulation quilt (λ = 0.035 W/mK) suspended by Insumate tray system between floor joists. An Isover Vario KM Duplex UV nylon based microporous airtightness and moisture membrane installed below the floorboards with overlaps and floor perimeter sealed with Isover KB1 adhesive tape
Fenestration	Replacement A+++ rated glazing units with argon fill and Low-E coating. No change was made to the window frames
Loft insulation	170 mm Isover Spacesaver mineral wool quilt (λ 0.043 W/mK) laid above 100 mm existing insulation, perpendicular to the ceiling joists

The retrofit was performed in five stages and included one or a combination of the previously described components. A summary of the stages is presented in Table 2.

Table 2: Summary table of the different stages of the retrofit performed and the elements upgraded.

Test stage	**Thermal element subject to upgrade**			
	Wall	**Ceiling**	**Glazing**	**Floor**
Full retrofit	X	X	X	X
Full retrofit without floor insulation	X	X	X	

Solid wall insulation	X			
Glazing			X	
Loft		X		
Reference				

2.2 Coheating test HLC measurement

A modified version of Leeds Beckett University's 2013 Whole House Heat Loss Test Method [16] was used to measure the test house HLC at each retrofit stage. The test method was modified to account for the absence of dynamic external environmental conditions such as temperature fluctuations, solar radiation and wind.

To ensure continuous heat flow through the building envelope to the test chamber during the coheating test, a constant ΔT of 15 K was selected. The test chamber HVAC system was set to maintain an air temperature of 5°C. A constant internal air temperature of 20°C was achieved using portable electric resistance heaters located within each room of the test house; each heater was controlled by a fuzzy-logic thermostat connected to a RTD temperature sensor. Two air circulation fans on each floor facilitated a homogenous air temperature throughout the test house. The internal air temperature of the neighbouring house was also maintained at 20°C during each coheating test to minimise inter-dwelling heat transfer across the party wall.

Internal and external air temperatures were measured using shielded RTD temperature sensors. The electrical energy consumption of the heaters, fans and logging equipment was measured using an energy meter with pulse output; registering one pulse per 1 Wh. Measurements of heat flux density through each thermal element were also undertaken during each test using heat flux plates in accordance with ISO 9869 [26]. Data was collected at one minute intervals throughout each test.

For the energy balance in Equation 2 to be strictly valid, a steady state between the internal and external environment should be in existence. A steady state was evident when a constant rate of power input to the test house, and constant rate of heat flow through its thermal elements, was measured. Each coheating test had a minimum duration of 72 hours; this period allowed the thermal elements of the test house to reach thermal capacitance. During coheating the test house and chamber were left undisturbed. The HLC was derived from measurements obtained during the final 24 hours of each coheating test when a steady state was achieved.

2.3 QUB method HLC measurement

In order to heat the house quickly and homogeneously it was necessary to use low power sources with low inertia. Aluminum-covered heat mats of around 100 W were rolled and placed vertically to minimize heat exchange with the floor. Most of the energy was therefore dissipated through the air via natural convection. Using this equipment meant that improved reproducibility of the measurements and a homogeneity of the inside air temperature was achieved. The heating was controlled electronically to perform the forced heating and free cooling phases automatically without occupant inside.

Temperature measurements in the centre of each room were taken using a network of thermistor sensors with a resolution of 0.1°C and an accuracy of ±0.5°C within the range 10°C to +85°C.

The monitoring system allowed for many readings, including gas and electricity consumption, to be recorded as well as all the sensors in the house.

3.0 Results

3.1 Coheating measurement

The HLC measured during the coheating test at each stage of the retrofit process is provided in Table 3.

Table 3. HLC of the test house each retrofit stage measured during coheating

Test stage	**HLC (W/K)**
Full retrofit	69.7 ± 2.9
Full retrofit without floor insulation	82.7 ± 2.8

Solid wall insulation	101.2 ± 2.8
Glazing	174.2 ± 3.2
Loft	180.5 ± 3.2
Reference	187.5 ± 3.2

3.2 QUB measurement

The temperature response of all the rooms in the Energy House during a QUB measurement and the average used for HLC calculation at the full retrofit stage are shown in Figure 4.

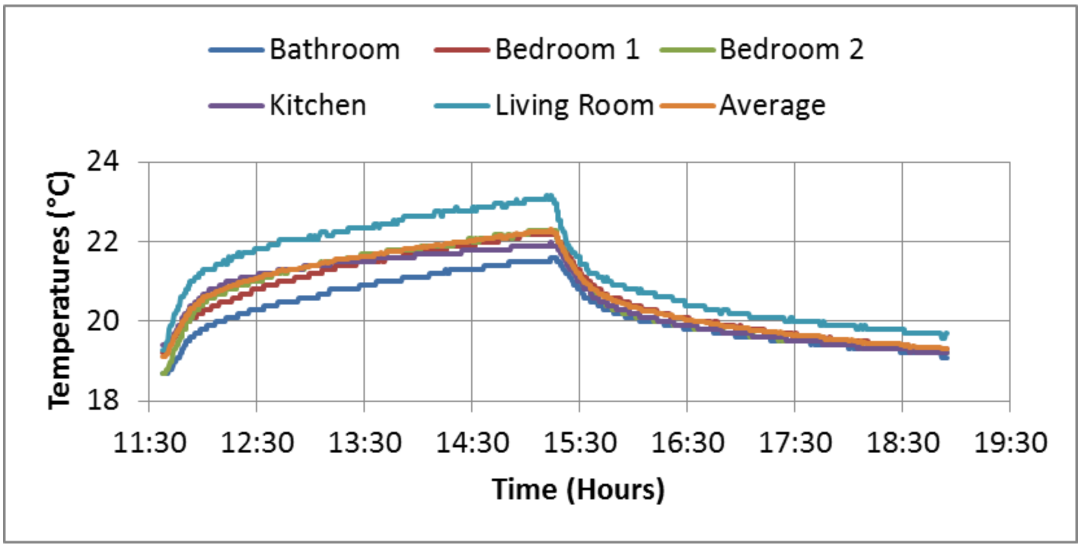

Figure 4. Room temperatures during a QUB measurement.

The room temperatures in different rooms exhibited very similar progressions. Using the average of both floors temperatures, the calculation of gradients at the end of each phase was performed and the data analysis is shown in Figure 5.

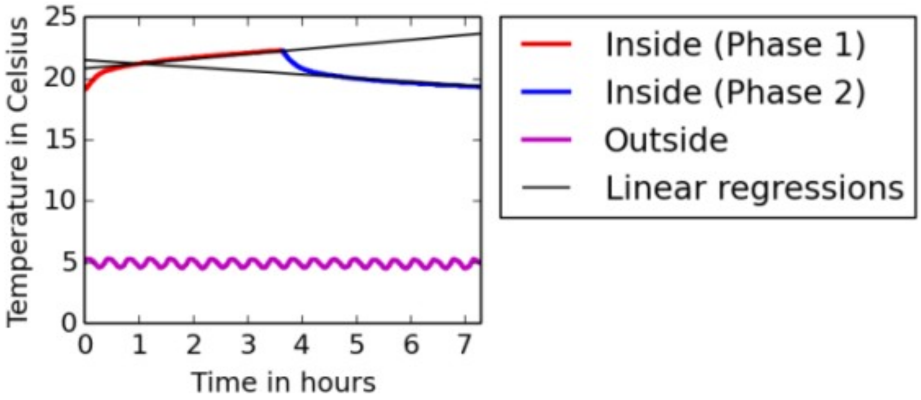

Figure 5. Inside/Outside temperature and data analysis during a QUB measurement.

Temperature inhomogeneity between the different rooms was not taken into account. The data analysis could have been improved by considering each zone independently and performing a QUB analysis on each zone of the building, then it would be necessary to measure the heating power and the temperature associated to each zone. Even if the result for each of these may be incorrect due to additional heat transfer between the different zones, the summation of all the zone heat losses should reflect the whole building HLC. In this paper we present a single zone analysis by using the average inside temperature. The summary of the results obtained for the different stages of the retrofit where a single measurement had been performed is shown in table 4.

Table 4. QUB parameters assessed during the various measurements and results for the HLC identified.

Test stage	**Full retrofit**	**Full retrofit without floor**	**Solid wall insulation**	**Glazing**	**Loft**	**Reference**
Heating duration (hh:mm)	3:38	0:35	3:57	3:59	3:59	3:58
Criterion power (W)	1907	2594	3090	5463	5511	5658

P1 (W)	2495	2984	3418	4946	5415	5912
a1 (°C/hour)	0.42 ± 0.05	2.39 ± 0.23	0.37 ± 0.04	0.29 ± 0.03	0.4 ± 0.03	0.45 ± 0.05
ΔT1 (°C)	16.4 ± 0.4	17 ± 0.4	18.4 ± 0.4	19.2 ± 0.17	19.4 ± 0.4	19.7 ± 0.5
P2 (W)	125	303	136	150	139	141
a2 (°C/hour)	-0.33 ± 0.06	-2.1 ± 0.2	-0.45 ± 0.07	-0.63 ± 0.08	-0.64 ± 0.09	-0.68 ± 0.09
ΔT2 (°C)	14.1 ± 0.4	15.9 ± 0.4	14.7 ± 0.4	13.5 ± 0.4	13.4 ± 0.5	13.1 ± 0.5
QUB HLC (W/K)	77 ± 8	95 ± 6	116 ± 8	198 ± 8	198 ± 10	212 ± 11

4.0 Discussion

QUB tests were undertaken by Saint-Gobain at each stage of the retrofit following the coheating testing by the Leeds Beckett University. Figure 6 shows a comparison between the QUB measurement for each stage of the retrofit with the coheating measurements. During the full retrofit tests the heating phase stopped after half an hour due to an electrical issue. Despite this shortened time the results were found to have less than a 15% difference with the coheating result.

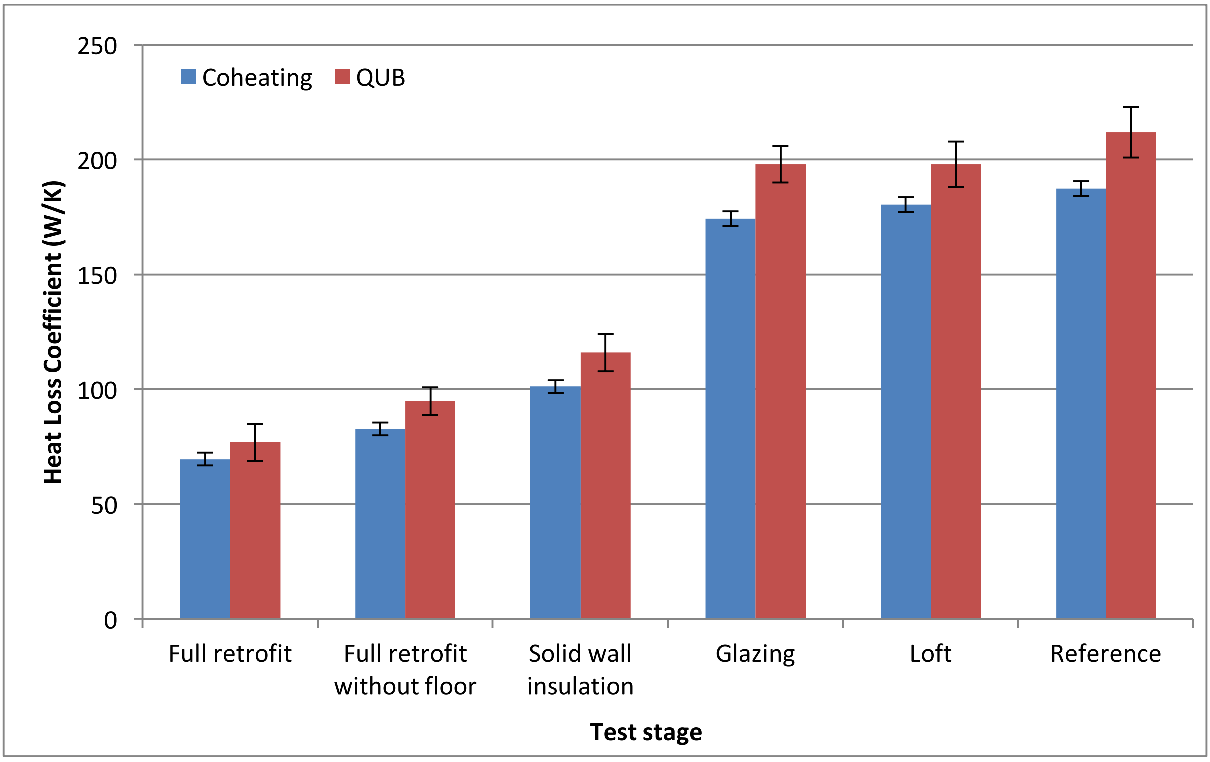

Figure 6: Comparison of HLC identified by coheating and QUB measurements for the various stages.

A close correlation between the two testing methodologies at all stages of retrofit is apparent. This demonstrates that the QUB method is a useful tool in determining whole building heat loss in a relatively short period of time, less than 8 hours in these experiments. It can also be seen that the QUB method is robust as indicated by the correlation with the results from coheating at all stages of retrofit.

A maximum deviation of 15%, with an average deviation of around 13%, was obtained at the solid wall insulation stage. These results demonstrate that both methodologies are very powerful tools to determine whole building heat loss.

These results have been obtained using a unique testing facility within a climatically controlled chamber with constant external temperature and no solar radiation. Validation in the field remains to be done.

By performing the retrofit by stages the contribution of each stage to the whole house HLC can be determined. This is summarised in Table 5.

Table 5. HLC gain for each stage identified using coheating and QUB

	Coheating HLC gain in W/K (% of the ref. HLC)	Uncertainty in W/K (%)	QUB HLC gain in W/K (% of the ref. HLC)	Uncertainty in W/K (%)
Full retrofit	-117.8 (-63)	4.3 (3)	-135.0 (-64)	13.6 (7)
Floor insulation	-13.0 (-7)	4.0 (2)	-18.0 (-8)	10.0 (5)
Solid wall insulation	-86.3 (-46)	4.3 (2)	-96.0 (-45)	13.6 (7)
Glazing	-13.3 (-7)	4.5 (2)	-14.0 (-7)	13.6 (6)
Loft	-7.0 (-4)	4.5 (2)	-14.0 (-7)	14.9 (7)
Estimation based on the sum of single element upgrade	-119.6 (-64)	8.7 (5)	-142.0 (-67)	26.3 (13)

The uncertainty of each upgrade is higher using QUB than coheating. This can be explained by the duration of the measurement which is much shorter than when using coheating. In cases when the measurement is of relatively modest improvements of thermal performance coheating will be more accurate. It is notable that the relative benefits of the stages are better estimated by using QUB rather than coheating method. This suggests that a systematic bias might exist and further research is needed.

With regards to individual upgrade measures, it is apparent that the greatest improvement is obtained when using solid wall insulation, with around a 46% reduction of heat loss. This is reasonable as the greatest heat loss area are the opaque walls.

The improvements from glazing, floor and loft insulation contribute reductions of 7%, 7% and 4% respectively. These lesser improvements are due to the smaller ratio of associated heat loss area compared to the whole area and by the minimum loft insulation and glazing elements in the reference case.

Finally, from the measurements of each element's contribution we can estimate the full retrofit improvement by combining them. This estimation differs by less than 1%

of the whole HLC from the coheating tests and less than 4% for the QUB method. This suggests that the coheating method maybe a more precise method for HLC estimation in this test environment.

This also suggests that there is no additional contribution coming from the combination of element upgrades, nor a higher loss that could be caused by thermal bridging. This must be considered as the uncertainty is comparable to the difference. From the coheating measurements uncertainty there is a maximum potential difference of 5% of the reference HLC. This must be compared to the large improvement from thermal insulation which is almost 63% of the reference HLC.

5.0 Conclusions

In this paper we have presented a unique experiment that assessed the HLC of a retrofitted building located in a climatic chamber. Starting from a baseline representative of the current UK house stock element upgrades of each component using widely available retrofit products were performed. At each stage two different measurements to assess the HLC of the building were taken. First, a reference measure was obtained using a modified coheating methodology equivalent in this case to a static measurement. Secondly, the dynamic QUB method was used to investigate the possibility of reducing the duration of a measurement without a significant loss of accuracy.

With regards to the methodologies used we showed that both methodologies can be used to assess the HLC of a building whatever the thermal inertia and insulation level of the building. Coheating appears to be an accurate method for thermal diagnosis whereas QUB provides a reasonable accuracy in a much shorter duration. These methods have a non-negligible uncertainty which must be considered.

Although it can appear difficult to use these measurements to guarantee less than 10% in small improvements of the fabric, significant retrofit actions can be assessed using these methods. It could be used to qualify the thermal performance of buildings to be retrofitted to assess the potential need of envelope improvements. It could also be used at the commissioning stage of new-built or retrofitted buildings to validate the predicted thermal performance.

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Appendix Drawings of House

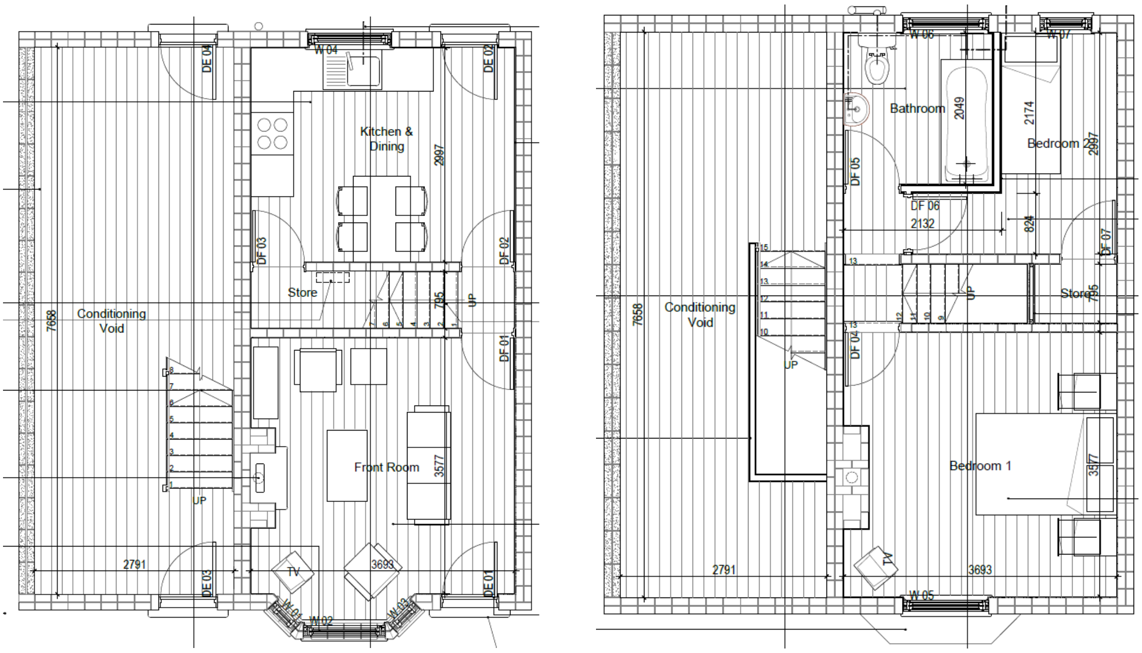

Figure 7. Floor Plans of Energy House

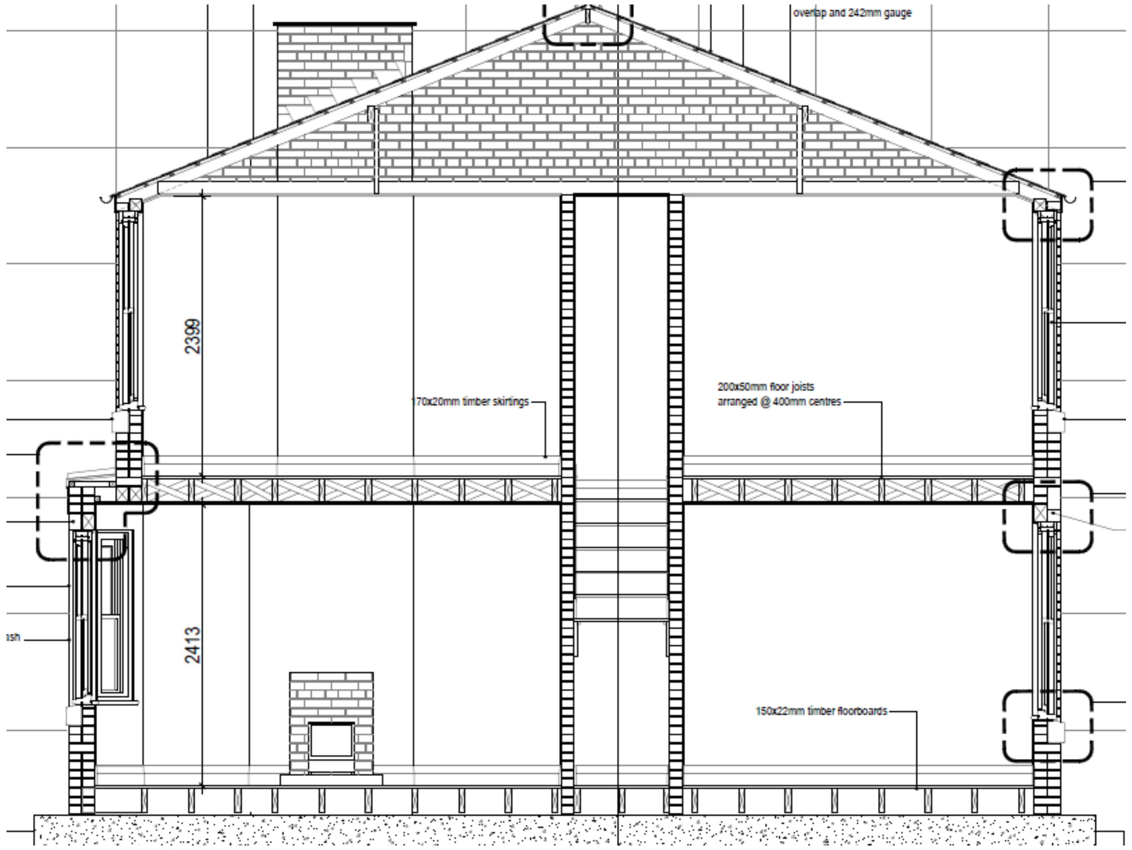

Figure 8. Section of Energy House

QUB: a fast dynamic method for in-situ measurement of the whole building heat loss

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Abstract: QUB is an innovative method for the experimental measurement of the total heat loss coefficient (HLC) of a building envelope in less than 48 h and usually in only one night. It is based on a very simple theory, yet can be demonstrated to be accurate even in a very short time and in complex buildings, as long as certain experimental conditions are fulfilled. QUB is validated by both theoretical and experimental approaches. Different models based on RC networks and thermal quadrupoles and several test cases are presented in order to prove the feasability, validity and accuracy of this method in different conditions. Validation tests are mainly done in a unique facility where steady-state can be reached experimentally: the Energy House, developed by the University of Salford, built inside a chamber whose temperature can be regulated. Steady-state and QUB values of the total HLC are compared, showing very good agreement between both methods when the experimental setup is optimized.

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QUB: a fast dynamic method for in-situ measurement of the whole building heat loss

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Abstract

QUB is an innovative method for the experimental measurement of the total heat loss coefficient (HLC) of a building envelope in less than 48 h and usually in only one night. It is based on a very simple theory, yet can be demonstrated to be accurate even in a very short time and in complex buildings, as long as certain experimental conditions are fulfilled. QUB is validated by both theoretical and experimental approaches. Different models based on RC networks and thermal quadrupoles and several test cases are presented in order to prove the feasability, validity and accuracy of this method in different conditions. Validation tests are mainly done in a unique facility where steady-state can be reached experimentally: the Energy House, developed by the University of Salford, built inside a chamber whose temperature can be regulated. Steady-state and QUB values of the total HLC are compared, showing very good agreement between both methods when the experimental setup is optimized.

Keywords:
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1. Introduction

The reduction of the energy consumption of buildings is one of the main ways identified to reduce the overall energy use, especially in today's developed economies. Technical solutions to reduce this consumption exist. Some are related to the occupants' needs, by optimizing the heating and cooling schedule. Most aim at improving the quality of the building's intrinsic energy performance, for instance by increasing the insulation of walls, windows, roofs, by improving the building's airtightness, or by improving the architectural design, among others. But there is no easy way to control the quality of the finished building. Methods and standards exist to measure this performance gap, but some of these have found to be lacking in standardized method and other difficulties, thus measurement is not widespread [1]. Therefore there is a growing body of the evidence which highlights the performance gap in newly built dwellings [2]. This performance gap could undermine the acceptance of energy improvement programs if costs associated with energy performance in construction or deep renovation do not appear to lead to reduced energy consumption. It seems, therefore, important to be able to identify, as soon as a construction or renovation is finished, a building with a high performance gap.

A second difficulty regarding the characterization of energy performance of buildings is the choice of the appropriate indicator. The final aim is of course to understand and reduce the energy consumption, but this factor is also strongly influenced by occupants' behavior (interior temperature, occupation time, opened enclosures) or weather conditions (external temperatures, solar radiation, rain). Thus, studying the energy consumption itself requires the ability to compare the energy use with that which would have been reached for given occupation scenario and weather. This can be done, but is a rather long and difficult task which also requires a large data set, i.e. a long period of measurement of all the relevant powers, temperatures and many other informations regarding climatic conditions and building occupation.

A different choice is an indirect indicator, representing not the energy consumption, but the intrinsic thermal loss of a building envelope. A common such indicator is the Heat Loss Coefficient (HLC), expressed in W/K, which represents the thermal power loss due to the thermal difference between interior and exterior temperatures (independently of the solar radiation), divided by this temperature difference. The HLC is the sum of two effects: transmission losses and air infiltration losses. It is a global parameter, related to the overall building envelope, and, therefore, is the sum of the losses through all envelope components.

The main advantage of the HLC is that it is a parameter simple enough so that it can actually be measured in several ways, for example by a co-heating test [3], by the PStar method [4], or by identification methods [5], among others [6]. Additionally, its theoretical value can be easily calculated for a building. It is thus possible to compare design and measured value of this parameter and estimate a performance gap related to the building envelope.

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These measurement methods of the HLC have the same drawback: the measurements need several days or even weeks. This might be satisfying for a research project, but it cannot be applied at a larger scale, which means that these methods have a limited application. It is, therefore, important to search for a method that would be both much faster, and as reliable as the other ones. Such a method is presented in this paper; it is called QUB [6, 7, 8, 9, 10, 11].

QUB has been shown to be able to measure the HLC of a dwelling in at most 48 h [8, 11]. This method can in principle be adapted to any kind of building. This may seem deeply counter-intuitive as buildings have time constants that can be much longer than this value. For this reason, this paper presents the theoretical, numerical and experimental evidences for the validity of the QUB method in two stages. In the first, RC models are used to explain QUB in a simple way that enables a good understanding of the theoretical bases and the proper experimental conditions for the test. In the second stage, another approach is shown using a quadrupole model. This method is more complex than the first but is also more detailed, and yields important results for the optimization of the QUB test. For both approaches, a theoretical model is presented and is then validated using several cases, both numerical and experimental.

2. RC models

2.1. Description of the QUB method

The QUB method, at its heart, is a dynamic analysis method in which the HLC denoted H_{tot} is calculated by using the interior air temperature response to two consecutive internal thermal loads. The simplest model one can use to represent a body submitted to transient heat transfer is probably the lumped capacitance analysis with internal energy generation. It supposes that the interior of the body is at homogeneous temperature, that all exchanges happen with a medium of homogeneous temperature through an infinitely thin interface, and that the exterior temperature is constant. Thus, it is an RC model with only one resistance and one capacity. The result is the well-known Eq. 1.

$$C_{\mathrm{QUB}} \frac{\mathrm{d}T^*}{\mathrm{d}t} = \Phi - H_{\mathrm{QUB}} T^* \quad (1)$$

where C_{QUB} is the apparent internal heat capacity [7, 12] of the body in J/K. It corresponds to the total energy stored in the body, going from one steady-state to an another, when its interior temperature increases by 1 K. Φ is the internal power in W brought by all internal heating sources , H_{QUB} is the HLC identified with this method and T^* is the difference between the interior and exterior temperatures in K. If two separate experiments (1) and (2) are done, with two different powers, and if we assume H_{QUB} and C_{QUB} to be constant during these two experiments, then

$$H_{\mathrm{QUB}} = \frac{T'_{(1)}\Phi_{(2)} - T'_{(2)}\Phi_{(1)}}{T'_{(1)}T^*_{(2)} - T'_{(2)}T^*_{(1)}} \quad (2)$$

$$C_{\mathrm{QUB}} = \frac{\Phi_{(1)}T^*_{(2)} - \Phi_{(2)}T^*_{(1)}}{T'_{(1)}T^*_{(2)} - T'_{(2)}T^*_{(1)}} \quad (3)$$

where we introduced $T' = \mathrm{d}T^*/\mathrm{d}t$. Thus it is quite easy in this simple case to calculate H_{QUB} from only two experiments with two different interior heat loads. Of course, such a model is too crude to represent the real behavior of a building; more nodes are needed for that. The model we then used is a larger RC network with an indefinite number of nodes n (but with a unique internal ambient temperature, hence homogeneous inside the building). The problem takes the form of a system of n differential equations with n unknown temperatures. It is well-known that the temperatures evolution in time is a summation of n time exponential decays. If we focus on the interior node, the long-term temperature value is given by $\lim_{t\to\infty} T^*(t) = \Phi/H_{\mathrm{tot}}$ in the case of heating of constant power Φ. The general solution takes therefore the form of Eq. (4).

$$T^*(t) = \frac{\Phi}{H_{\mathrm{tot}}} + \left[T^*(0) - \frac{\Phi}{H_{\mathrm{tot}}}\right] \sum_{i=1}^{n} a_i e^{-t/\tau_i} \quad (4)$$

where τ_i are time constants (it will be assumed here that they have an increasing value from τ_1, the smallest time constant, to τ_n, the largest) and a_i are constants depending on model resistances and capacitors and on initial conditions.

By injecting Eq. (4) in Eq. (2) it is easy to reach the conclusion that $H_{\mathrm{QUB}} = H_{\mathrm{tot}}$ if Eq. (5) is true.

$$\frac{\sum_{i=1}^{n}\left[a_{i,(1)}/\tau_i\right] e^{-t_{(1)}/\tau_i}}{\sum_{i=1}^{n} a_{i,(1)} e^{-t_{(1)}/\tau_i}} = \frac{\sum_{i=1}^{n}\left[a_{i,(2)}/\tau_i\right] e^{-t_{(2)}/\tau_i}}{\sum_{i=1}^{n} a_{i,(2)} e^{-t_{(2)}/\tau_i}} \quad (5)$$

Equation (5) is obviously true if $n = 1$, but it must be noted that it also becomes true when $t_{(1)}$ and $t_{(2)}$ increase enough so that all values of $\exp(-t/\tau_i)$ become negligible except $\exp(-t/\tau_n)$. This means that after a sufficient time $t_{\mathrm{L}} \gg \tau_{n-1}$, the problem with multiple nodes and time constants can be treated as if only one time constant existed. If this sufficient time is shorter than a night, then the QUB method can be applied experimentally when solar radiation is nil. This verification, mostly done experimentally, is presented in 2.2.

2.2. Experimental setup

The QUB method is based on very simple equations and considerations. Some of them have an important influence on the way the tests have to be done. For instance, in Part 2.1, the thermal power is considered constant and known with accuracy. This means that it is important to eliminate or reduce all sources of uncertainty. The most important step in that direction is to do the test during the night without occupancy. Without solar or internal loads, the heat source used for the test can be measured with accuracy, especially if it is an electrical heater, and in particular a simple Joule effect heater with very low inertia. Other heating systems either require conversion coefficients (gas boiler, wood burner, heat pumps...) or decrease the accuracy of the test by reducing the knowledge of the instantaneous power dissipated (inertial heating). However, even with an electrical heater, it is essential to measure the real power consumed. Indeed, the voltage cannot be assumed to be equal to its theoretical value. For instance, a deviation of 5 % of the network voltage leads to a larger deviation of Φ and thus of H_{QUB} of about 10 %. This means that it is difficult to guarantee good accuracy of the test results unless the heating source is not the one already installed in the house, but is a specific test material that is brought into the building.

Besides, the interior ambience is considered to be a single node. The internal temperature is thus implicitly considered homogeneous, even if there are several rooms or even floors. But heating a building in a way that the temperatures in all rooms are identical, or at least close to each other, is a difficult task in a dynamic test. It requires the power to be adapted to each room. There are two ways to do this. The first is to regulate the power of each heating element, depending on the temperature of the room in which it is placed. It is thus possible to ensure a perfectly homogeneous heating, but the system required to do this is rather complex. The second way is a heating source that can be easily adapted to each room's surface. This solution has been used and consists in the use of a large number of small power heat sources (approximately 100 W), placed in a way designed to maximize the convective heating, and reduce direct heating of the walls by radiation, or of the ground by conduction (see Fig. 1). The number of mats shall be calculated using the design heat loss figure for the building, or when this is not available, a simple steady state heat loss calculation, for example RdSAP in the UK [13]. This installation has been shown [11] to improve reliability and reproducibility. An alternative would be to use usual fan heaters with various powers to be selected.

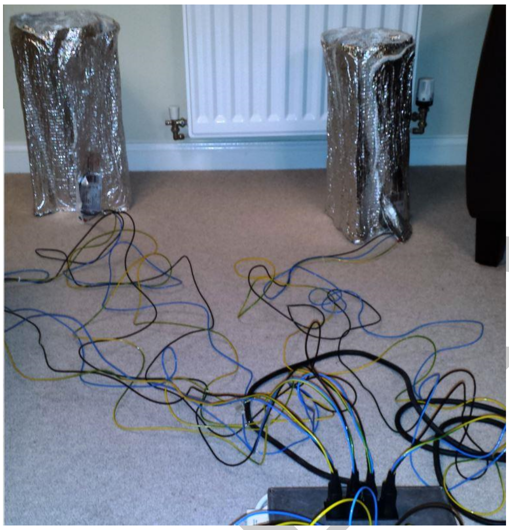


Figure 1: Aluminum heat mats of about 100 W used to perform the heat load. All are connected to boxes allowing to switch simulteously ON/OFF at requested time.

The QUB method requires two different powers to be applied. For practical rather than theoretical reasons (mainly related to the possibilities of the equipment used), most of our tests are done with 100 % of the installed power in the first stage and 0 % in the second. But these two stages have to be done during the night. There are two ways to do this. The first is to have each stage during an entire night, which leads to a test duration of about 36 h (less than 48 h with preparation and clean-up); the second is to have both stages in the same night, for a test duration of 8 to 12 h (less than 24 h in total).

Eq. (5) shows that test duration must be as long as possible, but also that if we assume that there is no strong influence of the initial conditions on the values, that is to say if $\forall i, a_{i,(1)} \approx a_{i,(2)}$, then $H_{\mathrm{QUB}} = H_{\mathrm{tot}}$ only if $t_{(1)} = t_{(2)}$. For this reason, and because it has been shown to to lead to more accurate and more reproducible experimental results [11], this condition is used in all tests in this paper. Furthermore, each variable of Eqs. (2) and (3) is calculated at the end of each stage. This data analysis period must be long enough to reduce the measurement noise, but short enough to ensure that the calculated data are representative. There is no absolute optimal value for this duration; it must be evaluated on a case-by-case basis depending on the measurement noise and the duration of each stage.

2.3. Validation of the QUB method

Although several validation cases exist, either on numerical [10] or on real [10, 9] buildings, the one presented here is probably the most conclusive. It has been done in the Energy House at the University of Salford [14]. The Energy House shown in Fig. 2 is constructed to meet the specification of a typical 1910 terraced property from the UK that has been through reasonable modifications. The house is located inside a well insulated concrete chamber which has a solid concrete floor. It consists of a test house, connected via a party wall to a smaller neighboring building. The heating system is a gas condensing combination boiler fed via a wet system to radiators in each room in the test house and electric panel heaters in the neighboring house. The chamber itself is cooled by an air handling unit that is supplied with cooling by 4 condenser units, with a total of 60 kW of cooling (15 kW per unit). This is supplied to the chamber via a ducted HVAC system. This system reacts to the heat load of the house in the chamber and maintains the temperature in a range of ± 0.5 K around the setpoint. Tests have been done in different configurations, two are presented here: with and without insulation over the ceiling. Additional technical information on the Energy House can be found in [14, 8].

Figure 2: Energy House of the University of Salford. It is a full size typical Victorian House build inside a climate chamber.

The Energy House is therefore a real building which can be submitted to either a variable or a constant external temperature. It can hence be used to measure the value of H_{tot} in steady-state conditions, and compare the value obtained with the QUB method with a reference with a low uncertainty—something that is very complicated to have in a building in external conditions. An example of a steady-state measurement is presented in Fig. 3. In this case, the HLC is calculated by simply dividing the power by the temperature difference between inside and outside, both values averaged over the considered 12-hour long period (between the two vertical solid black lines).

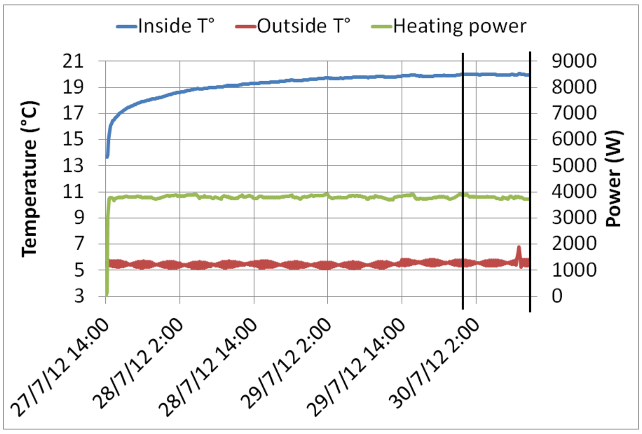


Figure 3: Steady-state measurements at the Energy House in Salford. The solid blue is the average inside temperature, the solid red is the outside temperature and the solid green is the heating power. The period used for average is delimited by the two solid black lines.

Such a calculation can be considered to give reference values H_{ref} of the HLC H_{tot}. An example of inside temperature evolution is presented on Fig. 4. It shows the average temperature measurements on the house, and curves derived from an RC model with two time constants. One is the best fit found called Fit, and one is the same model with only the largest time constant identified call Trend. It thus shows the exponential trend towards which the model tends. The model used is derived from Eq. (4) by keeping only two time constants. This corresponds to a RC model with two capacitors and a minimum of two resistances.

Fig. 4 shows that the model fits the data rather well; although three or more time constants would be needed for a perfect fit, two seem sufficient in these specific conditions to describe the behavior of the air temperature. Furthermore, the first time constant is around 23 minutes and has significant effects for only an hour in this specific case. After that, the temperature behaves as a single exponential function. This tends to confirm the logical reasoning presented in Part 2.1 and thus show that the QUB method can indeed be applied.

Yet showing that QUB can be applied does not mean that it actually works. For that, it is necessary to compare the results of the QUB method with the reference given by the steady-state measurements. The results of three different QUB tests are presented in Table 1. They show each test's characteristics, the durations of the heating and the cooling phases, the reference values and the results of the QUB test.

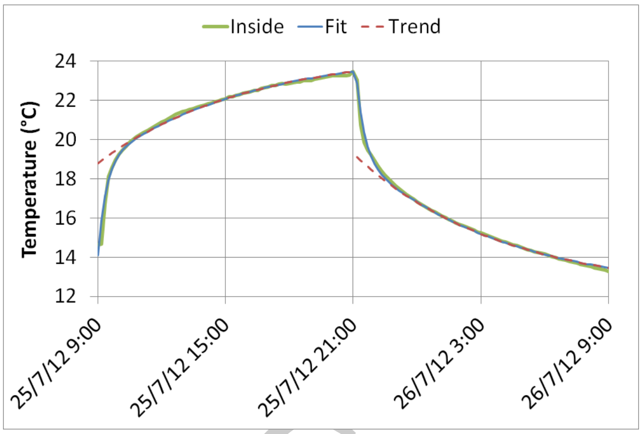


Figure 4: QUB measurements at the Energy House in Salford. The solid green lines represents the average inside temperature, the solid blue is the best fit obtained using a two time constant model and the dashed red is the trend using only the largest time constant of the best fit.

Case	1	2	3
$t_h = t_c$ [h]	12	8	12
Roof insulation?	No		Yes
H_{ref} [W/K]	263.9 ± 2.7		209.5 ± 2.3
H_{QUB} [W/K]	255 ± 9	264 ± 8	216 ± 7

Table 1: Results of three measurements at the Energy House in Salford in two different building configurations.

Uncertainty for the HLC obtained from the static and QUB measurement was calculated by error propagation of the uncertainty associated with the measured variables Φ and T in Eq. (2). The differences between H_{ref} and H_{QUB} are very low, which is strong evidence of the reliability of the QUB method. The theoretical basis of the QUB method and its experimental feasibility and accuracy are therefore proven.

Yet some important questions remain, in particular, about the relation between the error, the building characteristics, and the test duration. For instance, H_{QUB} is theoretically equal to H_{ref} if $t_h = t_c > t_L$. But the model described in Part 2 does not say how large the error is if $t_h = t_c < t_L$. To have an idea about this, tests with different durations have been done in Salford, with t_h being as low as 0.5 h. The result of several such tests compared to the reference value are presented in Fig. 5. The dots are QUB results and the red lines are the reference ±10 %. They show that results can be very good even with the shortest durations. As this effect is not anticipated by the simple RC model, a more complex one has to be developed. This new model and its validation are presented in part 3.

3. Quadrupole model

In order to understand the behavior of the building for the very short times, a different model has been developed. It is based on a quadripolar description of the monodimensional heat transfer through a wall [15]. The principle of this approach is

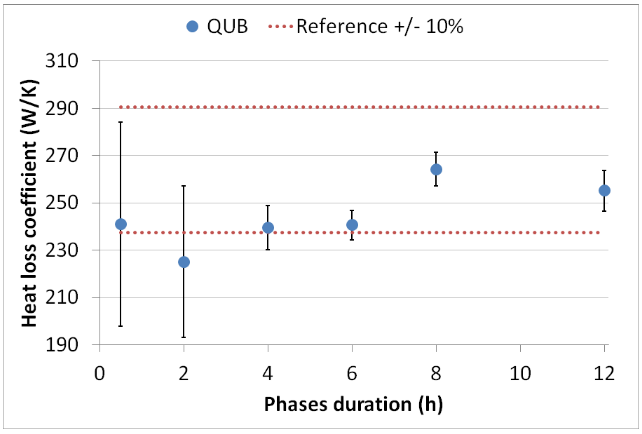


Figure 5: Results of QUB tests of different durations at the Energy House in Salford. The blue dots are the HLC results obtained via the QUB method as a function of the heating and cooling durations and the dashed red lines delimit the reference value ±10 %.

to describe the heat equation in the Laplace frequency space. In the frequency space, the equations for the temperatures and heat fluxes can by solved easily, quickly, and exactly. The solution in the time domain is calculated by inverse Laplace transforms of the frequency space solution. For a monodimensional heat transfer, this can be done semi-analytically (it still needs a numerical integration in the complex space). The main advantage of this approach is that there is no differential equation to be solved, thus there is no discretization in time and space, which is an approximation of the diffusive process (due to an insufficient number of resistances and capacitors in the nodal network formalism). The main drawback is that analytical expressions are needed in the Laplace domain for all the boundary conditions (temperatures and/or heat fluxes).

In the case of the QUB method, we focus on the understanding of what happens in the shortest times. To do so it does not require a more detailed spatial analysis of the case, but rather a better description of the dynamic properties of the heat equation than with simple RC models.

3.1. A quadrupole model of the QUB method

In this section we describe the physical model chosen using the thermal quadrupole formalism and provides the main equation to be solved in the frequency space. We consider the case of a semi-infinite slab of thickness e represented in Fig. 6. The outer face (noted out) is at a constant temperature during the experiment whereas we use a thermal load on the inner face (noted in) as in a QUB experiment. To prepare the initial state we consider first a constant power P_0 until the time t_0 preceding the QUB experiment. The QUB measurement is then done in a first phase with a constant load of power P_h on the inner face during a time t_h. Then the second phase lets the temperature evolve freely without any power for the same duration t_h. A steady state at the beginning of the QUB measurement is therefore obtained by letting t_0 tend to ∞. A representation of the power evolution is provided in Fig. 7.

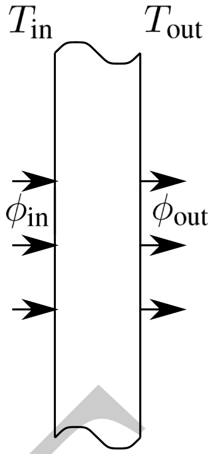


Figure 6: Representation of a semi-infinite slab of a homogeneous material

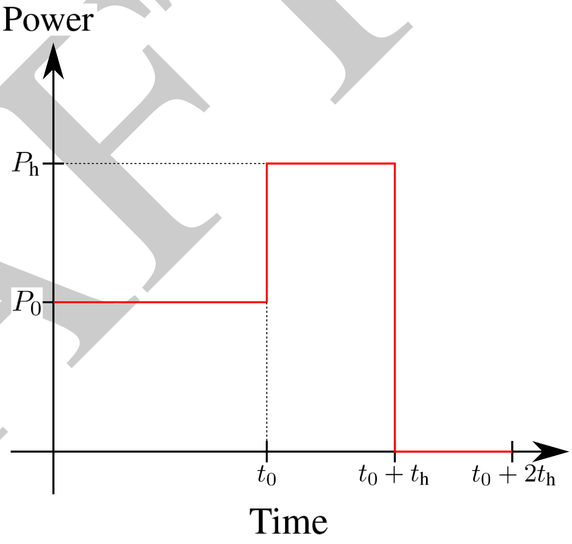


Figure 7: Power on the inner face as a function of the time

The temperature response of the inner face is then fully described by the thermophysical properties of the homogeneous material and the boundary conditions. The properties are the thermal conductivity λ, the specific heat capacity c and the density ρ. These three parameters can be combined with the thickness to obtain the thermal resistance $R = e/\lambda$ and the thermal characteristic time of the slab $\tau = e^2\rho c/\lambda$. The boundary conditions are the power evolution of the inner face and the temperature evolution of the outer face. The interior temperature is $T^*(t) = T_\mathrm{in}(t) - T_\mathrm{out}$, where T_out is supposed to be constant.

Calling $\theta(p)$ and $\phi(p)$ the Laplace transforms of T^* and Φ, these two boundary conditions can be written as Eqs. (6) and (7).

$$\theta_\mathrm{out}(p) = 0 \tag{6}$$

$$\phi_\mathrm{in}(p) = \frac{P_0}{p} + \frac{P_\mathrm{h} - P_0}{p} e^{-pt_0} + \frac{-P_\mathrm{h}}{p} e^{-p(t_0+t_\mathrm{h})} \tag{7}$$

If the slab is supposed to be constituted of N different layers in series, then standard quadrupole theory [15] gives the relationship between the interior and exterior temperatures and fluxes in Eqs. (8) and (9).

$$\begin{bmatrix} \theta_{\mathrm{in}}(p) \\ \phi_{\mathrm{in}}(p) \end{bmatrix} = \begin{bmatrix} A\,(p) & B\,(p) \\ C\,(p) & D\,(p) \end{bmatrix} \cdot \begin{bmatrix} \theta_{\mathrm{out}}(p) \\ \phi_{\mathrm{out}}(p) \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} A\,(p) & B\,(p) \\ C\,(p) & D\,(p) \end{bmatrix} = \prod_{i=1}^{N} \begin{bmatrix} \cosh\left(\sqrt{p\tau_i}\right) & \frac{R_i}{\sqrt{p\tau_i}} \sinh\left(\sqrt{p\tau_i}\right) \\ \frac{\sqrt{p\tau_i}}{R_i} \sinh\left(\sqrt{p\tau_i}\right) & \cosh\left(\sqrt{p\tau_i}\right) \end{bmatrix} \tag{9}$$

By injecting Eqs. (6) and (7) in Eq. (8) the temperature of the inner face is given in Eq. (10).

$$\theta_{\mathrm{in}}(p) = \frac{B(p)}{D(p)} \left[\frac{P_0}{p} + \frac{P_{\mathrm{h}} - P_0}{p} e^{-pt_0} + \frac{-P_{\mathrm{h}}}{p} e^{-p(t_0+t_{\mathrm{h}})} \right] \tag{10}$$

Knowing the thermophysical properties of the different materials, Eqs. (9) and (10) describe the exact temperature behavior of the inner face in the frequency space. In the next section, we show how to address the temperature evolution in time during a QUB measurement and what is the consequence of the RC model on the result of a QUB measurement.

3.2. Semi-analytical solution and consequence on QUB

Going back to the definition of inverse Laplace transform the inversion to the time domain rests on the identification of the poles of θ_{in} which are obviously 0 and the poles of $B(p)/D(p)$ and their associated residues.

It has been shown [15] that each individual layer i can be described by an infinity of RC circuits in series, as represented in Fig. 8. Using this description of a thermal quadrupole Eq. (9) can be rewritten as in Eq. (11). This is valid by taking the limit where the number n_i of two resistors and one capacitor pairs tend to infinity.

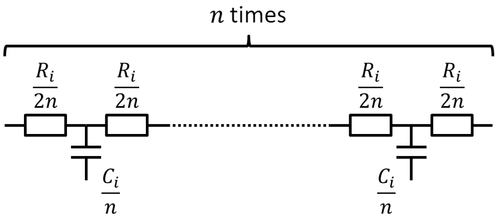


Figure 8: Equivalent RC network of a semi-infinite slab

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \prod_{i=1}^{N} \lim_{n_i \to \infty} \left\{ \begin{bmatrix} 1 & \frac{R_i}{2n_i} \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 \\ p\frac{C_i}{n_i} & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & \frac{R_i}{2n_i} \\ 0 & 1 \end{bmatrix} \right\}^{n_i} \tag{11}$$

In Eq. (11), it is straightforward to show that all the functions entering the matrix are polynomial functions of degree n with positive and real coefficients, as are the functions entering the matrix in Eq. (9). So $B(p)$ is a holomorphic function of p in the complex plane and the roots of $D(p)$ have real negative parts. Furthermore, the general shape of the solution of this type of problems being known, it can be safely assumed that the temperature response is a sum of exponentially decaying functions [16]. This means that only the residue of $D(p)$ will contribute. It has to be first order negative poles located at p_i and related to the time constants τ_i by $p_i = -1/\tau_i$.

By using the residue theorem, it is possible to write Eq. (12), with r_i the residue of $\theta_{\mathrm{in}}(p)$ for the pole p_i and r_0 the residue for the pole 0:

$$T^*(t) = \sum_{i>0} r_i e^{-t/\tau_i} + r_0 \tag{12}$$

where each τ_i is a time constant of the model which can be calculated numerically by solving Eq. (13). r_i is its associated residue and can be calculated using (Eq. 14). These residues, or weights, are therefore obtained by calculating the contour integral in Eq. (14) where Γ_i is a contour circling $p_i = -1/\tau_i$ in the positive direction where the only singularity inside the contour is the one of θ_{in} located at $p_i = -1/\tau_i$. The residue of the pole at $p_0 = 0$ is straightforward using Eq. (9).

$$D\,(-1/\tau_i) = 0 \tag{13}$$

$$r_i = \lim_{p \to -1/\tau_i} (p + 1/\tau_i)\,\theta_{\mathrm{in}}\,(p) = \oint_{\Gamma_i} \theta_{\mathrm{in}}\,(p)\,dp \tag{14}$$

Using Eqs. (14) and (10) we can calculate the residues r_i in the time phases of interest for the QUB formula. It means for the time periods $t_0 \leq t < t_0 + t_{\mathrm{h}}$ and $t \geq t_0 + t_{\mathrm{h}}$. The results are shown in Eqs. (15) and, for the residue at $p = 0$, (16).

$$r_i = \begin{cases} -\frac{B_n(-1/\tau_i)}{D_n'(-1/\tau_i)} \tau_i \left[P_0 + (P_{\mathrm{h}} - P_0) e^{\frac{t_0}{\tau_i}} \right], & t_0 \leq t < t_0 + t_{\mathrm{h}} \\ -\frac{B_n(-1/\tau_i)}{D_n'(-1/\tau_i)} \tau_i \left[P_0 + (P_{\mathrm{h}} - P_0) e^{\frac{t_0}{\tau_i}} - P_{\mathrm{h}} e^{\frac{t_0+t_{\mathrm{h}}}{\tau_i}} \right], & t \geq t_0 + t_{\mathrm{h}} \end{cases} \tag{15}$$

$$r_0 = \begin{cases} \sum_{i=1}^{n} R_i P_{\mathrm{h}} = R_{\mathrm{T}} P_{\mathrm{h}}, & t_0 \leq t < t_0 + t_{\mathrm{h}} \\ 0, & t \geq t_0 + t_{\mathrm{h}} \end{cases} \tag{16}$$

where $R_{\mathrm{T}} = 1/H_{\mathrm{tot}}$ is the sum of all the resistances in the wall.

In order to calculate all temperatures, it is necessary to give an initial condition not only on the interior temperature, but on the entire distribution of temperatures in the envelope. To this aim, a strong assumption, the consequences of which will be discussed, is made: we suppose that $t_0 \to +\infty$. It means that until the heating starts, the building is at a steady state with a internal temperature $T^*_{\mathrm{in}}(t_0) = T^*_0 = P_0/R_{\mathrm{T}}$. With this assumption it is possible to write the values of the internal temperature at all times during the QUB measurement in Eq. (17), with $s_i = B_n(-1/\tau_i)/D_n'(-1/\tau_i)$ and the variable change $t + t_0 \to t$:

$$T^*_{\mathrm{in}}(t) = \begin{cases} R_{\mathrm{T}} P_{\mathrm{h}} + (P_0 - P_{\mathrm{h}}) \sum\limits_{i=1}^{n} s_i \tau_i e^{-\frac{t}{\tau_i}}, & 0 \leq t < t_{\mathrm{h}} \\ \sum\limits_{i=1}^{n} \left[P_{\mathrm{h}} + (P_0 - P_{\mathrm{h}}) e^{-\frac{t_{\mathrm{h}}}{\tau_i}} \right] s_i \tau_i e^{-\frac{t-t_{\mathrm{h}}}{\tau_i}}, & t \geq t_{\mathrm{h}} \end{cases} \tag{17}$$

Using Eq. (2) with temperatures and temperature derivatives for phase (1) evaluated at $t = t_{\mathrm{h}}$ and for phase (2) at $t = 2t_{\mathrm{h}}$, writing $\Phi_{(1)} = P_{\mathrm{h}}$ and $\Phi_{(2)} = 0$, and simplifying with $\alpha = 1 - T_0^*/R_{\mathrm{T}}P_{\mathrm{h}}$ and $\beta_i = e^{-t_{\mathrm{h}}/\tau_i}$, the value of H_{QUB} can be written in function of the total heat losses coefficient H_{tot}, as presented in Eq. (18):

$$H_{\mathrm{QUB}} = H_{\mathrm{tot}} \frac{1}{1 - \alpha^2 \frac{\sum_{i>j} s_i s_j \beta_i \beta_j (\tau_i - \tau_j)(\beta_i - \beta_j)}{R_{\mathrm{T}} \sum_i (1 - \alpha\beta_i) s_i \beta_i}} \tag{18}$$

This model leads to the conclusion that there are two main ways to ensure that $H_{\mathrm{QUB}} = H_{\mathrm{tot}}$. The first, already reached with the first model, is to have long test durations. If t_{h} is larger that the second largest time constant, then all β except one tend to 0, and the second term in the denominator of Eq. (18) becomes negligible. The second way is to have $\alpha = 0$. Taken directly, this simply means that $P_{\mathrm{h}} = P_0$, thus that the building stays at steady state during the heating phase, implying that the temperature slope is nil during this phase, which transforms Eq. (2) into the simpler, $H_{\mathrm{QUB}} = \Phi_{(1)}/T^*_{(1)}$, which is an obvious conclusion in steady-state conditions.

Yet the consequences are more interesting that this simple equation. For instance, even though a steady state with $\alpha = 0$ is not physically achievable, it is possible to approximate it with $\alpha \to 0$, which should lead to $H_{\mathrm{QUB}} \approx H_{\mathrm{tot}}$ even if the test duration is very low. On the other hand when α increases, the corrective factor differs from 1 and the error between H_{QUB} and H_{tot} increases, with a difference which is reduced when the test duration increases.

Of course, the shorter the test duration, the higher the importance of the initial conditions. Furthermore, low values of α also correspond to low amplitude excitations compared to initial conditions, which once again reinforce the importance of the initial conditions, in particular the hypothesis that the test starts from a steady state. Thus, it is important to understand the influence this hypothesis has on the QUB tests results, both theoretically and experimentally.

3.3. Numerical analysis of the quadrupole model

In order to illustrate the impact of t_{h} and α on the test result, a numerical application is performed with a semi-infinite multi-layered wall, for which inverse Laplace transform is done numerically using Eqs. (13), (14) and (18). A three-layered wall is composed of a 12.5 mm thick plasterboard, 120 mm of insulation and 200 mm of brick. The internal node represents a simple volume of air of about 34 m^3 with an internal convection coefficient $h_{\mathrm{int}} = 10\,\mathrm{W/(m^2\,K)}$. A convective resistance $h_{\mathrm{ext}} = 25\,\mathrm{W/(m^2\,K)}$ between the outer concrete surface and the exterior node is also considered. With these parameters, the envelope HLC is about 12 W/K so $R_T \sim 0.0824$ K/W. All the thermophysical properties of the solid materials are given in Table 2.

	Plasterboard	Insulant	Brick
Thickness [mm]	12.5	120	200
λ [W/(m K)]	0.35	0.035	0.39
ρ [kg/m^3]	950	30	1150
c [J/(m^3 K)]	1000	1500	1000

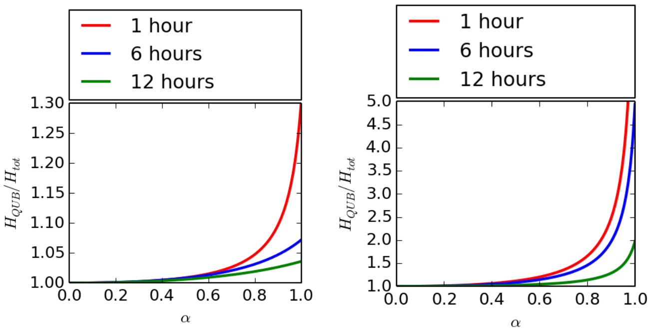
Table 2: Thermophysical properties of the wall components namely the thermal conductivity, the specific heat capacity and the density of the plasterboard, the insulant and the brick.

To describe the temperature response in time, we used Eqs. (13) and (14) to compute the time constants longer than 20 minutes and their associated residue. We only keep the ones where the residue is significant. The figures are presented in Table 3 for the previous case (called IWI for internal wall insulation) and another case where the insulation and the brick are switched (called EWI for external wall insulation).

	IWI case		EWI case	
i	$s_i\tau_i/R_T$	τ_i	$s_i\tau_i/R_T$	τ_i
1	65.97%	21 h 36 min	92.57%	10 d 7 h 37 min
3	30.63%	10 h18 min	2.60%	3 h 38 min
5	0.07%	1 h 42 min	0.70%	57 min
7	0.06%	38 min	0.07%	32 min
9	0.25%	28 min	0.32%	24 min

Table 3: Significant time constants and associated weights for the wall component models IWI and EWI. Only the time constants greater than 10 minutes are shown and the ones associated to significant weights.

Using the values in Table 3 and Eq. (18), we can calculate the error on a QUB measurement at a given heating duration as a function of α. Figure 9 represents the error of a QUB measurement ($H_{\mathrm{QUB}}/H_{\mathrm{tot}}$) for these building envelopes as a function of α for three different durations: $t_{\mathrm{h}} = 1$ h, 6 h and 12 h.



(a) IWI case

(b) EWI case

Figure 9: $H_{\mathrm{QUB}}/H_{\mathrm{tot}} = f(\alpha)$ for IWI wall (9a) and EWI wall (9b), calculated using a numerical resolution of the quadrupole model. The solid blue lines are the results for 6 hours of heating and cooling, the solid green for 12 hours and the solid red for 1 hour.

This cases are extreme because in reality there is always a mix between lower and higher inertia systems. As the heat transfer happens in the different parts of the enveloppe in parallel most of the building will behave differently. Figure 9 shows that the HLC measured is overestimated and confirms that the increase of the heating duration will reduce the error during a QUB measurement. It also shows that the error increases with the inertia of the system.

These results are valid for an initial steady state before the QUB measurement. The same experiment can be done numerically without the strong hypothesis that the initial condition of the QUB test is a steady-state. In order to assess the effect of a non steady state before the measurement we modify the power pattern defined in Fig. 7 by adding a zero power phase between the steady regime and the QUB measurement for a duration t_c. This corresponds to performing a QUB measurement after a few hours of free cooling. Using the same approach we can calculate the time evolution of the inside temperature which depends on the same time constants and residues shown in Table 3. Then we can calculate the results of a QUB measurement as a function of α and for different cooling durations before the QUB measurement. We show this evolution in Fig. 10 for a QUB measurement of 4 hours of heating and cooling, for the EWI case and for different duration of t_c. We impose the initial building temperature (before the QUB measurement) to be 20°C and temperature variations of at least 1°C during heating and cooling phases.

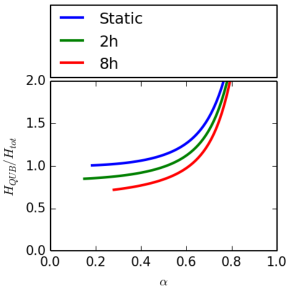


Figure 10: $H_{\text{QUB}}/H_{\text{tot}} = f(\alpha)$ for a heating and cooling durations of 4 hours in the EWI case, calculated using a numerical resolution of the quadrupole model. The solid blue line is the result starting from a static initial state, the solid green for 2 hours of cooling before the QUB and the solid red corresponds to 8 hours of cooling.

This more realistic model confirms that H_{QUB} presents a strong dependence on α, which is related to the fact that for the shorter measurements, several time constants play a role on the temperature evolution. By preventing large values of α, it is possible to have a correct measurement of the HLC even with a short test duration. It must be noted that the free cooling period before the beginning of the test also creates a underestimation of H_{QUB} for low values of α, although it is much less important than its overestimation at high values of α. These phenomena show that α values around 0.5 should be favorable. In the next section, experimental proofs of this hypothesis are provided.

4. Experimental validation of the quadrupole model

For all QUB measurements presented here, the same protocol has been applied. The temperature difference between the inside and the outside is always positive and the building is heated during the first phase, cooled down with no controlled power (but possibly residual power, like the electrical equipment consumption). The heating is performed using the small heating power sources discussed in Part 2.2. Temperatures are recorded with Pt100 sensors or aluminum-covered K-type thermocouples. Furthermore, as has already been explained in Part 2.2, heating and cooling phases last for the same duration such as $t_{(1)} = t_{(2)} = t_{\text{h}}$. Several experiments have been presented in a previous article [11]. The two described here are the ones for which the comparison of H_{QUB} with H_{ref} have been possible. The first is a small bungalow, the second is the Energy House at the University of Salford.

4.1. Small scale building in real climate

The first test building is a bungalow located in Saint-Gobain Recherche at Aubervilliers, near Paris, France. The bungalow has a floor area of about 13.5 m^2, a volume of about 34 m^3 and a total heat loss area of about 68 m^2. The inertia is low as there is little furniture and the thermal mass mainly comes from plasterboard and glazings. Two kinds of experiments are performed to assess the HLC of this building.

The first one is a quasi-static measurement based on the coheating methodology provided by Leeds Metropolitan University [3]. The result is used as a reference. The principle is to maintain the inside air of an unoccupied building at a constant temperature during at least two weeks and to analyze daily averages of energy consumption as a function of external weather conditions. Using a very simple model that takes into account total heat losses and solar heat gains, it is possible to write Eq. (19):

$$\overline{\Phi_{\text{in}}} + g_{\text{S}}\overline{\phi_{\text{rad}}} = H_{\text{ref}}\overline{T^*} \tag{19}$$

where Φ_{in} is the heat load in the building, g_{S} the solar factor in m^2 and ϕ_{rad} the solar heat gain, measured in W/m^2. All overlined symbols are averaged over 24 h.

The reference HLC calculated with this methodology is:

$$H_{\text{ref}} = 33 \pm 2 \text{ W/K} \tag{20}$$

The second experiment is a large number of QUB measurements which have been performed during the first semester of 2013. Four different heating durations have been studied (30 min, 1 h, 2 h and 4 h) with very different heating powers and initial temperature differences. This allows to verify if H_{QUB} is indeed correlated with α (Figure 11).

Figure 11 confirms the qualitative results obtained from theory and modeling. It is first possible to observe a strong dependency of H_{QUB} on α, with a low underestimation at low values of α and a high overestimation at high values of α. In both cases, the augmentation of the heating duration reduces the error, although it is much clearer for the overestimations (in part because very low values of α are harder to reach than very high values). On the other hand, for $\alpha \approx 0.4 - 0.7$, a good agreement between H_{QUB} and H_{ref} is obtained for all heating durations.

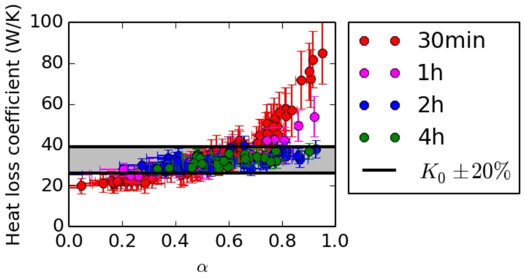


Figure 11: $H_{\rm QUB} = f(\alpha)$ in SGR bungalows. The red, magenta, blue and green dots are obtained respectively for durations of 30 minutes, 1 hour, 2 hours and 4 hours. The solid black lines delimiting the grey zone corresponds to ±20 % of the reference value.

4.2. Real scale building in controlled climate

In order to complete the validation of the QUB method for short test durations, additional tests have been done at the Energy House at the University of Salford, already presented in 2.3. The additional short tests have been done later than the longer ones, and the configuration of the house had slightly changed in between (modifications of the window frames and doors), thus the value of $H_{\rm ref}$ had to be measured again. The result is $H_{\rm ref} = 229.2 \pm 2.4$ W/K.

Short QUB measurements were performed with two different heating durations, 1 h and 4 h. As in Part 4.1, various settings for the heating power and the initial temperature difference were used in order to have a variation of α. Figure 12 presents the HLC measured by a QUB experiment as a function of α for the Energy House, compared to the reference $H_{\rm ref}$.

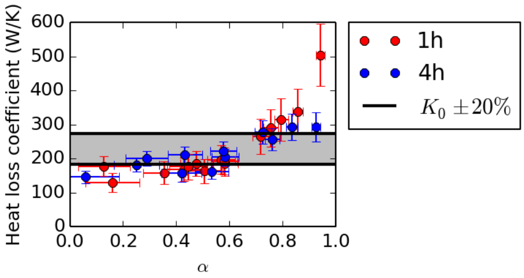


Figure 12: $H_{\rm QUB} = f(\alpha)$ in the Energy House at the University of Salford. The red and blue dots are obtained respectivelly for durations of 1 hour and 4 hours. The solid black lines delimiting the grey zone corresponds to ±20 % of the reference value.

Figure 12 confirms all previous qualitative conclusions, especially those obtained in the small building in real climate. Firstly, the HLC measured increases strongly when α is higher than approximately 0.8, but increasing the heating duration allows to reduce the error performed on the measurement. Most of the measurements performed at α values between 0.4 and 0.7 are in good agreement with the reference measurement for both values of the heating duration. Secondly, for low values of α, $H_{\rm QUB}$ is lower than $H_{\rm ref}$, which also confirms conclusions reached by numerical calculations.

It is important to note that if α has to be chosen between 0.4 and 0.7 during an experimental test, it means that the internal load must be between $1.7\, T_0^*/R_{\rm T}$ and $3.3\, T_0^*/R_{\rm T}$, which leaves a rather wide range of acceptable values. This explains why, even though experimental values of α should be controlled, it is often possible to have good results even if α has not been controlled, as was the case in Part 2.3.

5. Conclusion

This paper presents a new and efficient way of measuring the total heat losses of a building envelope. The main problem of existing methods is their duration, which makes them unsuited for use at a large scale. The QUB method solves this issue by using dynamic measurements done only at night, in preferably empty buildings. Furthermore, only two power steps are used, usually a constant heating followed by free cooling, which simplifies the temperature responses. These experimental conditions make it possible to use a very simple model to identify the envelope resistance in a short time. The two problems that arise, and that this article tries to solve, are the justification of the thermal model and the validation of the experimental results.

It has been shown in the first section that using an RC model can explain why QUB tests can give very good results in only one night, provided some experimental conditions are respected, in particular homogeneous conductive heating and identical heating and cooling durations. In the second section, a model developed using the quadrupole method has been used to show that it is even possible to measure the HLC of a building in one night only, with test durations being as short as one hour. In order to achieve such results, experimental requirements are more strict than those required for whole night tests. In particular, it has been shown that the thermal load must be included in a range that depends on the value of the internal and external temperatures. This condition is expressed through the use of an adimensional parameter called $\alpha = 1 - T_0^*/R_{\rm T}P_{\rm h}$, which should be included between approximately 0.4 and 0.7 (although these values depend on the experimental conditions before the test starts: free cooling or temperature regulation, for instance).

This model has been validated in different ways: by theoretical considerations, by numerical applications, and also by experimental validations in buildings where a very good estimation of the heat loss estimation could be found with a second method. The buildings are a bungalow for which extensive coheating measurements have been done and the Energy House at the University of Salford, which is a Victorian house located in a climatic chamber and can therefore be put in steady-state conditions. All these validation cases lead to the same conclusions: low values of α can lead to slight under-evaluations of H, high values can lead to high overestimations of H, and the error, which depends on the building structure, can be reduced by increasing the measurement duration. In other words, with quite simple experimental conditions and requirements, it has been proven possible to measure accurately the HLC of a building in a very short time.

Even if this can be considered a very worthy objective, the developed model and associated experimental setup have other advantages, in particular for building scientists. Current HLC measurements take two to three weeks. In that time, it is possible to run as many as 20 QUB tests, and hence study the influence of exterior conditions, like the weather, on the results. For instance, it is possible to study the impact of wind velocity on the resistance, which is a way of estimating the thermal impact of infiltrations. It is also possible to use them not for studying the building envelope resistance, but the second parameter of the simplified model—its heat capacity—and in particular the influence of time, as has been presented in [11]. It can therefore be used to complete the understanding scientists have of the buildings behavior in many different conditions.

The principal next steps are the quantification of the uncertainty linked to a QUB measurement and the development of a methodology to measure in-situ the thermal transmittance of building elements. This will validate this methodology and so prescribe in which context the method is suitable. This will also allow to have a detailed thermal diagnosis of a building heat losses.

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