Building Diagnostics: Practical Measurement of the Fabric Thermal Performance of Houses

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Doctoral Thesis

Submitted in Partial Fulfilment of the Requirements for the Award of Doctor of Philosophy of Loughborough University, United Kingdom

July 2015

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Abstract

This thesis is concerned with measuring the fabric thermal performance of houses. This is important because the evidence shows that predictions of performance, based upon a summation of expected elemental performance, are prone to significant inaccuracy and in-situ performance is invariably **worse** than expected – the so-called 'performance gap'. Accurate knowledge of the thermal performance of houses could cause a shift in the way that houses are built, retrofitted and managed. It would enable quality-assurance of newly-built and retrofitted houses, driving an improvement in the energy performance of the housing stock. The current barrier to achieving these benefits is that existing measurement methods are impractically invasive for use on a mass-scale. The aim of this research is to address this issue by developing non-invasive fabric thermal performance measurement methods for houses.

The co-heating test is currently the most used method for measuring whole-house fabric thermal performance; it is used to measure the Heat Loss Coefficient (HLC) of a house, which is a measure of the rate of heat loss with units of Watts per degree Kelvin. It has been used extensively in a research context, but its more widespread use has been limited. This is due to a lack of confidence in the accuracy of its results and the test's invasiveness (the house must be vacant for two weeks during testing, which has so far been limited to the winter months, and testing cannot be carried out in newly-built houses for a period of approximately one year due to the drying out period). To build confidence in the results of co-heating testing, the precision with which test results can be reported was determined by the combination of a sensitivity analysis to quantify measurement errors, and an analysis of the *reproducibility* of the test. *Reproducibility* refers to the precision of a measurement when test results are obtained in different locations, with different operators and equipment. The analysis of the reproducibility of the test was based upon a direct comparison of seven co-heating tests carried out by different teams in a single building. This is the first such analysis and therefore provides a uniquely powerful analysis of the co-heating test. The reproducibility and sensitivity analyses showed that, provided best practise data collection and analysis methods are followed, the HLC measured by a co-heating test can be reported with an uncertainty of ±10%.

The sensitivity analysis identified solar heat gains as the largest source of measurement error in co-heating tests. In response, a new approach for co-heating data collection and analysis, called the *facade solar gain estimation* method, has been developed and successfully demonstrated. This method offers a clear advancement upon existing analysis methods, which were shown to be prone to inaccuracy due to inappropriate statistical assumptions. The *facade* method allowed co-heating

tests to be carried out with accuracy during the summer months, which has not previously been considered feasible. The demonstration of the facade method included a direct comparison against other reported methods for estimating solar gains. The comparison was carried out for co-heating tests undertaken in three buildings, with testing taking place in different seasons (winter, summer, and spring or autumn) in each case. This comparison provides a unique analysis of the ability of the different solar gain estimation methods to return accurate measurements of a house's HLC in a wide variety of weather conditions.

Building on these results, a testing method was developed: the Loughborough In-Use Heat Balance (LIUHB). The LIUHB is a non-invasive measurement method, designed and tested in this study, which can measure the HLC of a house with an accuracy of ±15% while it is occupied and used as normal. Measurements of energy consumption and internal temperature are discreetly collected over a period of three weeks, and combined with data collected at a local weather station to inform an energy balance, from which the HLC is calculated. This low impact monitoring approach removes the barriers to fabric thermal performance testing on a mass scale.

The LIUHB has been successfully demonstrated in several comparative trials versus a baseline measurement provided by the co-heating test. The trials have included the application of extreme examples of synthetic occupancy conditions, testing in an occupied house, and quantification of the effects of a retrofit. Subject to further validation, the LIUHB has the potential to deliver many of the benefits associated with mass-scale measurement and quality assurance of housing performance.

Acknowledgements

Carrying out this PhD has been a fantastic experience which is due largely to the people I have shared it with.

I owe particular thanks to my supervisors, Dennis, David and Kevin, for all their discussion, encouragement, opportunities and debates over whether 'data' can be used as a singular.

I'd like to thank everyone in the hub in Loughborough and in the Lolo Centre for creating such a great environment to work in, and Tom Kane, Karen Holmes, Karen Chadwick and Stephen Porritt in particular for their help and support throughout.

Thanks to my family and friends, in particular my Mum and Dad and to Nicola for all your encouragement and advice. And finally, thanks to my bike and my planes for taking me somewhere else.

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Chapter 1 Introduction

The aim of this research is to develop fabric thermal performance measurement methods for houses that can be practically applied on a wide scale. This aim encompasses two major research challenges:

- The fabric thermal performance of individual houses is largely uncertain and extremely difficult to accurately predict.
- Existing methods to measure whole-house fabric thermal performance are impractically invasive for use in occupied houses.

Accurate and reliable knowledge of the thermal performance of individual houses could cause a shift in the way that houses are built, retrofitted and managed. It would enable a method for quality-assurance of newly built houses and retrofit measures, better estimates of energy savings resulting from retrofits, and a method to compare the performance of houses independent from the effects of different weather conditions, season and occupant behaviour. This information would allow more accurate assessments of retrofitting measures to be undertaken so that they could be directly compared to supply-side emission-reduction measures, which would help to inform policy design.

The housing stock accounts for just under a third of all energy use and associated CO_2 emissions in the UK (Parker and Cooper, 2011), and of this around two thirds is used for space heating (DECC, 2012). Additionally, the UK housing stock is amongst the oldest in the world (BPIE, 2011; Meijer et al., 2009) and has relatively low thermal efficiency (BPIE, 2011). These factors make housing a clear opportunity for emissions and energy demand reduction, which is particularly pertinent in view of the statutory target of an 80% reduction in CO_2 emissions compared to 1990 levels by 2050, set out in the 2008 Climate Change Act (H.M. Government, 2008). There is a rather low rate of demolition of houses in the UK (Parker and Cooper, 2011), which means that the majority of the 2050 housing stock has already been built. As a result, both retrofit of existing houses and improvement in the performance of new houses will form a critical part of reducing the CO_2 emissions of the housing stock.

An increasingly persuasive body of evidence has been generated that shows that houses rarely perform as predicted, a phenomenon commonly referred to as the ‘performance gap’ (Zero Carbon Hub and NHBC Foundation, 2010a). The performance gap has been shown to be significant in most cases, with differences between as-designed and measured in-situ thermal fabric performance of more than 20% common and of more than 100% in some cases (Stafford et al., 2012). Of particular concern is that this performance gap has been observed to invariably operate in one direction, so that the actual performance is **worse** than was predicted. The evidence has shown the sources of the performance gap to be varied for different houses, including both underperformance of individual elements and the way in which they interact (ibid). The performance of residential buildings is therefore extremely variable, and seemingly similar houses may have dramatically differing levels of performance. For these reasons, the traditional method of summing the laboratory-defined performance of each building elements to define the total performance of a house is prone to significant inaccuracy. Given the issues with accurate performance prediction on a single house basis, and the value of such an assessment, the demand for a measurement method that could be practically applied on a wide-scale is clear.

Much of the evidence for the performance gap has been gathered by the application of the 'co-heating test' (described fully in section 2.6.1), which is used to measure the fabric thermal performance of a house as a whole rather than the performance of individual elements. In a co-heating test, the amount of energy required to maintain the air inside a house at a constant elevated temperature using electric heaters installed during the test is measured. The measured energy input and the measured temperature difference between inside and outside are used to inform an energy balance from which the rate of heat loss from the house is inferred. The output of the test is a house's Heat Loss Coefficient, (HLC) with units of W/K, a metric which defines a house's thermal fabric performance. The measured HLC of a house can be directly compared with as-designed value in order to identify cases of underperformance, which could be used for quality assurance of newly built and retrofitted houses. This information could also be used to provide feedback leading to remedial works or improved construction, and lower performance gaps in subsequent builds. The HLC of a house can also be used to inform building energy models, generating more accurate estimates of likely energy consumption. The HLC can be normalised by the size to allow direct comparison between houses, the most common metric is the Heat Loss Parameter (HLP), with units of W/Km^2 (surface area), which is calculated by dividing a house's HLC by its external surface area.

The co-heating test has been instrumental in proving the existence of the performance gap; however, the test procedure means that it is impractically invasive for widespread use. The test method requires that the house being tested is vacated for a period of at least two weeks, involves heating the internal air to a temperature of $25^{o}C$ or higher (which can cause rapid drying and may cause damage, especially in newly built houses), and can only be carried out during the winter months.

Furthermore, the accuracy of the co-heating test has not been yet been defined, which has limited its acceptance by the building industry. At the time of writing the co-heating test is the most commonly used whole-house fabric performance test, however the factors described have largely restricted the use of the test to research applications. There are examples of more rapid whole house performance tests, such as the PSTAR and QUB tests (which are described in section 2.6.2), which can be carried out over 1-3 days rather than 2-3 weeks (Mangematin et al., 2012a). However, these tests still require the house to be vacated for that period and suffer the same issues of unknown accuracy as the co-heating test.

The combination of the demand for a whole-house measurement method generated by the performance gap, and the unacceptably invasive and expensive nature of existing measurement methods provide the justification this research. Following the literature review three key issues with the co-heating test, currently the most used whole-house performance test, were identified, leading to these research questions:

(i) Accuracy – to what level of accuracy can the results of a co-heating test be stated? How repeatable is the co-heating test given different weather conditions and test methods?

(ii) Solar gains – solar gains are the heat gains to the house caused by the sun. They cause the largest source of uncertainty in the co-heating test as it is not possible to directly measure them. This is significant because in some cases they may be of the same order of magnitude as the electrical heat input (which is used to maintain the elevated temperature in the house during co-heating). This is the reason why the test is limited to application during the winter months in most climates. Several methods have been used to account for solar gains, which is the most accurate/repeatable and can it be improved upon?

(iii) Invasiveness – as already described, the co-heating test requires that a house be vacated for the period of the test, which is currently recommended to be at least two weeks, and is impractically invasive for widespread use. Can a test be developed that can be applied while a house is ‘in-use’ (a term which described a house which is under normal occupied conditions) to remove this obstacle to mass performance measurement?

Research and experimentation was therefore undertaken to address each of these three issues, and provides the structure for this thesis. This is reflected in the structure of this thesis, which comprises a literature review and method chapters leading into three results chapters, which address each of the three core issues outlined above in turn.

The measurement uncertainty of the co-heating test has been estimated using the three most commonly applied data analysis methods and an additional analysis method which has been developed in this study. The measurement uncertainty was defined by a sensitivity analysis carried out on data collected during an extended co-heating test that was carried out over a total period of approximately eight months. This extended dataset allowed the effect of differing weather conditions to be taken into account in the sensitivity analysis. The reproducibility of the co-heating test given slight variations in data collection and analysis techniques was also calculated, based upon the results of sequential testing of the same detached test house by seven testing bodies. *Reproducibility* is a term which defines the precision of a test, given that it is carried out in different locations and with different operators and equipment (BSI, 2000). These new and unique methods of calculating the measurement uncertainty and reproducibility of the co-heating test have shown that the HLC resulting from the test can reasonably be stated with an uncertainty boundary of ±10%. The analyses have also led to a series of recommendations on the best practise method of carrying out and completing the data analysis for the co-heating test (given in section 5.4).

The current most commonly used methods for calculating the solar gains during co-heating tests are based upon various forms of linear regression analysis (they are fully described in section 2.6.1). The results of the long term co-heating test, and repeated co-heating tests carried out in test houses in Loughborough, have been used to further prove that these methods are prone to inaccuracy if a suitable range of weather conditions does not occur during the measurement period. Additionally, it is suggested that the complex interaction between the input terms to the regression (usually internal-external temperature difference and global solar radiation) means that the assumptions inherent to linear regression are invalidated, which has been shown to lead to significant inaccuracy in some weather conditions (note: in this thesis all global solar radiation measurements are assumed to be measured on a horizontal plane). To overcome these issues a new testing and data analysis method to account for solar gains, the *'facade solar gain estimation'* method, has been developed during this study. The method is based upon direct estimation of the solar gains occurring through the glazed elements of the building and does not rely on a regression analysis. The method has been successfully demonstrated, and has been shown to provide more consistent and repeatable estimations of the HLC. The method has also been shown to be capable of generating accurate HLC measurements from co-heating tests carried out during the peak summer months, addressing one of the primary limiting factors of the wider application of the co-heating test.

Even if the co-heating test was extremely well characterised, with a method capable of producing an accurate measurement of the HLC in any conditions, the invasiveness of the test would be likely to heavily limit its application. Overcoming this obstacle is therefore key to enabling routine fabric performance measurement of buildings, enabling the sort of quality assurance measures and information provision that are likely to ultimately close the performance gap and reduce energy use for heating in domestic buildings. There are two ways that the issue of invasiveness could be addressed; either by the development of a much more rapid test, which could be completed in a matter of hours and therefore remove the requirement for a vacant house, or a test which can carried out while a house is 'in-use' without disturbing the occupants. An 'in-use' approach would drastically reduce the financial and practical restrictions introduced by a long testing period, as the house can be occupied during the test; this also means that house builders would not be required to leave new buildings unoccupied for any additional period. Furthermore, with the advent of smart meters and greater sensing equipment in houses in general through zonal heating controls, there is a possibility that an in-use test could be applied completely offsite, removing the requirement for costly home visits.

An in-use approach has been adopted for the *'Loughborough In-Use Heat Balance'* method, which has been developed during this study. The method is based upon an energy balance, as in the co-heating test, but is carried out while a house is in-use with no disruption to the normal running of the house except that no secondary heating from non-metered sources is permitted (this is most likely to apply for solid fuel or gas fires where the efficiency cannot practically be measured, electric secondary heating is not limited). The results of the research carried out to estimate the measurement uncertainty of the co-heating test, and how best to account for solar gains fed directly into the development of the In-Use Heat Balance method so that the three research themes were complementary to each other. The In-Use Heat Balance method has undergone a thorough initial testing, including successful comparative testing versus the co-heating test in: vacant test houses, with and without the application of extreme synthetic occupancy conditions; before and after a thermal performance upgrading retrofit; and in one occupied house.

The Loughborough In-Use Heat Balance has already been applied commercially in conjunction with industrial partners; including its use to test the effect of retrofitting measures, in conjunction with the Energy Technologies Institute (ETI) and PRP Architects, and to test the performance of two test houses for Mitsubishi Electric. Its dissemination to the building industry has been aided by the publication of an article briefly announcing the method in the Innovation and Research Focus newsletter, organised by the Institution of Civil Engineers (ICE) (Jack et al., 2015). These applications and publication demonstrate the industrial appeal of the method, and have begun to identify future applications for the method.

1.1. Policy Landscape

The UK committed to an ambitious carbon emission reduction target of 80% compared to 1990 levels by 2050 in the Climate Change Act of 2008 (H.M. Government, 2008). This target creates a clear need for energy demand reduction given the high cost of low-carbon energy generation technologies.

Several policies have been introduced aimed at reducing energy demand, and hence carbon emissions, in houses. Part L1A Guidance for Compliance with The Building Regulations stipulate energy efficiency requirements that newly built houses must meet, they include statutory minimum limitations for both elemental performance (for walls, roofs, floors, party walls, windows and other openings and air permeability) and minimum whole-house performance, as measured by the Standard Assessment Procedure (SAP – described in section 2.1) (H.M. Government, 2013). From 2006 onwards, Part L of The Building Regulations has included a requirement for the partial testing of the air tightness of new buildings. Partial testing means that a certain fraction, dependent upon the total number constructed, of the houses built on one site must be tested (H.M. Government, 2006). This represented a shift in compliance testing which had, until 2006, been carried out solely based upon modelled performance. In the 2012 consultation on Part L it was suggested that co-heating, or similar, tests could be used as part of a post-construction quality assurance testing program (H.M. Government, 2012). Although this suggestion was not eventually included in the final regulations, it does show a willingness to move towards measured rather than as-designed targets for energy performance in the future.

The Green Deal is the most recent policy aimed at encouraging thermal fabric performance increasing retrofits (H.M. Government, 2011). The Green Deal is a financing mechanism whereby the loans are provided to cover some or all of the capital cost of a retrofit which is then repaid by expected savings in a consumer's energy bill (ibid). Green Deal loans are underpinned by the 'Golden Rule', which states that finance will only be provided for measures which are predicted to repay their capital cost within a prescribed period (ibid). The Golden Rule is calculated using an updated version of SAP, called the Green Deal Assessment (ibid). The uptake of the Green Deal has been drastically lower than predicted (Vaughan and Collinson, 2014), and as a result the policy may not remain in its current form for an extended period. However predicting the energy demand reduction due to a retrofit and the business case for those measures is likely to remain a key part of any retrofit-focussed policy. Therefore, accurate methods to carry out this assessment will be required in both new-build and building retrofit policy design.

1.2. Research Aim and Objectives

The aim of this work is to develop and validate non-invasive domestic building thermal performance measurement methods suitable for application on a mass scale.

Objectives:

1. Define the uncertainty of the co-heating test given the effect of changing weather conditions, testing procedures and data analysis methods.

2. Develop an improved method for accounting for solar gains during co-heating tests and assess whether this could lead to an extension in the period of the year in which testing can be carried out.

3. Develop a non-invasive method to measure the fabric performance of a whole house in-situ.

1.3. Thesis Structure

The thesis begins with an introduction which gives an overview of the thesis's contents, sets out the context for the research and defines the three clear objectives of the study. The context is further developed in the literature review (Chapter 2), which describes the state of the art in building performance measurement and defines the knowledge gap which this study seeks to fill.

Chapter 3 described the design of the experiments carried out, essentially explaining what was done and why. Chapter 4 gives a more detailed description of the facilities, testing methods and equipment that was used, explaining how and where the work was carried out.

The results of the study are given in Chapter 5, Chapter 6 and Chapter 7, each addressing respectively the three clear research objectives defined in the introduction: defining the uncertainty in co-heating, better accounting for solar gains and development of the Loughborough In-Use Heat Balance method.

The findings of the research are discussed in Chapter 8. It contains a critical appraisal of the work, recommendations for further research, and reflections upon applications of the research's findings and their potential impact. The thesis's conclusions are presented in Chapter 9.

Chapter 2 Literature Review

In this chapter a review of relevant literature is given to provide the context and justification for the thesis. The key research summarised in the literature review is associated with: the common error (mostly overestimation) of a house's energy performance – the so called 'performance gap'; current methods for estimating building thermal performance; elemental and whole building performance measurement methods; the effect of occupants on measurement and how that can be taken into account experimentally and (subsequently) in practice. These topics define the justification for the project (sections 2.1 and 2.2), the current measurement techniques being used (sections 2.2, 2.4, 2.5, and 2.6) and the specific challenges for an in-use testing method (section 2.6.3).

2.1. Prediction of Building Thermal Performance and Energy Consumption

The simplest method of predicting the energy performance of a building is through design heat loss calculations. In the calculation the performance of each building element is summed to deduce the overall performance of the building, and the performance of each element is defined empirically using laboratory-based measurements. This could be thought of as the simplest model of the thermal performance of a building.

As an additional step, the estimated performance can be combined with a set of assumptions about the operating conditions for the building in order to predict energy consumption. This set of assumptions includes properties such as the weather conditions, internal temperature, level of occupancy, appliance use, and so on. Information can be incrementally added to a model with the aim of increasing the accuracy of the predicted energy consumption; the decision of how much information to input is a trade-off between complexity and ease of use (Zero Carbon Hub and NHBC Foundation, 2010a).

In the simplest calculation of a building element's performance, measured by the U-value, the thermal resistance of each layer is simply added, with all heat flow assumed to be travelling in a direction normal to the surface of the element, from inside to outside. However, in reality, building elements will have non-uniformities which affect the direction of the heat flow and in turn the amount of heat transfer (Anderson, 2006). This can make the calculation of U-values rather complex, and thorough guidance on the appropriate methods to do so has been published by the Building Research Establishment (BRE) (Anderson, 2006). In addition, complex geometries of the building fabric and more commonly joints between two materials lead to areas of increased heat loss termed thermal bridges. These are commonly accounted for using defined linear thermal transmittance valued for specific thermal bridges, with units of W/mK, and must be added to the calculation of the heat loss from a whole building (Anderson, 2006). This can cause a problem when calculating the performance of existing walls as it is difficult to detect all possible thermal bridges by visual inspection, a further problem is accurately judging the material and thickness of each layer of the element (Biddulph et al., 2014).

The U-value can also be affected by the conditions at the surface of a building element, in particular the amount of air movement and the presence of moisture (Biddulph et al., 2014). For this reason, the U-value of building elements adjacent to unheated spaces is commonly adjusted to take this into account (Anderson, 2006).

Energy models used to predict the energy consumption and thermal performance of buildings can be broadly divided into two categories: dynamic models and those that use time-averaged data inputs (i.e. steady-state models). Averaged data is used to represent typical external and internal conditions, such as weather and occupancy patterns, over varying time periods, typically monthly or annually, in order to simplify performance calculations. Dynamic models calculate energy consumption on a much shorter time scale, often hourly, so these models can therefore account for changing conditions. Dynamic models can utilise measured or predicted patterns for weather, heating, appliance use and occupancy to create a more detailed representation of the real world (Zero Carbon Hub and NHBC Foundation, 2010b).

Different methods are used to define the weather conditions which are input to energy models, depending upon the purpose of the use of the model; for instance, data representing extreme conditions is used when designing to mitigate against the risk of overheating (CIBSE, 2002). For predictions of energy consumption, data which seeks to represent the most 'typical' weather conditions for a particular location is used. The Test Reference Year (TRY) generated by the Chartered Institution of Building Services Engineers (CIBSE) is an example of such data. TRYs are based upon twenty years of collected weather data, with the TRY constructed of the 'most typical' months which occurred during this period at a given location (Levermore and Parkinson, 2006). The selection of the most typical month was based upon cumulative distribution functions of daily mean values of dry bulb temperature, global solar horizontal irradiation and wind speed (ibid). This method is an improvement upon the previous process of simply using averaged monthly data, which was found to generate an example year which was uncommon by virtue of being constantly 'typical' throughout (ibid). By contrast, the TRY represents a range of weather conditions in a location, while still representing annual average values consistent with those occurring over a longer period. The Typical Meteorological Year (TMY) is generated by a similar process, and with similar aims, for locations in the USA by the National Renewable Energy Laboratory (NREL) (Wilcox and Marion, 2008).

The model most commonly used in the UK to estimate energy consumption is the Standard Assessment Procedure (SAP) (BRE, 2011). SAP was developed in order to produce more robust estimates of energy consumption than design heat loss calculations, but in a less complex manner than detailed simulation models (Shorrock and Anderson, 1995). SAP is used to test compliance with Part L of the UK Building Regulations (H.M. Government, 2006), a simplified version called the Reduced Data Standard SAP (RdSAP) is applied for existing dwellings using information that can be gathered by a site survey (BRE, 2012). A modified version of an RdSAP assessment is used for Green Deal assessments that takes into account occupancy conditions observed in the specific house and generates a list of possible improvement measures (BRE, 2014a). SAP is underpinned by the Building Research Establishment Domestic Energy Model (BREDEM), which uses a rigorously validated set of assumptions to characterise a building based upon a series of user defined inputs for variables such as: dimensions, construction materials, number of occupants, appliance use and heating system (BRE, 2011). SAP has been validated against a statistically significant dataset of measured energy consumption (NHBC Foundation and BRE, 2012). An updated version, SAP 2012, was introduced in 2014 (BRE, 2013); however at that point the analysis work for this project had been completed so all information in this thesis is sourced from SAP 2009.

The energy consumption estimated by SAP is calculated by a sum of that used for space heating and cooling, domestic hot water heating, electricity for pumps and fans and electricity for lighting only (BRE, 2013); this is referred to as the *regulated* energy consumption. As such, it does not include the cooking and appliances, referred to as the *unregulated* energy consumption, this is an important distinction which can be the cause of a discrepancy between observed energy consumption and that predicted by SAP.

Two key issues can affect the accuracy of the output of a building energy model: (i) does the model used inherently create an accurate representation of the real building? And (ii) is the data that has been inputted into the model correct (NHBC Foundation and BRE, 2012)? This second issue is the focus of this research.

2.2. The Fabric Performance Gap

The term 'performance gap' is usually used to describe the difference between the energy performance of buildings as predicted by models (such as SAP) and that measured in-situ. A combination of recent whole-house and older elemental in-situ studies provide considerable empirical evidence (which will be discussed below) for the existence of such a gap whereby buildings are not delivering the energy performance that is predicted.

This research is mainly concerned with the *fabric thermal performance of buildings*. Fabric performance is defined by heat transfer, for which there are three fundamental modes: conduction, convection and radiation. In each mode heat transfer is driven by a temperature difference. In conduction, heat is transferred by contact between adjacent molecules, with the energy passing from highly-vibrating molecules at a higher temperature, to cooler molecules vibrating at a lower speed. For this process to take place the molecules must be sufficiently close to each other, which means that conduction is practically limited to solids and liquids, and hence is most relevant in building to heat transfer through solid elements. Convection refers to heat transfer by the movement of fluids. Although typically described as a distinct mode of heat transfer, heat is actually transferred by both the movement of the fluid itself and conduction. In buildings, convective heat transfer occurs both by movement of air and the movement of air across the surface of building elements. Finally, radiation is caused by the emission and absorption of electromagnetic waves, and as such does not depend on any solid or fluid medium. Radiative heat transfer is most common in buildings as a heat gain from the Sun, or a heat loss to the night sky.

To simplify matters, heat loss from buildings can generally be broken down into two heat loss mechanisms, heat transfer through the fabric of the building and heat lost due to the replacement of warm internal air with cool external air. Evidence for a performance gap in fabric heat loss will be considered first.

Comparisons between the heat loss coefficient (HLC) of buildings as predicted by SAP and as measured by co-heating tests carried out by Leeds Beckett University, showed that the measured HLC was higher than that predicted in thirty of the thirty four total tests (Stafford et al., 2012). The reasons for these discrepancies are numerous, ranging from the way that models are used and the calculation methods that they employ through to variations in as-designed and as-built construction. Some specific examples:

- The Stamford Brook Project showed a far greater than expected thermal bypass at party walls due to circulation of external air in the cavity (Lowe et al. 2007).
- The performance gap found in The Elm Trees Mews Project was due mainly to a larger amount content of timber in the construction[1] than had been inputted to the model, causing a variation in U-value (Bell et al., 2010).

A 2012 publication from Leeds Beckett University reported the results of 34 co-heating tests carried out over the preceding six years to measure whole-house thermal performance. In 30 of the 34 studies the measured HLC was found to be greater than that predicted (Stafford et al., 2012). The results showed a huge range of discrepancies between prediction and measurement, ranging from 1% to over 120% (Stafford et al., 2012), a performance gap of orders of magnitude in scale.

Alongside Leeds Beckett University's whole-house measurements, in-situ U-value measurements have also provided evidence of an under-performance compared to predictions and laboratory based measurements. Siviour found empirical U-values up to 50% higher than calculated U-values and attributed the difference to air movement between plasterboard and masonry, thermal bridging and inaccurate thermal conductivity values (Siviour, 1994). This is supported by the work of Dudek et al which observed a 25% average difference between calculated and measured U-value, highlighting the significant effect of thermal bridging due to inaccurate application of mortar (Dudek et al., 1993). Doran found that there was a range of differences between actual and predicted U-value which was heavily dependent upon wall construction, with timber frame walls performing at a very similar level to predictions while masonry walls had a U-value up to 30% higher (i.e. worse) than predicted (Doran, 2000).

Interestingly, a number of studies of the U-value of solid walls have actually shown a better than predicted performance (Barker, 2008; Li et al., 2014; Rye, 2010). In these studies in-situ measurements of the U-value of solid walls were carried out using heat flux meters in a total of around 75 buildings. The buildings tested were of both stone and brick walls of various ages. The results consistently found U-values in the range of 1.3-1.4W/m^{2}K (ibid), significantly less than the previous most commonly assumed average value for pre-1976 solid walled houses in the UK of 2.1W/m^{2}K which is used in SAP (BRE, 2011). This evidence of higher than expected in-situ performance of solid walls is seemingly contradictory to the majority of results reported earlier in

[1] The houses were of timber framed construction and were found to have a large local variation in the amount of timber used between different houses and walls, which were not built as the design specified.

this section, further demonstrating the general lack of accurate knowledge of the performance of buildings in practice.

A second route for heat loss from buildings is through background ventilation in which warm internal air is replaced by cooler exterior air. There has been considerable empirical testing of the air-tightness of buildings, even prior to the requirement for the partial testing for new buildings introduced in Part L of the 2006 Building Regulations (H.M. Government, 2006). In reference to the performance gap, the most crucial finding of the results of these tests has been the scale of variation in air tightness which is not represented in energy models. Several studies have found a large variation in air tightness between buildings of similar construction and age (Johnston et al., 2004b; Sinnott and Dyer, 2012; Stephen, 1998); this is well demonstrated by the measurements taken in the Sinnott and Dyer (2012) study (Figure 2-1).

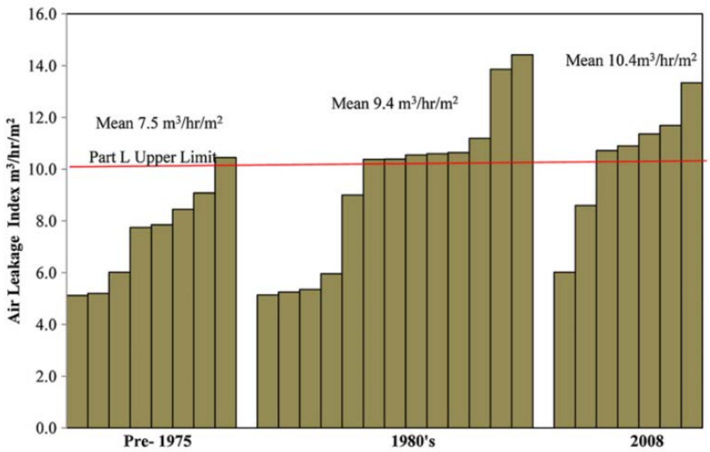


Figure 2-1: Measured air permeability of 28 houses in Ireland, figure sourced from the Sinnott and Dyer (2012).

In each case, construction quality was highlighted as important in achieving high levels of air tightness, particularly around penetrations of walls such as at pipe outlets. It is also recognised that the air tightness of buildings is likely to degrade over time; this is thought to be due to shrinkage cracks occurring as building materials dry out, and wear and tear on the seals around door and window openings (Elmroth and Logdberg, 1980; Johnston et al., 2004b).

Despite a generally held hypothesis that older buildings, with their greater prevalence of chimneys and sash windows, are less air tight than new designs (Sinnott and Dyer, 2012; Stephen, 1998), empirical evidence does not support this notion. In a study of 28 homes in Ireland, Sinnott and Dyer found no simple relationship between air-tightness and building age, indeed this study found that despite increasingly stringent regulations newer buildings were less air tight (Sinnott and Dyer, 2012).

This finding is supported by the results of Stephen's 1998 review of the BRE database of air tightness measurements. This numbered 471 when the report was written and showed no strong relationship between building age and air tightness (Stephen, 1998).

An improvement in air tightness has been revealed by studies undertaken since the introduction of the partial testing requirement to Part L of the Building Regulations (Pan, 2010; Zero Carbon Hub and NHBC Foundation, 2010a). This research gives some evidence of the positive role that testing and the specific performance targets that they allow can have. The importance of this function in forcing a focus in both the design and construction processes has been highlighted by Torcellini et al (Torcellini et al., 2006) and statistical evidence has been developed by Pan (Pan, 2010). Significantly both regulatory requirements and measured air leakage rates in UK buildings are higher (i.e. more leaky) than those observed in Scandinavia and Canada, suggesting that there is room for improvement of the UK stock.

This summary of research provides compelling evidence of a difference in fabric performance between real life and modelled predictions. Furthermore, it shows that this error in predicted performance occurs almost universally in a positive direction, that is to say buildings invariably have lower performance levels than predicted. This provides a clear motivation for the development of a convenient empirical method of measuring fabric performance. This conclusion has been echoed by Oreszczyn & Lowe (Oreszczyn and Lowe, 2010), Stevenson & Rijal (Stevenson and Rijal, 2008) and the findings of the Zero Carbon Hub task group chaired by Malcolm Bell, who reported that:

> *"Despite recent development work, as a result of the Stamford Brook and other projects, the central method (co-heating) has remained essentially the same as when it was first developed some 30 years ago. This and other methods are in need of urgent development."* (Zero Carbon Hub and NHBC Foundation, 2010a)

The considered import of this within the research community is highlighted by Lowe and Summerfield, who emphasise the need for a 're-invigoration of the role of empirical evidence' in the editorial in the 2012 special edition of the Building Research and Information journal: *Next Challenges for Energy and Building Research* (Summerfield et al. 2012).

2.3. Elemental In-Situ Measurement Methods

In laboratory conditions the thermal performance of a sample of a building material or construction element can be tested using the guarded hot box or guarded hot plate apparatus. In both tests a heat flow is applied across the sample. In the hot plate method the sample is sandwiched between two plates with the thermal conductivity measured by the rate of heat input to the heating plate (BSI, 2001a).

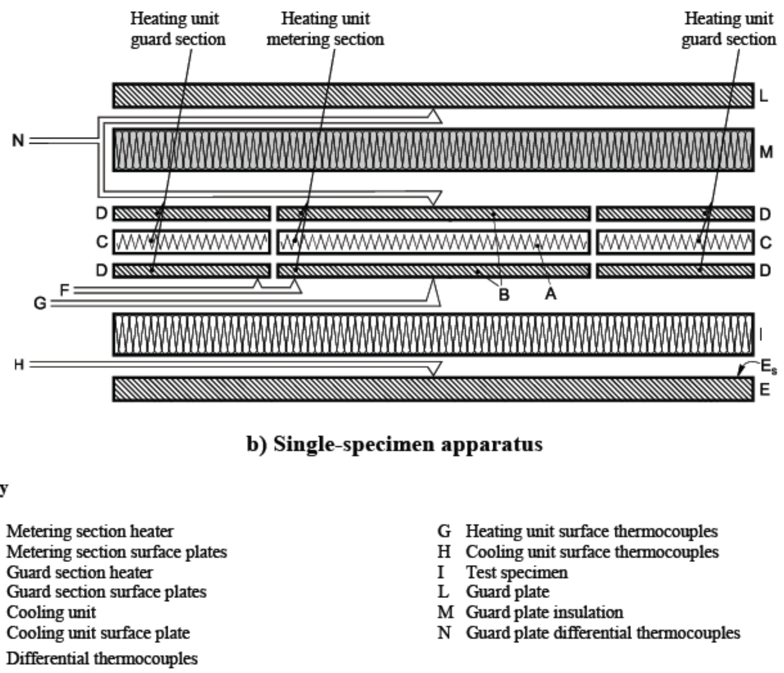


Figure 2-2: Diagram of the guarded hot plate apparatus, image sourced from BSI (2001a).

In the guarded hot box method the sample is placed between a hot and cold chamber, the surface and air temperatures are measured on each side together with the heat input to the hot side, allowing the thermal properties of the sample to be measured (BSI, 1996). Though both of these methods can be applied to carry out measurements with high accuracy, it has been shown in section 2.2 (The Fabric Performance Gap) that in-situ performance may differ widely from the laboratory-based measurement. Tools are available that can measure the U-value of a section of a building element in-situ, the most commonly used are heat flux sensors but thermal probes are also used.

Heat flux sensors consist of a series of thermocouples which measure the temperature difference across a thin layer of material of a known thermal resistance. This temperature difference causes a voltage difference in the sensors which is related by calibration to the heat flux, in W/m^2, through the sensing region (ASTM, 2007). The heat flux is then divided by the internal-external temperature difference to give the U-value in W/m^{2}K (Siviour and McIntyre, 1982).

These sensors have been used to measure U-values in-situ for some 30 years and the drawbacks with the method that Siviour and McIntyre reported then are as just as relevant today (Siviour and McIntyre, 1982). The problem with this method is that the thermal capacitance of the element being measured (e.g. a wall or floor) means that heat does not flow at a constant rate through the wall, some is stored and released later, creating a phase difference between temperature and heat flux (McIntyre, 1985). This means that although the U-value doesn't change the measured flux does, therefore the measured U-value will also vary according to the conditions during the testing period.

Solar irradiation has the effect of increasing the effective temperature of the exterior wall and therefore slowing the rate of heat transfer (in the case of a higher internal temperature) (Siviour and McIntyre, 1982). Both of these factors (thermal capacitance and solar irradiation) affect different materials differently making the measurement of U-values complex. The accepted method to reduce the error is to measure over a longer period, in the order of weeks, and to average the results (ASTM, 2007). The necessary testing period will vary depending upon the specific conditions of the site, and perhaps because of this there is not an accepted minimum testing period. Barker calculated that a period of at least one week was necessary (Barker, 2008), while Doran and Rye recommended a period of 14 days (Doran, 2000; Rye, 2010). A significant temperature difference between inside and outside, ideally larger than 10^{o}C (Desogus et al., 2011), is required to ensure a large enough heat flow to be accurately measured which limits the test's use primarily to the winter months (Biddulph et al., 2014).

Recently Biddulph et al. (2014) have suggested a new analysis method which seeks to address these issues by applying a dynamic, rather than assumed steady-state analysis, characterising the effect of thermal mass rather than trying to eliminate it. In their method a lumped mass model is applied to the wall, which is then solved using Bayesian analysis. As described in the previous paragraph, the classic data analysis method requires a long monitoring period in order to carry out an averaging procedure that removes imbalances in the charging and discharging of thermal mass. Biddulph et al's new method removes this necessity and hence can drastically reduce the minimum measurement period, from 10 days for the averaging method to 3 days for the lumped mass model in the results reported in the 2014 paper (ibid). As the method utilises temperature changes rather than consistently high temperature differences it is less seasonally dependent, and may be suitable for use in summer (ibid). The method has been applied to in-situ data from a total of 93 walls, showing close agreement with results from the traditional averaging approach (Li et al., 2014).

A further issue is that heat flux sensors are usually rather small, with a diameter of only a few centimetres, therefore only a small section of the wall can be measured. This means that the measurement will not take into account the effect of thermal bypasses which can have considerable impact on constructions' thermal performance (Wingfield et al. 2010). This is compounded by the accepted testing method, which recommends performing a thermal image survey to find a homogeneous section of wall to test (ASTM, 2007). This approach means that areas of wall that might cause higher than expected heat loss, such as areas with thermal bypasses or missing insulation, are deliberately avoided by the measurement. This is necessary because areas with thermal bypasses can cause local distortions to the heat flow of around 17%, which would introduce a significant error into the measurement (Siviour and McIntyre, 1982).

It is crucial that heat flux sensors are applied to the wall with a good thermal contact, which presents a more practical constraint upon their use. Technical standards recommend that this is achieved with the use of glue or tape which can damage the wall surface, limiting their use in occupied buildings (ASTM, 2007). Furthermore, a U-value can only be measured by a heat flux sensor if the temperature on each side of the element being tested is known.

A second method of measuring a component's thermal properties in situ is through the use of a probe measuring tool. This tool uses the transient source method, whereby a probe is inserted into a hole that has been drilled into a wall. The probe is heated with a known power while simultaneously the temperature is measured along the probe. The time taken for the probe to heat up can be related to the thermal resistance of the material (inverse to the U-value) (Pilkington et al., 2006). The advantage of this method is that it does not require the long testing period associated with the use of heat flux meters (Pilkington and Grove, 2012). However, a hugely limiting factor is that the probe can only measure a single material and not a construction composed of layers, such as a masonry wall with a cavity for instance (Pilkington et al., 2006). Furthermore, this method suffers from the same issues associated with measuring the U-value in only one location and achieving a good thermal contact with the wall as is the case with heat flux sensors.

These limitations mean that, while heat flux sensors can provide a revealing analysis of building elements as built, they cannot provide a complete picture of the whole building. Furthermore, there are several practicalities involved with taking measurements which may limit their widespread use.

2.4. Infiltration Rate Measurement

Heat is lost from buildings by two main mechanisms, through the fabric of the building and by exchange of warm internal air with cool external air. The second heat loss mechanism occurs both through infiltration and by intentional ventilation – which can be supplied naturally or by a mechanised system. It is important to note a distinction in definitions here:

- Infiltration rate refers to air movement through the building fabric
- The background ventilation rate refers to infiltration plus air movement through intentionally installed passive ventilation, such as trickle vents, air bricks or open windows (note that this excludes any mechanical ventilation).

The proportion of heat loss through the building fabric and due to air exchange is specific to each house, depending upon its particular thermal performance and air tightness. It follows that as thermal performance increases the importance of infiltration heat loss will increase as it forms a larger percentage of the total.

UK houses have, in general, been shown to be less air tight than those in most other developed nations in comparable climates, for instance the BRE database showed an average air tightness for pre-1994 dwellings in the UK approximately three times higher than Scandinavian equivalents (Pan, 2010). However, evidence is showing rapidly improving levels of air tightness in newer buildings in the UK; in 2008 the National House Building Council (NHBC) measured the air tightness of 1293 newly built dwellings in the UK, finding an average air tightness of $6m^3/$ (h m^2) (NHBC Foundation, 2008). This compares to the average of a sample of 471 dwellings found by Stephen in 2000 of $11.5m^3/$ (h m^2). There are several causes of variation in air tightness between buildings such as building age, construction type, the complexity of the building (and hence number of junctions between building elements), seasonal variation and longevity (Johnston et al., 2004a). These last two are particularly interesting as they show that air tightness is not a constant quantity, it can be heavily affected by factors such as thermal expansion and moisture content (ibid). In 2011 the NHBC Foundation carried out a study investigating the way in which air tightness changes over time in which repeat measurements in 25 new houses were carried out 1-3 years after construction. The results showed that for two thirds of the sample became more leaky (by $1.5m^3$ / (h m^2) (39%) on average) and that the remaining third became more airtight (by $0.63m^3$ / (h m^2) (19%) on average) (NHBC Foundation, 2011). This variation in air tightness should be taken into consideration when interpreting the results of measurements.

The infiltration rate of a building is most commonly measured with a fan pressurisation test (also known as a 'blower door test'), but is also measured by observing the decay of a tracer gases introduced to buildings (ASTM, 2012; ATTMA, 2010; BSI, 2001b). In pressurisation tests a fan is installed in an external door which is used to pressurise or depressurise the building. The airflow into the building is monitored at different internal/external pressure differences and the air leakage of the building is calculated using the power law equation:

$$Q = C(\Delta P)^n \qquad \text{(EQ 2-1)}$$

where Q is the volume of air flow through the fan in m^3s^{-1}, ΔP is the internal/external pressure difference applied to the building and C and n coefficients that relate to the size of the opening and the characterisation of the flow regime, respectively (Sinnott and Dyer, 2012). The best practise method involves temporarily sealing all purpose-made vents and openings, holding all internal doors open, carrying out a pressurisation and depressurisation test, and then averaging the results (ATTMA, 2010). Both pressurisation and depressurisation tests should be carried out as leakage paths have complex shapes and could react differently to different air flow directions. BRE tests have shown that the results can vary by as much as 20% depending on the direction of airflow (Stephen, 1998). When pressurising a building smoke sticks can be used to find particularly prevalent leakage paths (Sinnott and Dyer, 2012).

The results of pressurisation tests are most commonly reported as the volume flow rate of air passing through the fan at a pressure difference of 50 Pascals normalised per metre squared of envelope area, termed 'q50' and with units of $m^3/hr/m^2$. The envelope area includes all perimeter walls, the roof and the floor (ATTMA, 2010). They are also reported as the air changes per hour at a pressure difference of 50 Pascals. This can be converted into a value for air changes at standard pressure using the rule of thumb that the air change under normal pressure is equal to that at 50Pa divided by 20, which Sherman attributes to Kronvall & Persily (Sherman, 1987). This rule of thumb is applied slightly differently in SAP with the q50 value, in $m^3/hr/m^2$, being divided by 20 rather than the air change rate at 50 Pascals to give the air change rate at atmospheric pressure (BRE, 2011). The change in units is included in the division by 20.

The advantage of the pressurisation method is that it is, to some extent, independent of weather conditions due to the high pressure differences used (Stephen, 1998). However, the ATTMA technical standard for the method does advise that extreme weather conditions can seriously affect the measurement, with wind speed above 6m/s having a noticeable impact (ATTMA, 2010).

The other commonly used method to measure infiltration rate is through the dilution of tracer gases that are introduced to the building. This method is generally be applied in one of three ways: (i) concentration decay, (ii) constant injection, and (iii) constant concentration. All of the methods work on the basic principle that by measuring the rate of change of the concentration of a traceable gas in a space, the amount of air leaving that space can be calculated. The advantage of these methods is that the measurements can be carried out regularly throughout a testing period; this is advantageous as the infiltration rate is a dynamic parameter which is driven by changes in temperature and wind speed (ASTM, 2012). However, the concentration decay method has the disadvantage of being a discrete measurement during one period, while the other two tracer gas methods described can provide a constant monitoring of the building. A significant source of error in these measurements is that the monitoring time over which the tracer gases disperse is of the order of hours, during which time the infiltration rate can vary. A study by Stymne et al (1994) suggested this could cause an underestimate of the infiltration rate of between 15-35% in a leaky house.

While pressurisation tests offer a relatively quick, cheap and robust test of leakage, they do not provide a direct measurement of the infiltration rate at atmospheric pressure, which is what is required to calculate the associated energy losses (Warren and Webb, 1980). A rather simplistic rule of thumb is used to generate the infiltration rate from the results of pressurisation tests (Sherman, 1987), which is likely to introduce errors given the aerodynamic complication of leakage paths that will not be accounted for (Stephen, 1998). Indeed, studies have shown a tendency for the pressurisation tests to overestimate the infiltration rate (Judkoff et al., 2001).

Tracer gas tests can help to overcome these technical issues, though they are significantly more expensive and require long unoccupied periods for testing (Warren and Webb, 1980). For this reason, pressurisation tests have become more prevalent and have been used as a compliance check in building regulations. This inclusion on building regulations, and the evidence for a consequential increase in air tightness (Pan, 2010) (Zero Carbon Hub and NHBC Foundation, 2010a), provides an encouraging case study for the positive effect of measured performance standards.

2.5. Thermal Imaging

Thermal imaging, or Infrared (IR) thermography, can be used to provide a quick, cheap, non-intrusive two dimensional picture of the apparent temperature field on a surface. This makes it an ideal testing tool for use with occupied buildings from a practical point of view. Thermal imaging works by detecting the IR radiation that every object above absolute zero emits. The amount of IR radiation that an object emits increases with temperature, so that an image showing variations in temperature, usually represented by a range of colours, can be created. IR radiation is electromagnetic energy with a wavelength of between 0.7µm and 1mm, though IR cameras typically detect radiation with a wavelength of between 3-5.6µm (Hart, 1990). In addition to the temperature, the amount of IR radiation emitted by an object is dependent on its surface emissivity, which is the ratio of radiation emitted by a surface, varying from 0:1. Each object has a different emissivity, and without knowing this value the temperature of a surface cannot be accurately measured. Furthermore, objects can also reflect infrared radiation, so that the apparent temperature of a surface can include an amount of reflected as well as emitted IR radiation.

Thermal imaging has been used extensively as a qualitative tool to identify features such as thermal bridging and poorly installed insulation (Hart, 1990), and can also be used to identify air leakage paths when a building is depressurised (Wingfield et al., 2010). However, in order for such features to be observable there must be an internal-external temperature difference, typically of at least 5°C (BSI, 1999). In the most common case of a higher internal than external temperature, areas of increased heat loss appear as warm spots when viewed from the exterior and cold spots from the interior, see Figure 2-3 (Titman, 2001).

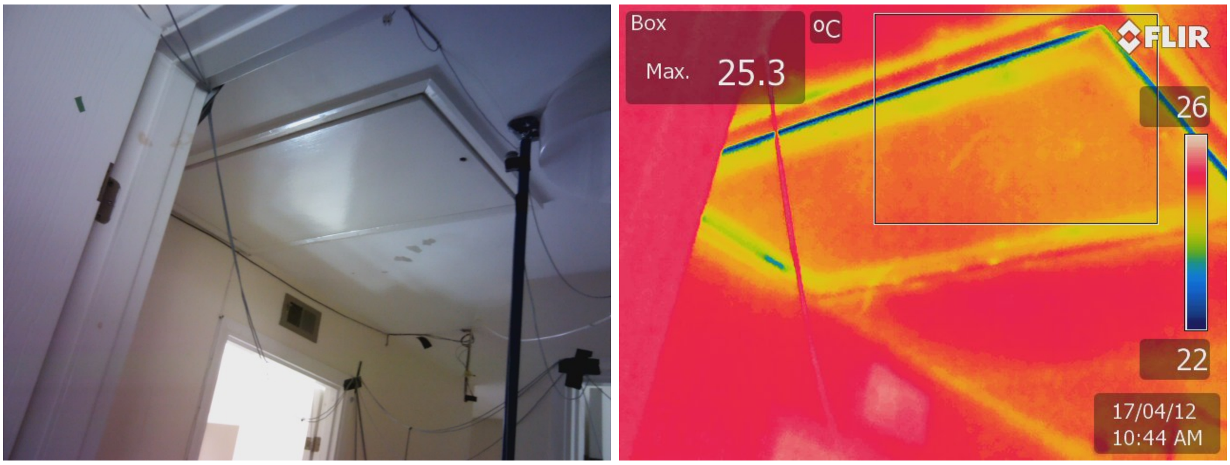


Figure 2-3: Thermal image (r) showing greater heat loss through a loft hatch (internal air temperature 22.0°C, external air temperature 7.9°C) (Jack et al., 2012)**.**

There are, however, practicalities that limit the use of thermal imaging and particularly its use as a quantitative method. Moisture and strong winds can affect the heat transfer coefficient at the surface of a material, masking the heat transfer through building elements and render thermographic surveying inaccurate (Lo, 1999). Furthermore, complex fluid flows across building elements will lead to a dynamic variation in wind velocities across different locations (ibid). Materials with high moisture content will also give inaccurate results as the moisture acts as a heat sink, this does, however, make thermography an extremely good tool for detecting damp (Titman, 2001). Surfaces also take time to react to changes in temperature, so an IR measurement includes a component dictated by the temperature history of the surface; for this reason measurements should be made several hours after sunset (Allinson et al. 2006).

Highly reflective surfaces, such as glass, plastic or ceramics are also problematic while using thermography. In this case the measured radiation will have significant elements reflected from surrounding sources, introducing significant error to the measurement (Titman, 2001). In a building surveying context the most likely surrounding sources are the sun, adjacent buildings and vegetation and a large sky view. Defining the emissivity of a surface is also problematic, particularly as emissivity varies as a function of temperature, surface roughness, wavelength and viewing angle (Marinetti and Giorgio Cesaratto, 2012).

These issues mean that despite its convenience thermography has largely been limited to a qualitative role in building research. However, one company in America, Essess (www.essess.com), is currently offering quantitative assessments on a huge scale, utilising Google Street View style data collection techniques. These assessments use thermal imaging alongside several other data streams to estimate cost savings due to a variety of retrofitting measures, the accuracy of these assessments is unknown at present. However, work by Allinson et al has shown that achieving reliable quantitative measurements from aerial infrared surveys is not possible (Allinson et al. 2005), and that similar problems exist using surveys completed at ground level (Allinson et al. 2006). In both applications the most significant issues were the variable emissivity of surfaces and different view angles which affect the amount of infrared radiation that reaches the camera. This is crucial as thermography does not measure surface temperature, it measures the amount of infrared radiation reaching the lens of the camera; this could perhaps be overcome but requires complex analysis of the images (Allinson et al. 2006).

2.6. Whole House Thermal Performance Measurement

The need for whole house thermal performance measurements have already been highlighted, the most pertinent being the inaccuracy of elemental methods for predicting or measuring the performance of a house as a whole. This observation begs the obvious question: why do whole house measurements remain relatively rare? This sub-section describes a review of the available measurement methods in order to address this question.

There are two methods for whole house thermal performance testing which have been widely used: the co-heating test and the Primary and Secondary Term Analysis and Renormalization (PSTAR) test. Both were developed in the late 1970s and early 1980s. The first use of the co-heating test in the UK occurred in the work of Siviour in the early 1980s (Everett, 1985), it was based upon the earlier research that led to the development of the PSTAR test in the late 1970s at the Solar Energy Research Institute (SERI) in the US (now part of the National Renewable Energy Laboratory – NREL) (Subbarao et al., 1988). The name 'co-heating' bears little relation to the current method; rather it describes the original purpose, which was testing the efficiency of heating ducts. In this first incarnation of the test, a building would be heated to a set temperature sequentially by electric heaters and by the building's heating system, the difference between the power required by each system to reach a set point temperature gave the efficiency of the ducts. The building is heated from two sources, hence the term 'co'-heating (Francisco et al., 2006).

The co-heating test is the most commonly applied method for whole house thermal performance measurement in the UK at present, while the PSTAR test is more common in the US. The main difference between the tests is in the method used to account for dynamic effects, such as diurnal temperature and solar radiation patterns. The co-heating method applies a constant internal temperature and accounts for dynamic effects through an averaging method over a longer measurement period. The PSTAR method aims to characterise the dynamic effects and incorporates cooling, warming and constant temperature periods.

Whole house measurements have been an active research area throughout the period of this study, including both further work into existing methods and the proposal of no less than three additional measurement methods. Research into the application and uncertainty of the co-heating test has been carried out in the UK and at KU Leuven in Belgium (Bauwens et al., 2012; Guerra-Santin et al., 2013; Stamp et al., 2013; White, 2014), while new measurement methods have been proposed by researchers in Europe (Berger et al., 2010; Caucheteux et al., 2012; Mangematin et al., 2012b).

2.6.1. The Co-Heating Test

The principle of the co-heating test is based upon an assumed steady-state energy balance; its purpose is to measure the total (both fabric and infiltration) heat loss rate of a building, with the result most commonly reported as a Heat Loss Coefficient (HLC) with units of Watts per Kelvin. The energy balance, which uses daily-averaged data and does not account for thermal storage affects, states that the total heat input rate to the building, provided by electrical and solar heating, is equivalent to the total heat loss rate (both fabric and infiltration) from the building (Siviour, 1981):

Electrical Heating + Solar Heating = Fabric Heat Loss + Ventilation Heat Loss (EQ 2-2)

or: $Q = Q_e + Q_s = Q_f + Q_v = \sum U.A.\Delta T + 0.33N.V.\Delta T$ (EQ 2-3)

and: $HLC = Q_f / \Delta T$ (EQ 2-4)

Where:

Q is the total rate of heat input to the building (both electrical and solar) (W)

Q_e is the rate of electrical heat input to the building (W)

Q_s is the rate of solar gains to the building (W)

Q_f is the fabric heat loss rate from the building (W)

Q_v is the ventilation heat loss rate from the building (W)

HLC is the total heat loss coefficient of the building (W/K)

And:

$Q_f = \sum U.A.\Delta T$ (EQ 2-5)

$\sum U$ is the sum of the U-values of each building element (W/m^2K)

A is the total area of each building element (m)

ΔT is the air temperature difference between the inside and outside of the building (K)

And:

$Q_v = 0.33N.V.\Delta T$ (EQ 2-6)

0.33 is an approximation of density multiplied by specific heat capacity of air at 25^oC ($kJK^{-1}m^{-3}$)

N is the air leakage rate in air changes per hour (1/h)

V is the internal volume of the building (m^3)

ΔT is the temperature difference between the inside and outside of the building (K)

During a co-heating test, the internal air temperature of a building is controlled (using electrical heating equipment) to a constant raised temperature, usually 25°C, for a period of 1-3 weeks. The rate of energy consumption required to maintain this elevated temperature and the weather conditions during the test are carefully measured. The HLC can be determined by plotting the daily average rate of energy consumption against the daily average temperature difference between the inside and outside of the building, where the gradient of a line of best fit forced through the origin is equal to the HLC, as shown in Figure 2-4. The procedure of forcing the line of best fit through the origin is commonly adopted and inherently assumes that at zero heat input there will be no temperature difference, this will only be true is all gains have been accurately accounted for, which is not necessarily the case (due to effects such as long-wave radiative heat loss and difficult to calculate solar gains, which will be described in more detail later in this section). The suitability of forcing the line of best fit through the origin is an ongoing subject of debate, with a best practise method yet to be agreed upon. Circulation fans are used to mix the contained air, ensuring an even temperature distribution within the building.

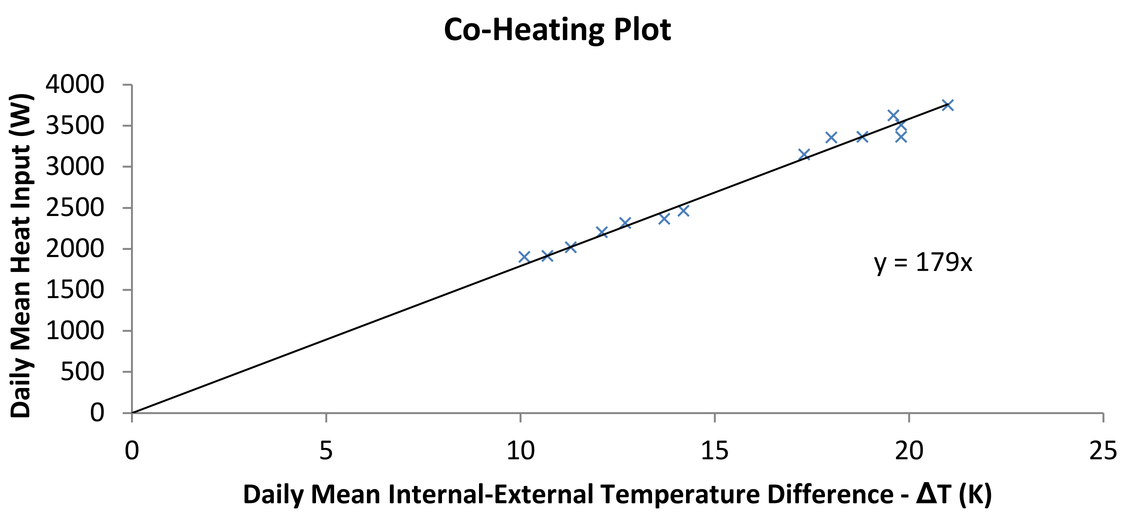


Figure 2-4: Example co-heating analysis plot created by the author. Each data point represents the averaged measurements over a 24 hour period (note that the line of best fit is forced through the origin).

In order for the method to be effective, there must be a significant internal-external temperature difference, a difference of at least 10K is recommended (Johnston et al., 2013). This, in conjunction with the high solar gains of the summer months, has restricted practical application of the co-heating test to the winter heating season (ibid).

The challenge with this seemingly simple test is that the building is operating in dynamic conditions. Application of the test is complicated by the effects of: i) solar gains, which act as an additional intermittent heating input to the building; ii) thermal storage by the building fabric, which causes a time lag in the rate of heat transfer as it responds to solar gains and diurnal temperature variations; iii) infiltration losses, which act as an additional load and can be affected by changes in wind speed; and iv) changes in wind speed and relative humidity that can change the rate of heat transfer on the external surface of the building (Everett, 1985).

To account for these issues, certain protocols are followed. To compensate for the effect of thermal mass, values for heat input rate and temperature difference are averaged over a period of 24 hours, thus incorporating a full diurnal temperature cycle. Everett (1985) recommends that this daily period should run from dawn until dawn, so as to allow the stored energy from the preceding day to dissipate as much as possible before the defined start of the next day. In this manner, the daily variations in solar conditions are separated to the greatest possible extent.

On sunny days, it is possible that solar gains could provide some or all of the energy for space heating during daylight hours. Solar gains must therefore be measured to accurately quantify the total heating input to the energy balance (Everett, 1985). A number of methods for accounting for solar gains have been proposed, which are described below, but at the time of writing there is not a consensus upon the most appropriate. In addition to the description given below, Bauwens and Roels (2014) have recently completed an in-depth review of co-heating analysis methodologies.

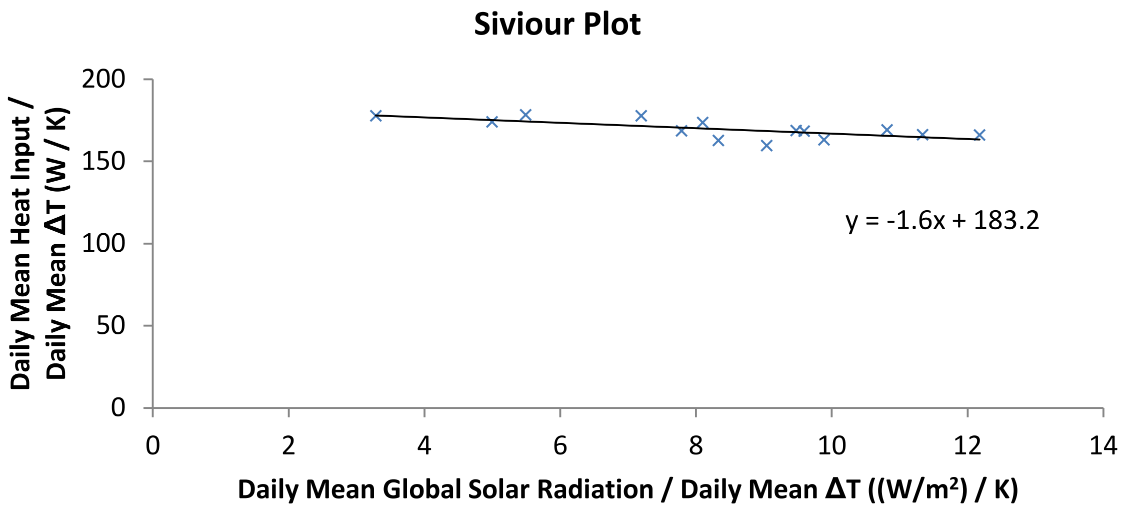


Figure 2-5: An example of the Siviour co-heating analysis method created by the author. Again each data point represents the averaged readings taken over a 24-hour period.

During the early stages of the development of co-heating analysis, Siviour proposed a graphical method (Everett, 1985), whereby the electrical heat input rate is plotted against the total solar irradiance received on a horizontal surface, with both terms divided by the temperature difference, as shown in Figure 2-5. This method is referred to as the 'Siviour' method throughout this thesis. Both axes are divided by daily mean temperature difference in the Siviour method in order to 'normalise' the data by this variable. In effect, this allows the HLC to be calculated by a simple linear regression which takes into account both internal-external temperature difference and solar irradiation. The y-intercept of a linear trendline is then the HLC of the building, and the inverse of the gradient is termed the *solar aperture*, the latter being a term that represents the equivalent area of vertically orientated, south facing, perfectly transparent facade, through which solar gains have occurred (ibid). More recent work by Bauwens and Roels (2014) has shown that the solar aperture is actually a term used as a proxy to represent a complex combination of effects, including the level of irradiance reaching each facade and the angles of incidence occurring on each glazed facade, overshading, glass characteristics and the cleanliness of the glass. Due to the variation of factors which the term is used to represent, the solar aperture term does not represent a direct measurement such as an area (ibid). Due to the complex and inextricable way in which the phenomena listed above are linked in the solar aperture term, Bauwens and Roels (2014) strongly recommend not to calculate the solar aperture by knowledge of the physical properties of the windows (ibid).

An alternative analysis method has been used by researchers at Leeds Beckett University (Johnston et al., 2013). In this method, a multiple regression analysis is carried out using daily averaged data where electrical power is the independent variable, and internal-external temperature difference and mean total solar irradiance on a horizontal surface are dependent variables, and the constant is assumed to be zero.

$$Q = HLC.\Delta T - R.S \qquad \text{(EQ 2-7)}$$

Where:
R is the solar aperture of the building (m^2)
S is the vertical, south facing solar irradiation (W/m^2)

The output of the multiple linear regression carried out upon equation 2-7 results in an estimate of the solar aperture (R), as in the Siviour method (Johnston et al., 2013). This value is multiplied by the mean global irradiance for each day to calculate the daily solar gain, which is then added to the electrical heating input (ibid). Although a measurement of solar irradiation on a south facing, vertical, plane is used in the Johnston et al (2013) method, a measurement of solar irradiation in a different orientation, such as horizontal global solar irradiation could also be used (note: global solar irradiation measurements throughout this thesis are all assumed to be measured on a horizontal plane). The HLC is then calculated using a co-heating plot, as shown in Figure 2-4. This method is referred to as the 'multiple regression' method throughout the thesis. Alternatively, the same method can be applied, but using the solar aperture defined by a Siviour analysis rather than a multiple regression. This is referred to as the 'Siviour plus regression' method throughout the thesis.

At the time of writing the co-heating test has been used almost exclusively as a research tool, with the access restrictions inherent to the test limiting its wider use. In the role of a research tool, however, it has been instrumental in providing the evidence for the performance gap, providing a unique measurement of the combination of all building elements in a house (Zero Carbon Hub and NHBC Foundation, 2010a). The test has also been used to test and demonstrate the in-situ performance of houses designed with high thermal performance (Guerra-Santin et al., 2013; Meulenaer et al., 2005), the motivation for testing in these cases is clear as the houses had been built as exemplars of high performance. This motivation has meant that the majority of co-heating tests have been applied in highly performing houses, which has been identified as problematic given that the difficult-to-quantify solar gains will form a larger part of the total heat input, thus increasing the total uncertainty of the measurement (Guerra-Santin et al., 2013).

Another research application was demonstrated by van Meulenaer et al, when the test was used to provide data to validate a model of a building's performance (Meulenaer et al., 2005). The test is particularly suited to this role as the output metric is the HLC of the house, which can be directly compared with the output of most building energy models (e.g. SAP). While the co-heating test does allow this comparison in performance, it does not generally provide a method to diagnose the causes for any variation from the predicted performance. The evenly-mixed elevated internal temperature required for the test does, however, provide the perfect conditions to carry out other diagnostic measurements such as elemental U-values, thermal imaging or tracer gas decay tests (Johnston et al., 2012). White used the co-heating test in an innovative way to show that it can be used for specific diagnostic work in certain cases (White, 2014). A comparison of the measured performance of a mechanical ventilation system to that predicted by a SAP model was undertaken by carrying out repeated co-heating tests, first with and then without the ventilation system in operation (ibid). The performance of the system was then analysed by comparison of the two results (ibid).

Despite the increasing use of the co-heating test, the testing procedure and in particular the data analysis method is yet to be fully defined. In 2011 the NHBC arranged a major research project aiming to address the continuing debate over the best practise co-heating procedure. The project involved a round robin co-heating test of a single detached house at the Building Research Establishment (BRE) in Watford, UK. In the project six teams drawn from both industry and academia sequentially tested the house with their version of the co-heating method, with each team having a two week measurement period. In addition, the BRE carried out co-heating tests prior to, and following, the set of six tests made by the teams, and constantly co-heated an adjacent house of the same construction for an extended period of eight months. Following the completion of the tests each team independently applied their analysis and reported their results and analysis procedures. These were then compared by the BRE and reported in *NF54 Review of Co-heating Methodologies* (Butler and Dengel, 2013). The participants in the project were: the Building Services Research and Information Association (BSRIA), Loughborough University, Stroma Technology, University College London, the University of Nottingham and the Welsh School of Architecture, Cardiff University; Leeds Beckett University took part in steering group discussions but did not carry out a test (ibid). The author of this thesis carried out the work on behalf of Loughborough University, with the evaluation forming a key part of the analysis of the total uncertainty in co-heating tests presented in Chapter 5.

The NHBC report of the project found that the maximum deviation of the co-heating test results compared to the HLC as-calculated by a SAP evaluation 17% (Butler and Dengel, 2013). It was concluded that the external temperature and solar radiation conditions during the each test were primarily responsible for variations between the results (ibid). Given the evidence for the performance gap, which has been demonstrated by conducting co-heating tests, it appears questionable to judge the accuracy of the tests by comparison with a value estimated by a SAP evaluation. It could be argued that even this seemingly large deviation (17%) may be an acceptable level of uncertainty for the co-heating test, when compared to the size of the performance gap observed in many houses.

In the comparison of data analysis methods it was observed that all the teams applied a regression based approach in order to calculate the solar gains – some version of the multiple regression and Siviour approaches described above. It was highlighted that in order for this approach to be accurately applied a range of solar and external temperature conditions must be obtained, as the standard linear regression technique using the least squares method is highly sensitive to data scatter and particularly outlying data points (Butler and Dengel, 2013). The crucial impact of this is that a reduced measurement period will reduce the likelihood of collecting data under a suitable range of conditions and so reduce the accuracy of the test (ibid); for this reason Butler & Dengel (2013) judged that co-heating is inappropriate for large scale application. It was also noted that it is assumed in the co-heating method that the entire building envelope is exposed to the external air temperature, in reality this is not the case for the floor of the building (ibid). This may add uncertainty, especially given the different conditions that will be experienced by solid and suspended floors (ibid).

Because solar gains were identified as a key source of uncertainty in the co-heating method, an additional set of tests involving the application of shading to the windows was undertaken. These tests were found to reduce the deviation between the co-heating measurement and the SAP estimation of the HLC, with an observed difference of only 3.8% (Butler and Dengel, 2013). Though the same question about using a SAP calculated HLC as the benchmark measurement needs to be raised, the results show promise in the method. It is also possible that shading the windows could cause a change in their thermal performance, which could in turn effect the HLC measurement. A small sample of three tests using window shading were completed and it was recommended that further tests should be carried out in different buildings at different times of the year to gain confidence in the method (ibid).

In order to remove the uncertainties associated with calculating solar gains, it was suggested that co-heating data collected only during the night time should be used in the analysis. This approach has a clear attraction in simplifying the data analysis, and may also remove the requirement for solar radiation measurements (Butler and Dengel, 2013). However, concerns were raised that large daytime solar heat gains remaining stored in the thermal mass of the building may introduce uncertainties into this method (ibid). Having found that environmental conditions significantly affected the measured HLC during in-situ co-heating tests, White (2014) used a thermal chamber to carry out a series of controlled co-heating tests to investigate the effect of a number of environmental conditions. The thermal chamber provides a thermally controlled space, inside which a second internal chamber is constructed in which the internal conditions can also be controlled. The internal chamber was constructed of a highly insulating material with a sample of wall inserted in one side; for the tests carried out by White, two types of wall sections were used – one of solid brick and a second of externally-insulated brick. Heat flux plates were installed on each side of the chamber, and the internal and external air and surface temperatures were measured while the co-heating tests took place (ibid). One of the factors investigated was the impact of daytime solar gains, and the possible effect that this could have on a night time only data analysis method. During the tests, lights were used to simulate solar radiation on the wall. In different tests, irradiance levels of 100, 200 and 350W were applied over a 6 hour period, with the wall allowed to cool over the subsequent 18 hours – simulating a night time period following the day (White, 2014). The tests showed that thermal lag caused by the solar gains could be considerable, with lags associated with the 100, 200 and 350W tests of 7, 9 and 17 hours respectively for the uninsulated wall and 2, 3 and 4 hours respectively for the insulated wall (ibid). These results provide evidence that thermal lags from solar gains may indeed cause inaccuracies in a night time only co-heating test analysis; solar radiation levels of 100W are likely in the UK even during the winter months, especially given the low altitude sun on south-facing facades at that time of year. White cautions that though this level of solar radiation is possible, it is likely that many days will not experience these conditions over a full 6 hour period (White, 2014).

Uncertainty in accounting for solar gains has been highlighted in all publications that have specifically investigated uncertainty in co-heating tests (Bauwens et al., 2012; Butler and Dengel, 2013; Stamp et al., 2013; White, 2014). In fact Guerra-Santin et al, of the Welsh School of Architecture, found that uncertainties in accounting for solar gains using the Siviour method in two low energy buildings were so large that that the test may be unsuitable for use in this application (Guerra-Santin et al., 2013). Researchers from the same institution then build upon this finding, using simulations to investigate the validity of co-heating tests carried out on highly insulated buildings (Alexander and Jenkins, 2015). In this study they found that the multiple regression analysis method provided the most accurate results, and that under certain conditions HLC measurements to within an accuracy of better than ±10% were possible even for the most highly-performing buildings (ibid). However, achieving this level of accuracy was found to be highly dependent upon the test length and the conditions during the test. The result was that in the higher-performing dwellings simulated, (which aligned with the 2007 Passivhaus requirements and 2012 Building Regulations) test lengths of 6-8 weeks were required to reach the ±10% accuracy limit, or if the test were limited to 3 weeks the window of opportunity for testing in UK weather conditions was less than 2 months (ibid).

Stamp et al (2013) also used simulated co-heating tests to investigate how four weather variables affected the results, uncertainty and bias of co-heating tests; the variables were external temperature, solar radiation, wind speed and long wave sky radiation. In common with other research, the work indicated that solar radiation was the largest contributor to the uncertainty in the HLC (ibid). This was caused both by inaccuracy in the calculation of the solar gain itself, and thermal mass effects associated with charging cycles taking place over a longer time span that the 24-hour period over which data is averaged causing a ‘hangover’ effect, where the weather conditions of the preceding day have an impact on the next (ibid). These observations concerning thermal mass effects reinforce the empirical evidence reported by White (2014). Stamp et al (2013) found that thermal mass effects could also be generated by variations in external temperature, which can generate a lag in the thermal response of the building in the same way as solar radiation.

A further investigation of the co-heating test using simulation was completed by Bauwens et al (2012), in their study simulated co-heating tests were applied to a section of insulated cavity wall. It is accepted in their paper that this tends to reduce the importance of solar gains as an opaque element is the subject of the study (ibid). Thermal lag effects were found to introduce uncertainty in the measurement of the HLC. To account for this, an adapted regression method was proposed whereby the heat input is correlated with a time weighted average internal-external temperature difference to take account of the thermal history of the wall (ibid). This method was found to give a more reliable calculation of the HLC by both the multiple regression and Siviour methods, and reduced the necessary monitoring time to achieve an accurate result (ibid).

In addition to their findings associated with solar gains, Bauwens et al (2012) also reported several findings associated with regression-based analysis. The study showed that the necessary monitoring time to achieve an accurate result was reduced by assuming a zero intercept in the multiple regression method (ibid). A particular problem with data collection when applying the Siviour method was identified, as the regression was easily corrupted on days where there was a very low internal-external temperature difference (ΔT) (ibid). This is because the low ΔT values dramatically scale the calculation of the daily heat input/ΔT and solar radiation/ΔT terms (which are plotted on the x- and y-axis in the Siviour regression (Figure 2-5)), introducing outliers to the regression. In common with Butler and Dengel (2013), Bauwens et al (2012) also note that a range of conditions are required in order that the regression is not affected by the cantilever effect of outliers (ibid).

Stamp et al’s (2013) co-heating simulations also demonstrated that during periods of negative net radiation long wave heat loss to the sky can introduce an error into the measurement of the HLC. In all contemporary data analysis methods these losses are unaccounted for; the result is that as the level of sky radiation varies throughout the year a bias is introduced into the measured HLC, as shown in Figure 2-6 (Stamp et al., 2013). During the winter months there is lower (more negative) net radiation, this results in a greater heat input for the same ΔT, hence a bias towards a higher measured HLC. This effect is nuanced though; the predicted HLC from most energy models is calculated in zero net radiation conditions, so the actual HLC of the modelled building will change dependent upon the sky radiation conditions (ibid). For the building simulated in the Stamp et al paper this effect could change the HLC by up to 10%, therefore a co-heating test may measure the correct HLC during a particular period, but this might to equate directly to the calculated HLC (ibid).

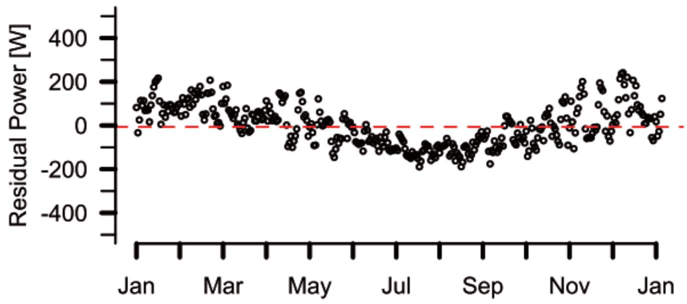


Figure 2-6: The additional heat loss due to sky radiation over a two week multiple regression for samples taken over a 12 month period, taken from (Stamp et al., 2013)**.**

Increased wind speeds primarily affect the heat loss from a house by increasing the infiltration rate, and hence infiltration heat loss, but they can also increase the convective heat transfer coefficient at the external surfaces (Butler and Dengel, 2013). At present there is little evidence available as to the possible size of these combined effects. White found that a variation of ±10% between daily HLC values could be caused by changes in wind speed during one co-heating test (White, 2014), while Stamp et al found that changes in wind speed had no significant effect in their simulated co-heating tests (Stamp et al., 2013). As infiltration heat loss is the mechanism is affected more heavily than the fabric heat loss, the uncertainty will be larger in less airtight buildings. The size of the effect will also be heavily dependent upon the length of a particularly windy period relative to the total sample length (Butler and Dengel, 2013). For instance, if only 1-2 days of a sample of 14 or more experience a 10% change in heat loss due to high wind speeds the effect for the whole period is likely to be very small.

Two methods have been suggested to account for wind speed effects, the first (and simplest) is to omit windy days from the co-heating analysis, however this may be impractical is the test length is limited and/or the number of windy days relatively large (Butler and Dengel, 2013). The second is to apply a multiple regression as is used to account for solar gains; however several studies have observed that this approach is likely to be prone to uncertainties due to the complex interaction between weather variables (Butler and Dengel, 2013; Stamp et al., 2013; White, 2014). In addition, the effects of the wind are not captured fully by average wind speed measurements. This measurement is prone to uncertainty when taken around buildings and trees which will cause local gusting, and wind direction is also likely to have an effect (Stafford et al., 2014).

Moisture effects have been identified as a possible source of uncertainty (Stafford et al., 2014; White, 2014). White (2014) conducted an experiment using the thermal chamber described earlier in which the externally insulated wall sample was wetted over a period of time during a co-heating test. Although there was an observed effect on the surface temperatures and heat flux at the external surface of the wall, they were not large enough to cause a significant change in the measured HLC (ibid). This testing does not however, conclusively show that moisture effects cannot have a significant impact on co-heating tests, they are likely to have a greater impact for uninsulated solid walls (White, 2014) and could be increased by a combined effect with high wind speeds. However, the results do suggest that moisture effects have a smaller impact on the test than solar gains or wind.

2.6.2. Faster Thermal Characterisation

While the co-heating test may be the most frequently applied method of measuring whole house HLCs in the UK, the length of the test and the extended access restriction to the house present major practical difficulties. The desirability of a test that could be carried out with a shorter measurement period is clear. At present there appear to be two methods that offer this possibility, both use a dynamic measurement approach, seeking to characterise the thermal mass of the building rather than averaging out its effect, similar to the development in elemental U-value measurements that was described in section 2.2. The two methods are the Primary and Secondary Term Analysis and Renormalisation (PSTAR) Test developed in the United States in the late 70s and 80s, and the Quick U-Value of Buildings (QUB) method that has recently been patented and demonstrated by Saint Gobain.

The PSTAR method uses a shortened version of the co-heating test, known as Short Term Energy Monitoring (STEM), to calibrate an audit model of a building (based upon calculations using laboratory measured elemental material performance values in a similar way to SAP) (Subbarao et al., 1988). The PSTAR and STEM methodologies were developed from the late-1970s until the early 2000s, but published work surrounding the method seems to have ceased at that time.

The PSTAR tool is designed to interpret the data from the STEM test in order to calibrate a model of the building. This is achieved by modelling the building in such a way that the heat flows in the building can be disaggregated and treated separately. The heat flows are then separated into flows that vary according to changing weather conditions and building parameters, called primary terms, and those that don't – called secondary terms. An hourly energy balance for each zone in the building is then carried out with the primary terms normalised by measured values from the STEM. The secondary terms remain as they were determined in the audit (Subbarao et al., 1988).

In the domestic application the primary terms are the HLC and terms to represent heat storage and solar gains. These are measured in a three day long STEM test, consisting of (Palmer et al., 2011):

- A short, 2 to 4 hour, co-heating phase to measure the HLC. This is usually carried out overnight as this is the most stable period for temperature and there are no solar gains; in this period, the heat input from the heaters and losses due to conduction are assumed to be dominant.
- A cool down phase, also carried out at night, to quantify the thermal mass of the building. During this phase the energy storage term is assumed to be dominant as the building's mass discharges.
- A 'free-running day', where no additional heat load is applied to the building to quantify the effective solar gain area.

The renormalisation process works by calculating re-normalising coefficients that balance the heat flows during each of the described phases using a linear least squares method (Subbarao et al., 1988). This three-step process is repeated until the difference between predicted and measured energy transfer is below an acceptable level, this is typically around 5% of the primary heat flows (Palmer et al., 2011). PSTAR is an automated testing computer program with associated software.

The PSTAR process requires a significantly shorter measurement period than the co-heating test, but it does share many other practical constraints with co-heating. The building must be unoccupied, there must be a significant internal-external temperature difference (>15K is recommended), and the monitoring must contain a period with clear skies during the daytime in order to estimate the solar aperture of the building (Palmer et al., 1993). This limits the use of the test to the winter months in most climates and can require an extended monitoring period to ensure data is collected during a suitable range of conditions (most commonly this applies to the requirement for a period with clear skies).

The PSTAR method has been validated against measurements made in an environmentally controlled chamber, this validation showed that with repeated tests the method is capable of detecting changes of 5% in the HLC (Judkoff et al., 2001, 2000). A one off test carried out in the UK found, however, that the annual energy consumption predicted using the building properties measured by a PSTAR test was 30% less than the actual monitored consumption (Palmer et al., 1993). This comparison cannot be considered conclusive however, as it is not possible to tell whether the discrepancy was caused by an error in the measurement of the building properties or by the model of the occupation of the building that was used to predict energy consumption (ibid).

A direct comparison between the PSTAR and co-heating test was carried in a building in York; the purpose of the comparison was to test the suitability of the PSTAR test to be included as a compliance check for Part L of the building regulations given a shorter measurement period (Palmer et al., 2011). The co-heating and PSTAR evaluation were carried out in February 2008 and March 2009 respectively, the PSTAR evaluation was carried out by a team that had no knowledge of the results of the co-heating test (ibid). The comparison did not find a strong agreement between the methods, with the PSTAR test giving a HLC 34% lower than that from the co-heating test. It was felt that the time elapsed between the tests could partially explain the disparity (i.e. that the house's performance may have changed during a year of occupation), however the main conclusion was that the tests actually measured a different parameter (ibid). In the case of the co-heating test the building is fully heat soaked throughout, thus largely negating the effect of thermal mass. In contrast, the heating periods in the PSTAR method are much shorter, so that the HLC measured includes a contribution towards charging the thermal mass of the building. Thus PSTAR is not a purely fabric metric disassociated from changing internal and external conditions, but the authors felt that it may provide a more accurate method of estimating annual energy consumption in real life (Palmer et al., 2011).

The Quick U-value of Buildings (QUB) method has been developed over the past few years by Saint Gobain (Mangematin et al., 2012b), it is a dynamic test with procedural similarities to the PSTAR test, and can be completed in around 48 hours, including installation and removal of equipment (Pandraud and Fitton, 2013). The outputs of the method are the HLC of the whole building, as in co-heating, and the internal heat capacity of the house; the HLC is estimated to be measured with an accuracy of ±15% by the QUB test (Pandraud and Fitton, 2013). The method is based upon the hypothesis that after a few hours of heating with a constant power the internal temperature in a house will vary as if there is only one time constant, and will therefore follow a single exponential function over time with variables of the HLC and the heat capacity (Pandraud et al., 2014). This assumption allows a simple R-C (resistor-capacitor) model to be applied as shown in EQ 2-7:

$$C\, d\Delta T = (Q - HLC_{total}\ \Delta T)\, dt \qquad \text{(EQ 2-8)}$$

Where:
C is the heat capacity of the house (MJ/K)
Q is the total rate of heat input into the house (from installed heating and solar gains) (W)
HLC_{total} is the total rate of heat loss (fabric plus ventilation) (W/K)

The variables in this R-C model (the HLC_{total} and heat capacity) are then calculated by analysis of the rate of change of ΔT during periods of constant heating and cooling (Pandraud and Fitton, 2013). Data is collected over a total period of between two and three days, including time for commissioning and decommissioning of the testing equipment (Mangematin et al., 2012b). At first, the building is constantly heated for a period of approximately 24 hours, using a heat source that ensures a homogeneous internal temperature throughout the building (ibid). The building is then allowed to cool overnight (to avoid solar gains) for a period of approximately 12 hours (ibid).

In order to ensure closely controlled internal conditions during testing the house is required to be unoccupied (Mangematin et al., 2012b). The total restriction of access to the house is the same for both the QUB and co-heating tests, though the QUB test takes only 2-3 days rather than 2-3 weeks.

Reports of three validation tests of the QUB method have been found, these have been carried out in a newly-built low energy detached house (Mangematin et al., 2012b); two thermally lightweight small, single storey modular buildings (Pandraud et al., 2014); and in 'The Energy House' at Salford University (The Energy House is a reproduction of an end terrace house built to 1910 UK building standards completely contained within a climate controlled chamber) (Pandraud et al., 2014). In the earliest test, in the detached house, the results of the QUB test agreed closely (within ±8%) with the HLC of the house as calculated by traditional elemental summation and as measured over a winter (Mangematin et al., 2012b). The detached house used in the trial was of a rather complex construction, but is likely to have low effective thermal mass as it is constructed partly with a wooden frame and partly with internally insulated concrete blocks.

For the modular building trials, the results of the QUB method were validating by comparison with the HLC measured by a co-heating test; 25 QUB trials were undertaken to test the reproducibility of the QUB (Pandraud et al., 2014). The greatest difference between the result of one of the QUB tests and the co-heating baseline was +17%, but the difference between the mean QUB and co-heating results was just 2.3% (ibid). Finally, the method was validated against a steady-state measurement carried out in The Energy House; in this test the QUB result was within ±7% of the steady-state measurement (Pandraud and Fitton, 2013). As yet, no validation of the QUB method has been reported for a building with significant thermal mass which is exposed to high solar gains. Such a test would be interesting given the issues of thermal lag in co-heating tests described in section 2.6.1, where exposure to high solar irradiation and external temperatures was shown to affect the house over a longer time period than is used for the QUB measurements.

2.6.3. In-Use Methods

Alongside more traditional post-occupancy evaluation and specific performance testing (e.g. co-heating, PSTAR and QUB) two versions of an in-use energy balance approach have been suggested by researchers in France: the BEECHAM method by Caucheteux et al and the EBBE method by Berger et al (Berger et al., 2010; Caucheteux et al., 2012). At this point it may be useful to restate that an 'in-use' test refers to one which is carried out while a house is occupied. Both methods are based upon an energy balance between fabric and ventilation heat losses against the heat gains to the house. The gains include space heating, electrical consumption, solar gains and heat gains due to occupants; in both methods measurements or estimates of these values are inputted to the energy balance to produce a model of a building's operation.

In the EBBE (Energy Balance of the Building Envelope) method each of the gains and losses in the energy balance are estimated and summed to output a calculated total heat supply for a weekly period (Berger et al., 2010). The energy balance is comprised of (ibid):

- Solar gains - calculated by first estimating an equivalent horizontal area over which solar gains occur for each facade based upon the location and time of year. The 10-year average global solar irradiance for that location at that time is then uses to calculate the solar gains for the week.

- Heat from lighting and electrical appliances - estimated from typical usage profiles defined per m^2 of floor area and rated power for a number of electrical items.
- Ventilation heat loss - estimated using measured energy consumption of fans and internal/external temperature difference.
- Infiltration heat loss - estimated using infiltration rate measured by blower door test.
- Heat gains due to occupancy - estimated from typical occupancy pattern, the number of adult and child occupants per m^2 floor area and metabolic energy production.
- Fabric heat loss - estimated using a notional whole building U-value multiplied by building surface area and internal/external temperature difference.

The energy gains and losses are then summed; with a range of possible fabric heat loss totals calculated using a range of estimate total U-values for the building. This process outputs a range of possible energy consumption totals (Berger et al., 2010). These possible totals are then compared with the actual measured consumption in the building, and the U-value which gives the best fit between measured and calculated data is then chosen as the measured whole building U-value (ibid). The method has so far been trialled on the electrically heated restaurant of a primary school in France, with an agreement to within around 12% on average (over several weeks of testing) between the EBBE calculated HLC and the HLC calculated by a traditional audit method (similar to SAP).

In the BEECHAM (Building Energy Efficiency CHAracterisation method) method the energy balance model contains four terms which describe solar gains, thermal inertia, infiltration heat loss and a combined term for fabric and ventilation heat loss (Caucheteux et al., 2012). Each term is described as a measured value, global horizontal solar irradiation in the case of solar gains for example, multiplied by a coefficient which is determined by statistical comparison between the energy balance model and measured energy consumption (ibid). A quasi-Newtonian algorithm is used to optimise the fit between modelled and measured data, using a 1 day time step and approximately 14 days of recorded data (ibid). The calculated coefficients are then inputted to the energy model so that it can be used to estimate the HLC of the building (ibid). The method has been applied to two detached buildings constructed to 2005 French building regulations and the results agreed with the HLC as calculated by the audit method to within ±10% (ibid).

The BRE's Building Energy Hub, also offers an in-use method to measure a building's HLC (BRE, n.d.). This is a wireless management system that collects data from sensors located around the house including: internal and external temperature, gas and electricity use, boiler use and occupancy sensors (ibid). This data is used in an algorithm to calculate the HLC of the building in real time (ibid). Another similar service appears to be offered by the Carbon Reduction Options for Housing Managers (CROHM), which has been developed by a combination of Parity Projects, Sustainable Homes and researchers at Oxford University (Sustainable Homes, 2014). At the time of writing a cross-European project, called Performer, is being carried out which also aims to deliver a similar methodology to measure the performance of buildings in-situ (Performer Project, 2015). For both the Energy Hub and CROHM systems, and the Performer project, there is little information available at present; their existence and ongoing funding demonstrates that this is currently a very active area of research.

Finally, methods similar to PSTAR and QUB, but using data collected while a building is in-use have been suggested (Bacher and Madsen, 2011; Rabl, 1988; Sonderegger, 1978). These approaches can be broadly termed *inverse modelling* or *system identification*, whereby a building's characteristics are inferred from measured temperature and energy consumption data by application of a thermal model of the building (Rabl, 1988).

2.7. Summary and Knowledge Gap Identification

The literature review has demonstrated a clear need for in-situ testing of thermal performance in houses and that there is not yet a satisfactory method. The aims and objectives of this study have been designed to fill this identified gap. The requirement for whole house in-situ testing has been generated by the growing body of evidence that there is a gap between predicted and in-situ thermal performance. It has been shown that this performance gap is unlikely to be successfully detected by elemental measurement methods, and requires a test that measures the performance of a house as a whole. This evidence has been mostly collected by application of the co-heating test which has shown a wide variety of causes for underperformance that vary between houses; and could for example be associated with inaccurate assumptions of elemental performance, unforeseen thermal bypasses or variable build quality. It is this variety in causes that undermine the traditional audit approach to predicting building thermal performance, where the properties of each element of the construction are summed to calculate the value for the whole. By the same reasoning, elemental measurements are unlikely to provide an accurate reflection of the house as a whole. Collectively, the factors described in the paragraph above provide the driving force and rationale for holistic in-situ testing when seeking to accurately measure the real thermal performance of a house.

An important distinction to be made when considering 'the performance gap'; a discrepancy between predicted and actual energy consumption can be caused by many factors and is not necessarily evidence of underperformance of the building fabric. The catch-all term 'performance gap' can apply to a number of sources of discrepancy between the predicted operation of a house and what happens in practice. These sources can be broadly separated into two categories: those associated with the thermal performance of the building and its systems, and those associated with accurately predicting the way that a house will be when occupied. Therefore a key property of any method designed to test the performance of the building fabric will be its ability to isolate fabric properties from the actions of the occupants. In the majority of methods reported in the literature this is achieved by requiring that the occupants are not present during testing, though it is clear that this presents significant practical difficulties. A different approach has been adopted in the case of the EBBE and BEECHAM methods, which seek to derive the thermal properties of the house while the building is 'in-use', that is, while the occupants are present.

The co-heating test remains the most commonly applied test of whole house thermal performance. Despite its widespread use the testing method is still in development, with no definitive method yet in place. This is true of the test procedure and even more so of the subsequent data analysis, for which several different approaches have been applied by various parties. In addition to the variety of data analysis approaches used there is no standard method for defining the uncertainty of the HLC measurement determined by a co-heating test. The only method observed in the literature was to state the standard error in the regression analysis used to calculated the HLC, which does not account for the uncertainty in all of the constituent parts of the test – such as internal and external temperature, global solar irradiation and electrical heat input. Accurately defining the uncertainty of the test would be a key step in increasing confidence in its results.

The minimum required measurement period of the co-heating test suggested in literature is at least 10 days, and could be longer depending upon the weather conditions that occur during the monitoring. This extended period is to account for solar gains and overcome the effects of thermal storage. In order to reduce the impact of these issues it is recommended that co-heating tests are only carried out in the winter months, and to further reduce uncertainties the test must be applied when the house is not occupied. These practical constraints are the main barrier to applying the co-heating test more widely as a quality control instrument. Recent work has investigated the minimum period necessary to obtain reliable HLC measurements by co-heating and the effect of certain weather variables on this minimum period (Bauwens et al., 2012; Stamp et al., 2013). However, it is clear that understanding the relationship between the characteristics of the house, the conditions during testing and the minimum time that is therefore required is a necessary area of further work. Development of a deeper understanding in this area would allow greater certainty about when an accurate measurement of the HLC has been obtained, which could lead to shorter testing periods.

Accurate quantification of solar gains has been identified in most co-heating research as the most significant source of uncertainty in the method. Addressing this issue is likely to reduce the uncertainty of the method and may also allow testing outside of the usual winter co-heating season.

Two approaches have been identified to addressing the practical constraints of the co-heating method; reducing the testing period and carrying out a measurement with the occupants in place – a so called 'in-use' method.

The PSTAR, and the more recent QUB test, have been identified as methods which seek to reduce the testing period, both of which do so by analysing dynamic temperature data, seeking to quantify the effect of thermal mass rather than removing its influence by an averaging method. This is similar to the dynamic approach to taking U-value measurements of walls using heat flux plates which has been recently suggested and demonstrated by researchers from University College London (Biddulph et al., 2014). As yet only a single comparison between the PSTAR and a co-heating test has been carried out (Palmer et al., 2011); however the results of this comparison suggested that the result of the two tests may be fundamentally different. Following their analysis Palmer et al. suggested that the HLC as measured by the PSTAR test included both the heat loss of the building and a proportion of heat contributing the charging the thermal mass of the building. This issue has not so far been identified in the validation of the QUB test, however both comparative experiments with the co-heating test have been carried out in buildings and situations where the influence of thermal mass is likely to be small (in thermally lightweight buildings and a climate controlled chamber). It will be interesting to see whether the issues associated with thermal lags that were experienced by the PSTAR test have been solved by the analytical approach used in the QUB test. Both the PSTAR and the QUB tests require that a house be unoccupied during testing, in common with the co-heating test. The testing period for both is greatly reduced compared to the co-heating test, being around 2-3 days; this could still provide a significant practical constraint in occupied houses but may be acceptable in a new-build application.

Two in-use methods to measure the HLC of a whole house have been identified: the EBBE and BEECHAM methods (Berger et al., 2010; Caucheteux et al., 2012), both of which have been published during the course of this research (in 2010 and 2012 respectively). The attraction of an in-use method is that they can be carried out with much less impact on the occupants. Indeed, disruption to occupants could well be further reduced in the future given increasing availability of suitable secondary data sources, such as that available from smart meters. Both the EBBE and BEECHAM methods have been demonstrated by comparison with the predicted thermal performance of a single building, as calculated by the traditional audit method. The evidence of inaccuracies in the audit method gives reason for concern about this method of validation, and demonstrates the benefit of an empirical baseline for such comparisons.

The literature review clearly shows that whole house testing is an active field of research which has been stimulated by the compelling evidence for a performance gap between predicted and in-situ thermal performance, and thus energy consumption, of dwellings. The review of measurement tools has shown that an empirical method to measure whole house performance is technically feasible but that current tools are impractical for widespread application. The limiting factors to the wider uptake of whole house performance measurement are primarily practical; specifically, the duration and invasiveness of current tests and the lack of confidence in the accuracy of the results.

Chapter 3 Design of the Experiments

This chapter describes the design of the experiments carried out, detailing what tests that were carried out and why. A full technical description of each of the tests and methods used is given in Chapter 4; effectively comprising a description of where, when and how work was undertaken. As described in the introduction, this study is comprised of three objectives which were defined based on the findings of the literature review:

- Assessing the accuracy of the co-heating test through an elemental sensitivity analysis of the measured HLC to uncertainties in constituent measurements and data analyses.
- Improving the method of quantifying the solar gains with the aim of increasing the reproducibility of the test and increasing the length of the traditional winter-only co-heating season.
- The development of a novel alternative test that can be applied while a house is in-use in order to overcome the highly invasive nature of co-heating tests.

Experiments were designed to investigate each of these objectives, with the findings from the co-heating research feeding into the development of an in-use method. The research into the co-heating test was carried out first as this provides the baseline measurements against which the results of the in-use heat balance test can be compared. It was therefore important to establish the method that would be used in the co-heating tests to allow a constant comparative approach throughout the development of the in-use method. An empirical comparative approach was considered to be important given the inherent uncertainty in calculations of building performance using traditional audit-based methods (Chapter 2).

This chapter is separated into two main sub-sections; the first describes the co-heating tests conducted, and the second describes the empirical work to develop the in-use test.

3.1. Co-Heating Tests

Two sets of co-heating tests are analysed in this thesis. The first set was completed as a part of a project investigating accuracy and reproducibility of co-heating tests, organised by the National House Building Council (NHBC). The results of the NHBC project were used to estimate the total uncertainty in the co-heating test and to investigate the effect of weather conditions during the measurement period. The second set of co-heating tests involved repeated co-heating tests carried out in two houses over multiple seasons during a single year. They were designed to investigate the possibility of increasing the proportion of the year during which co-heating tests can be accurately conducted, using a new method to account for solar gains. For each of the two houses tests were carried out during three seasons (summer, winter, and either spring or autumn).

3.1.1. Analysis of NHBC Co-Heating Project Data

In 2011, the NHBC Foundation arranged a research project in co-operation with the UK Building Research Establishment (BRE) with the aim of assessing the robustness and reproducibility of co-heating tests. The project involved round-robin tests in a single detached house whereby seven different organisations carried out a co-heating test according to their own method. The tests and data analysis were carried out and reported independently to the BRE who coordinated the testing schedule. The round robin tests were carried out one after another between December 2011 and May 2012 in an already well-characterised test house at the BRE Garston site near Watford, UK. In addition to the round-robin testing, an extended co-heating test was carried out continuously in a second adjacent test house of identical design for a period of nine months, from December 2011 to September 2012. Data collected during both the round robin and extended tests has been used in significant further analysis carried out for this study.

The organisations that took part in the testing were: the BRE, the Building Services Research and Information Association (BSRIA); Loughborough University; Stroma Technology; University College London; the University of Nottingham and the Welsh School of Architecture, Cardiff University. The continuous co-heating test was carried out by the BRE. Each team was assigned a testing period of approximately 2 weeks, though this varied slightly between teams. A stipulation of the project agreement was that all results would be reported anonymously, and in this thesis they are referred to by the randomly assigned the letters A-G (Table 3-1).

Start-End Dates of Testing Period	Assigned Letter	Length of Testing Period in Days
22 Dec 2011 – 2 Jan 2012	A	12
24 Jan 2012 – 6 Feb 2012	B	14
10 Feb 2012 – 24 Feb 2012	C	15
28 Feb 2012 – 15 Mar 2012	D	17
16 Mar 2012 – 2 April 2012	E	18
3 April 2012 – 16 April 2012	F	14
23 April 2012 – 8 May 2012	G	16

Table 3-1: Details of the testing period for each team participating in the NHBC co-heating project.

Tests were conducted in purpose-built, detached test houses, denoted as 50.3 and 50.4, constructed in 1995 to contemporary Swedish Building Standards (Figure 4-6). They are of a simple rectangular plan form over two floors (ground and first floor), with an unheated attic space, triple glazed windows and suspended timber floors. Details of the construction of the house were made available to all participants before the testing period, including a calculated theoretical HLC of 65.92W/K based upon an elemental summation of the area weighted U-value of each part of the building. A full description of the houses is given in section 4.1.3.

Each organisation was required to conduct their co-heating test and report the measured HLC together with a summary of the testing method and data analysis techniques used. This was the only guidance provided to the teams; a prescriptive list of results to be reported was not specified. This approach was adopted in order that each team could carry out their co-heating test as they would in any other situation, thus encapsulating a full range of possible testing and data analysis methods.

The changes in season (from the first test in winter (Team A) to the last in spring (Team G)), and the differences in testing methods, meant that it would not be possible to disaggregate the influence of individual factors (such as a particular weather condition or variation in testing method) on the test outcomes. Instead, the emphasis of the project was to observe the robustness, reproducibility and range of variability of measured HLCs.

The results of the project were reported in the NHBC Foundation's publication *NF54 Review of Co-heating Test Methodologies* (Butler and Dengel, 2013). This publication was based upon an analysis of the reports submitted by each of the participating teams, and a steering group discussion attended by each of the participants and additional researchers from Leeds Beckett University. Following the project, the results of the long-term co-heating test carried out in building 50.3 were shared with all participants. The reports of each of the teams were also shared with Loughborough University, who were invited to produce an academic publication. The author of this thesis, and the academic paper, carried out the testing on behalf of Loughborough University, and has undertaken significant further analysis of the resulting data.

The literature review undertaken by the author in preparation for participation in the NHBC project showed that the method published by Leeds Beckett University (then called Leeds Metropolitan University) was the most widely used (Wingfield et al., 2010) and gave comprehensive instructions on the empirical method. However, it also showed that there was a relative lack of information about how to carry out the data analysis associated with co-heating tests. In particular, there were several different methods of accounting for solar gains and no guidance on how to correct for other possible sources of inaccuracy, such as changes in wind speed. For this reason co-heating data analysis became a key research area for this study, eventually leading to the development of a new co-heating method by the author. The results of the tests used to develop this new method, which focusses on accurately accounting for solar gains, are the subject of Chapter 6.

The rationale for the development of the new co-heating method was provided by an assessment of the existing data analysis approaches, which were described in section 2.6.1. Each of the existing methods are based upon some form of linear regression analysis between the electrical heat input to the building, internal-external temperature difference and solar irradiance during a co-heating test. This approach could be prone to inaccuracy due to the complex interaction of the variables. These interactions will include factors not considered in a regression analysis using only the three terms listed above, such as wind speed and direction, the behaviour of the thermal mass of the building, rainfall and long wave radiative heat exchange. Therefore, a linear regression analysis using only these three inputs (electrical heat input, internal-external temperature difference and solar irradiance) may be an over-simplification of a complex process, resulting in errors in the calculation of the HLC. For example, it has been found that in some cases regression analysis (using both the Siviour and multiple regression methods, which were described in section 2.6.1) has resulted in a positive correlation between solar irradiance and electrical heating power. In these cases, a negative solar aperture is calculated by the regression analyses, which in turn results in a *negative* solar gain when the solar aperture is multiplied by the daily solar irradiance. Clearly an additional heat loss due to solar radiation does not make physical sense; however there are possible physical explanations for this seemingly anomalous result related to the assumptions inherent to the analysis method. For example, the phenomena could be caused by long wave radiative heat losses to the sky if it is clear during the night after days with low solar irradiance.

Additionally, the underlying assumptions of multiple linear regression analysis present a problem when the method is used in co-heating analysis. There are likely to be significant correlations between the internal-external temperature difference and the level of solar radiation which contravenes the assumption that the independent variables should be linearly independent of each other. Multiple linear regression analysis also assumes that there is little or no autocorrelation in the data; autocorrelation is cross-correlation of data with itself over time, it occurs when a variable is linked with its past values. In co-heating this would occur when there is an extended period of similar weather which lasts for more than the 24-hour period over which the data is averaged.

An alternative co-heating data analysis method, which does not rely upon multiple regression, was therefore designed in response to the problems identified with that approach, which have been described in the previous two paragraphs. The new method, developed in this work, is called the '*facade solar gain'* calculation method. It involves measuring the solar irradiance reaching each glazed facade and using this measurement to calculate the solar heat gain through each glazed element. It is referred to as simply the 'facade' method throughout this thesis. The method assumes that all solar gains occur through the glazed elements of the building, and does not currently account for solar gains through the opaque elements. By comparison with existing methods, the facade method simplifies the data analysis, but requires additional measurements. For this reason, a second variation of the method was also tested, where the solar irradiance reaching each facade is estimated from a measurement of global solar irradiance, which is the most common solar measurement undertaken at weather stations. A full technical description of both variants of the method is given in section 4.3.3.

The data from the NHBC project gave a unique opportunity to test the new 'facade' method in comparison with the other well established methods employed by the other teams. Participation in the project also provided quality assurance of the co-heating method developed in this study, which is particularly important as this was the method used to generate the baseline measurements reported in this thesis, against which the results of the *Loughborough in-use heat balance* test are compared.

The reports of each of the participating teams were used to carry out a comparative analysis of the methods applied, for both the measurement and data analysis approaches. The comparison highlighted several key factors in taking a successful measurement of the HLC by a co-heating test, leading to a series of recommendations on the best practise method which builds upon the current state of the art.

The data from the long-term co-heating test was used in a sensitivity analysis that investigated the effect on the measured HLC of uncertainties in a series of key measurements. The measurements considered were internal and external air temperature, electrical power consumption and the calculation of solar gains. The sensitivity analysis was used to make an estimation of the total uncertainty of the co-heating test. This is a novel approach, based upon real rather than simulated data, and is thus thought to be the most robust estimate of uncertainty in co-heating currently available. The sensitivity analysis was based upon all of the data collected during the long-term co-heating test, over a total period of 23/12/11 to 2/1/12. There were two periods of data which have been excluded from the sample; these periods were excluded due to an increase in the internal set-point temperature (which led to an imbalance in the energy balance due to charging of the building's thermal mass) and equipment failure, respectively. The final sample included 219 days of data (Table 3-2).

Start-End Dates of Data Collection Periods	**Days in Period**
23/12/11 – 2/1/12	11
12/2/12 – 13/6/12	123
19/6/12 – 11/9/12	85
Total (23/12/11 – 2/1/12)	*219*

Table 3-2: Dates of data collection during the long-term co-heating test in building 50.3.

The data from the long term co-heating test was used for a second purpose, to investigate the reproducibility of the calculation of the HLC as calculated by each of the methods used for calculating solar gains: multiple regression, Siviour, Siviour plus regression and facade. As previously described in this section, there are two variants of the facade method. Variant one uses measurements of solar irradiance on each facade, and variant two uses estimates of these values derived from a measurement of global solar irradiance. In this investigation variant two was used as measurements of solar irradiance were not taken on each facade during the long term test.

For this investigation the dataset was split into a series of two-week long periods (the recommended minimum length of a co-heating test (Johnston et al., 2012)), a co-heating analysis by each of the four different methods was then applied to each sample period. The result of this process is the HLC of the house as calculated for each 14 day period, by each of the four different data analysis methods. This approach generates a picture of how the results of a co-heating test can change over time as external conditions change. The extended length of the dataset allows a direct comparison of the reproducibility of each data analysis method in calculating the HLC during a wide range of weather conditions. This enabled an analysis of the possibility of carrying out co-heating tests outside of the usual co-heating season (i.e. during the winter months). Extending the usable season for co-heating would significantly reduce the practical constraints around the test which would make it more suitable for widespread use as a quality assurance measure.

3.1.2. Inter-Seasonal Repeat Trials

The inter-seasonal repeated co-heating trials consisted of sets of three tests, carried out in two different houses in Loughborough. The inter-seasonal trials were undertaken to further investigate the reproducibility of the four co-heating analysis methods (multiple regression, Siviour, Siviour plus regression and facade) in houses of different construction and locations to the test houses at the BRE. In particular, the aim was to further test the suitability of extending the period of the year during which co-heating tests can be accurately conducted.

For each inter-seasonal trial three co-heating tests were carried out in different seasons; with one carried out in the usual winter co-heating season, one in a transitional period (either autumn or spring) and one carried out during the summer – the latter two of which have traditionally been considered unsuitable for co-heating tests. Each test was carried out separately, with the equipment installed and removed afterwards. The test houses used were the detached, timber framed Holywell test house built in 2000 according to contemporary building regulations; and the semi-detached, masonry test house at 209 Ashby Road, which was built in approximately 1930 and is typical of the period. Both test houses are described in detail in section 4.1. They were used for research experimentation before the co-heating tests and not specifically pre-heated in preparation. The dates over which the tests were conducted are shown in Table 3-3.

Test	Holywell Test Dates (and Length)	209 Ashby Road Test Dates (and Length)
Winter	24/11/12 - 6/12/12 (13 days)	14/3/13 – 31/3/13 (18 days)
Summer	26/6/13 - 15/7/13 (20 days)	13/5/13 – 30/5/13 (18 days)
Transitional	17/10/13 - 31/10/13 (15 days)	19/4/13 – 6/5/13 (18 days)

Table 3-3: Dates and measurement period of the repeated inter-seasonal trials.

For each of the tests the same experimental method was applied which included measurement of the solar irradiance on each facade including glazing. The HLC was then calculated for each test using four different data analysis methods to account for solar gains. The first variant of the facade method, using the solar irradiance measurements taken on each facade was used.

Clearly, the choice to use the measured or translated solar irradiance could have an impact on the calculation of solar gains using the facade method; this effect was investigated using the data collected during the inter-seasonal repeated tests. The data was well suited to this application, as both the global solar irradiance and the irradiance reaching each facade was measured during the tests which allowed a direct comparison between the two values. The variation in calculated solar gain for each of the tests when using the measured and translated irradiances was evaluated and used to quantify the impact on the measured HLCs.

The combination of the evidence gathered from the long-term and repeated inter-seasonal co-heating tests was used to inform recommendations on the most appropriate measurement and data analysis methods to use when calculating solar gains. These recommendations are based upon both the reproducibility and accuracy offered by each method and more practical considerations, such as the number of measurements required and the consequent expense. Using this range of factors suitable applications for each data analysis method are suggested, with reference to both co-heating tests and the in-use heat balance test.

3.2. Loughborough In-Use Heat Balance Tests

The research into the co-heating test described so far in this chapter sought to address two significant issues with the method, accurately quantifying its uncertainty and extending the period of the year during which testing can be carried out. This research does not, however, address the most significant issue with the co-heating, the invasiveness of the test caused by the length of the test (circa 14 days) and the requirement that the house be empty throughout. The next set of experimental work was designed to test the viability of a method developed in this study which aims to address this issue: the Loughborough In-Use Heat Balance (LIUHB). The LIUHB method uses monitored data, collected while a house is in normal use, so that the test can be completed with little disruption to the occupants. The data collection and analysis methods for the LIUHB are described in detail in section 4.4.

The experiments were designed to investigate the effect of major possible sources of additional uncertainty associated with an in-use test, in comparison to a test carried out in an unoccupied house. Foremost among these are the possible effects of occupant behaviour, which could introduce uncertainties from a number of sources such as internal gains from use of heat-emitting appliances, window opening, compromised sensor placement or increased temperature variation throughout the house. The measurement of heat inputs to the energy balance during an in-use test are also likely to be harder to measure with accuracy than in co-heating, therefore experiments were designed to test variations in boiler efficiency due to different operating profiles.

The experimental applications of the LIUHB can be separated into three sets of tests, with the majority carried out in the Holywell test house. The house and measurement equipment used in the tests are described fully in section 4.1.1. The tests in the Holywell test house were carried out over three consecutive winter heating seasons, as shown in Figure 3-1. The trials in the Holywell test house started with unoccupied conditions, similar to standard co-heating tests, then moved on to synthesise different variables associated with occupation of the house. Each synthetic occupancy variable was applied individually to analyse its specific effect, then applied simultaneously to investigate their combined effect. The chosen synthetic occupancy variables were window opening, hot water use, metabolic and electrical internal gains (commonly referred to as simply 'internal gains' throughout the thesis) and window covering. For each variable extreme examples of realistic occupant behaviour were applied in order to find the maximum possible impact on the LIUHB.

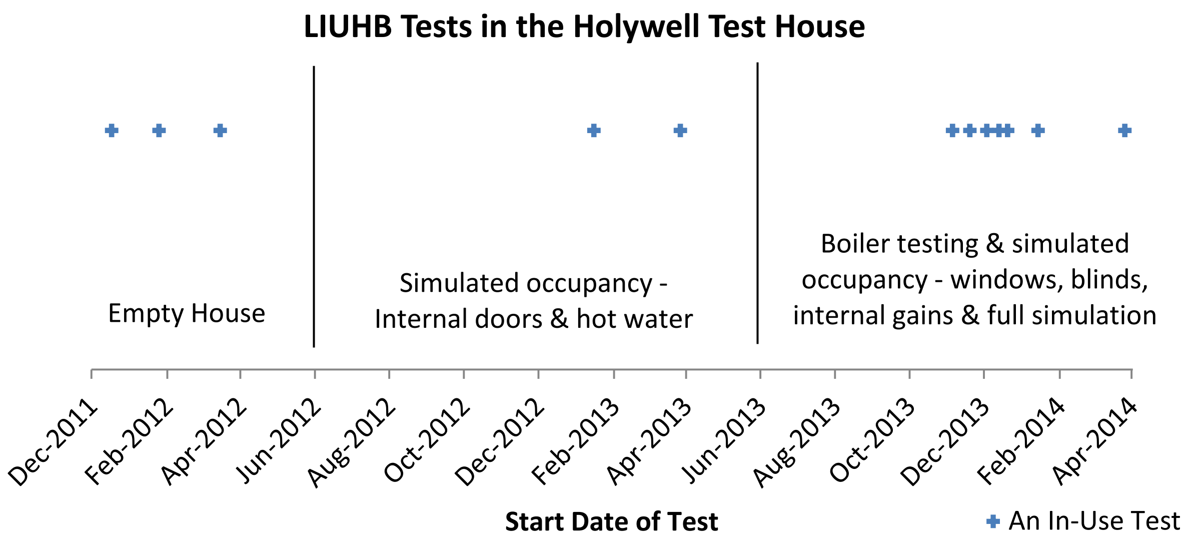


Figure 3-1: Testing schedule for the LIUHB trials.

For the second set of tests co-heating and heat balance tests were carried out in the Holywell test house before and after a retrofit carried out to improve the thermal performance of the house. These tests were carried out in conjunction with the Energy Technologies Institute (ETI) during May and June 2014 with the aim of testing the capability of the LIUHB to measure a change in the HLC following a retrofit, which is a likely practical application of the test. Finally a case study application of the LIUHB was carried out in an occupied home, for this case study a standard co-heating test was also carried out to establish the baseline HLC measurement for comparison with the LIUHB result.

Throughout the development of the in-use method the result of a standard co-heating test, analysed using the facade method, was used as the benchmark value against which the result of the in-use test was compared. This was considered important given the evidence for the inaccuracy of estimates of HLCs by traditional audit-based methods presented in the literature review.

The following sub-sections describe the development of the LIUHB and the experiments carried out to investigate the uncertainty in its measurement of the HLC. The pilot experiments that led to the conception of the test are described, followed by the tests undertaken in an empty house, tests with synthesised occupation, pre and post-retrofit testing, and finally a case study application of the LIUHB in an occupied house.

3.2.1. Pilot Experiments

The origin of the LIUHB is in testing that was undertaken to generate data during the development of the facade gain solar estimation method. Before equipment was available to carry out full co-heating tests, a reduced version of the test was carried out where the unoccupied Holywell test house was heated constantly to a set-point temperature of 25^{o}C using the incumbent central heating system.

The data from this test fulfilled the intended purpose of allowing a comparison between the different data analysis methods used to account for solar gains in co-heating. But they also showed that despite a wide variation between the internal temperature in different rooms in the house, particularly between upstairs and downstairs, there was a close relationship between the solar-adjusted heating power input and the internal-external temperature difference. Furthermore, when full co-heating tests were eventually carried out in the Holywell test house, the results agreed closely with those gathered using the central heating system, giving measured HLCs of 169W/K and 166W/K respectively (a full description of the results is given in section 7.1).

This unexpected result suggested that it may be possible to carry out a co-heating style analysis using data collected using a less controlled empirical method, yet result in a similar measured HLC. To further test this possibility, co-heating data analysis was applied to data collected in 10 occupied houses that had been collected as part of previous research carried out at Loughborough University (Kane, 2013). The data consists of average daily values for internal temperatures collected in each room and gas consumption in ten mainly terraced occupied houses located in Leicestershire, collected during the winter of 2010/11. Weather data was sourced from the weather station located on the Loughborough University campus. The Kane dataset is not ideal for application of the LIUHB method as it does not include all of the necessary measurements; in particular electricity consumption was not measured, so that not all of the heat inputs could be quantified. Despite this, a linear regression between total daily gas consumption and daily mean internal-external temperature difference showed a close relationship for the data collected in eight of the ten houses, despite the incomplete dataset used for the analysis. No HLC measurements by co-heating tests were carried out to provide benchmark values for comparison with the in-use analysis; for this reason, in addition to the incomplete nature of the Kane dataset, this analysis does not provide a full comparative investigation of the LIUHB method. The results of the analysis of the Kane dataset have therefore not been included in this thesis. Despite these limitations, the close relationship found between gas consumption and internal-external temperature difference indicate both that the HLC can be measured using a gas central heating system rather than electric heaters, and that it may be possible to measure the HLC using data collected while a house is occupied. These two pieces of evidence gave the justification to carry out further experimentation to investigate the viability of the LIUHB method.

3.2.2. Experiments in an Unoccupied Test House

In the pilot experiments the conditions of a co-heating test were recreated as closely as possible using the central heating system, with constant heating to a set-point temperature of 25°C. Clearly this is not a very common heating profile for an occupied house. The next step was to repeat the LIUHB test using more realistic heating profiles. These tests were carried out in the unoccupied Holywell test house with no synthetic occupancy applied.

In line with the internal temperature assumed in SAP of 21°C for living spaces and 18°C for bedrooms (BRE, 2011) a 20°C set-point temperature, controlled in the hall, was chosen for the second LIUHB test as a compromise between the two temperatures as the house does not have zonal temperature controls. For this second test, the heating was left on continuously in order to maintain a reasonably constant internal temperature, as in co-heating. This is a crucial point as the purpose of selecting a constant internal temperature is to reduce the influence of thermal mass as far as possible by maintaining it in a relatively steady-state. In reality the external conditions also have an impact, particularly in cases of high solar irradiation, so that the mass does not reach a steady-state condition in practice.

The third test was designed to investigate the importance of thermal mass charging by the application of a typical two heating period schedule, with heating periods from 06:00-09:00 and 16:00-21:00. Defining a ‘typical’ heating pattern is not a simple matter; the schedule used in this study was selected based upon the work of Kane at al. (2014). This work found that out of 249 dwellings in Leicester in which data was collected, 51% of homes with central heating were heated for two periods each day. Kane et al. (ibid) found an average daily heating period duration of 12.6 hours, but noted that this was longer than the estimated duration from a previous monitoring study carried out by Shipworth et al. (2010) of 8.2-8.4 hours (for weekdays and weekends respectively). For the tests carried out in this study a shorter heating duration of 8 hours was used after the findings of Shipworth et al. This choice reflects the general approach adopted in the testing of the LIUHB, where the least ideal realistic synthetic occupancy conditions were applied in order to test the robustness of the test. A shortened total heating period is considered more problematic for the application of the LIUHB test because there will be a smaller heat input to the house, resulting in a smaller internal-external temperature difference. The result of this is that there will be a lower heat flow from the house, so that any errors in the calculation of this heat flow will be relatively larger.

One of the primary differences in data collection between the co-heating test and the LIUHB is the lack of air mixing for the in-use test. This will result in a larger variation in temperature throughout the internal space which is minimised by the use of air mixing fans in co-heating tests. In the context of an in-use test there are two possible sources of uncertainty that this creates:

- An uneven temperature distribution applies different boundary conditions to different sections of the building fabric, which could cause a biased measurement of the whole house HLC.
- An inaccurate measurement of the average internal temperature throughout the house may be taken due to the particular location of a sensor. This is a problem particular to in-use data as sensors must be placed in a discrete manner, in order that they do not interfere with occupants' use of the house, rather than in the centre of a room as they are in co-heating tests.

Some of the most significant factors in influencing the temperature distribution are likely to be thermal stratification of the air, across the whole building and in each room, the location of heat emitters, sources of air infiltration and the open/closed state of internal doors. In addition to the factors influencing the actual temperature distribution in the space there are further difficulties in recording accurate measurements of air temperature. In particular sensors must be placed out of direct sunlight due to radiant heat gains and out of the immediate influence of heat emitters which will cause localised temperature increases.

These are all particularly pertinent issues for an in-use method, as measurements must be carried out in a non-invasive manner to avoid disruption to the occupants and sensor placement is necessarily compromised. It is essential therefore to understand what the likely extent of temperature variation will be, and most importantly, what impact this will have on the eventual calculation of the HLC of the house. Understanding this issue will allow informed decisions on the necessary number and location of temperature sensors for LIUHB tests.

During the in-use tests the temperature was measured in every room, these measurements were used to compare the variation in temperatures between rooms. To further understand the extent of spatial temperature variation within a single room an experiment was carried out in the bedroom on the front (north-west facing) side of the Holywell test house. A grid of temperature sensors was arranged in three layers vertically, with nine sensors in each layer. The three vertical layers were positioned at 10cm from the floor level, at the mid-height of the room and at 10cm from the ceiling respectively. Each layer was arranged in a 2m square, with sensors positioned at 1m intervals, as shown in Figure 3-2. The temperature was measured by each sensor at a 5 minute interval.

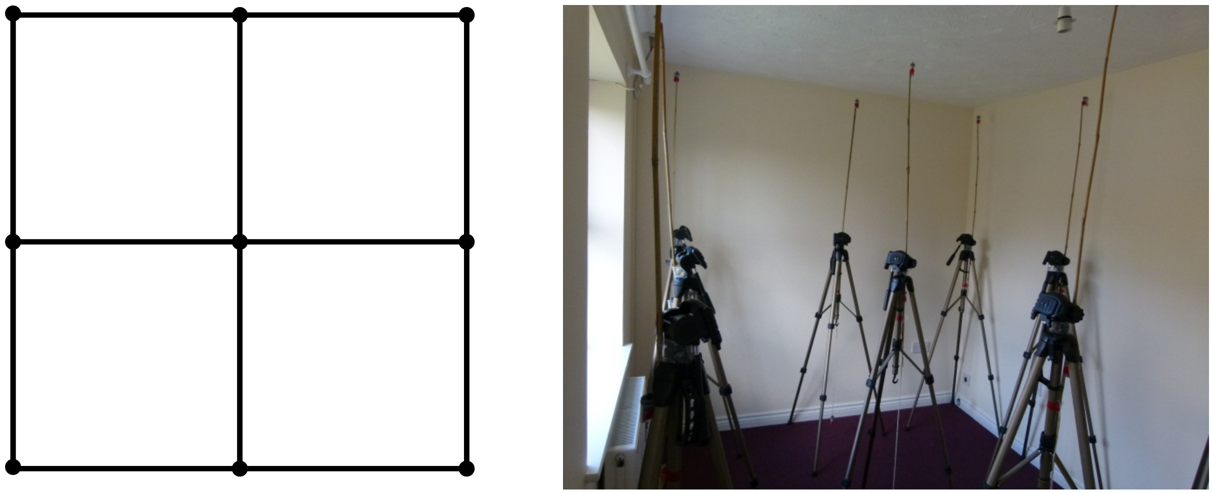


Figure 3-2: Left: A plan view of one layer of sensors used in the spatial temperature variation experiment; each circle represents a temperature sensor and the lines represent the 1 metre spacing between them. Right: A photograph of the experiment installed in the front bedroom of the Holywell test house.

In order to provide a comparison between the in-use test and a co-heating test the spatial temperature variation experiment was carried out with three different sets of conditions:

- During a standard co-heating test.
- During two in-use energy balance tests, one with constant heating and a 25°C set point temperature, and another with a 20°C set point and two heating periods.

3.2.3. Boiler Efficiency Testing

In 2008 space heating accounted for 66% of all domestic energy use, while 96% of houses had a central heating system installed and of these central heating systems 85% were fuelled by natural gas (Parker and Cooper, 2011). It is clear therefore, that in the vast majority of houses the heat supplied by a gas boiler will constitute the largest part of the input to the heat balance. There have been several studies that have shown variation in the performance of space heating systems. Not only has performance been shown to vary from stated performance levels, it also varies depending upon external conditions. A study of 27 condensing boilers carried out as part of The Carbon Trust's Micro-CHP Accelerator project found that in-situ condensing boilers are likely to operate around 5% under (worse than) their listed efficiency rating (Carbon Trust, 2011). Further confidence in these results is gained by their close agreement with the findings of in-situ studies carried out by the Energy Savings Trust, which have also shown that there can be considerable variability between similar machines (Orr et al., 2009).

The combination of these observations makes quantifying the uncertainty in the measurement of the heat input from the boiler a vital part of establishing the total uncertainty of the LIUHB test. This uncertainty will be higher than that associated with measuring an electrical heat input, which provides all of the heat in standard co-heating tests, due to the variable efficiency of boilers in converting the energy stored chemically in fuel into heat. While the notional efficiency of any particular boiler can be easily found in the SAP boiler database (BRE, 2014b), the performance of a particular boiler in-situ is dependent upon a number of factors associated with the installation of the boiler, the way it is operated and the conditions in which it operates.

The year-long, in-situ monitoring study of 60 condensing boilers carried out on behalf of the Energy Savings Trust in 2009, provides excellent information regarding the variation in performance of installed boilers across a reasonably large sample (Orr et al., 2009). In addition to this evidence, a series of experiments was carried out in the Holywell test house to investigate the effect on boiler efficiency of a series of different control strategies. The aim of the experiments was to assess the possible additional uncertainty due to the way in which a particular boiler is operated – similar to the influence of the driver on vehicle fuel efficiency. The boiler tests included changes to the internal temperature set-point, the length and timing of heating periods, and the setting of thermostatic radiator valves (TRVs) throughout the house.

The boiler installed in the Holywell test house is an Ideal Classic He-9 model; this model is a regular, fan assisted, mains gas-fuelled condensing boiler. The boiler has a SAP 2009 annual efficiency of 86.4% and a SAP winter seasonal efficiency of 87.3% (BRE, 2014b). The heat is distributed by a standard radiator system, with hot water stored in a tank in the front bedroom. To simplify the testing program, no hot water heating was applied in any of the boiler tests. This is thought to be reasonable as it was found in the Energy Savings Trust in-situ monitoring study that hot water was produced at the same efficiency as space heating during the winter months (Orr et al., 2009), when the LIUHB is proposed to be applied.

The total heat output and gas input were measured so that the efficiency of the boiler could be calculated. The boiler efficiency was calculated using (EQ 3-1), having calculated the energy content of the gas input using (EQ 3-2).

$$\eta_{boiler} = Q_{boiler} / E_{gas} \qquad \text{(EQ 3-1)}$$

$$E_{gas} = V_{gas}\, CV \qquad \text{(EQ 3-2)}$$

Where η_{boiler} is the efficiency of the boiler, Q_{boiler} is the heat output of the boiler (as measured by the heat meter), E_{gas} is the energy content of the gas input, V_{gas} is the total volume of gas input and CV is the calorific value of gas. For all tests the mean calorific value of the gas supply to the East Midlands area, as supplied by the National Grid, was used, this was 39.3MJ/m^3, or 10.9kWh/m^3 (standard deviation 0.3MJ/m^3 or 0.6%) (National Grid, 2014).

The full schedule of seven boiler tests is shown in Table 3-4; each test was run for a period of at least two days though in some cases the tests ran for a longer period. This is not significant and was simply defined by access restrictions to the test house. The tests were completed consecutively, beginning on 10/3/2014 and finishing on 11/4/2014.

Test	Heating Periods	Temperature Set Point (°C)	TRV Setting	Monitoring Period
1	2: 0600-0900, 1600-2100	20	5/5	2 days
2	2: 0600-0900, 1600-2100	20	3/5	2 days
3	1: 0600-2100	20	3/5	3 days
4	1: 0600-2100	16	3/5	2 days
5	1: 0600-2100	16	5/5	11 days
6	24 hours	20	5/5	7 days
7	24 hours	16	5/5	2 days

Table 3-4: Description of the boiler efficiency testing program.

The analysis of the boiler efficiency tests included an investigation into links between the measured boiler efficiency and conditions occurring during the test such as internal temperature, external temperature, boiler flow and return temperatures and total heating hours. This investigation is described in full alongside the results in section 7.3. The results of the boiler efficiency tests carried out in the Holywell test house were analysed and used, together with evidence from other sources, to calculate the uncertainty in the measurement of the heat input from a gas boiler during LIUHB tests.

3.2.4. Synthetic Occupancy Tests

The presence of occupants in a house causes an extra, unpredictable, set of variables in an in-use test compared to a test carried out in an empty house. Understanding the possible impact of these variables is a key step in the development of an in-use method. The possible impact of occupants on accurate measurement of a house's HLC can be broken down into three major risks:

1. The actions of the occupants cause a change to the total HLC of the building.
2. The actions of the occupants introduce added uncertainty into the measurements taken during the test, which in turn increase the uncertainty of the HLC estimation.
3. The actions of the occupants cause a change in the testing conditions (e.g. increased temperature variation between spaces), which leads to a change in the measured HLC.

In this study an investigation into the effect of four key 'occupancy variables' was undertaken using synthetic occupancy, this approach was adopted in order that each variable could be isolated and considered individually. For all of the synthetic occupancy tests a two period heating schedule and a set point temperature of 20^{o}C was applied. These heating settings were chosen for the synthetic occupancy tests as they are the most commonly used in UK houses, a full description of their derivation has already been given in section 3.2.2.

The four key variables selected for investigation using synthetic occupancy were: window opening, use of hot water, internal gains (due to both electrical appliances and metabolic heat generation of people) and window covering (opening and closing curtains). They are termed 'occupancy variables' throughout this thesis. Together, they cover the main sources of uncertainty that could be introduced through the actions of occupants. For each variable, extreme examples of realistic behaviour, referenced from previous research where available, were applied in order to attempt to establish the largest possible additional uncertainty in the HLC measurement that they could cause.

For each of the synthetic occupancy variables, an in-use test of at least one week duration was carried out while synthesising its effects. Following the synthesis of each variable individually all variables were applied together in order to investigate any combined interactive effects, this is described as the 'full synthetic occupancy test' in this thesis. The full synthetic occupancy test was carried out over an extended period of 55 days in order that smaller samples could be selected from the dataset to investigate the effect of differing weather conditions during the monitoring period.

For each variable, the potential impact on the measurement of the HLC was estimated theoretically and then compared to the measured impact observed in the synthetic occupancy test. In this way any unexpected observations were identified for further investigation. The estimated and measured impact of each variable were then compared to the total heat loss from the building in order to estimate the size of any uncertainty introduced relative to the measured HLC. The calculated uncertainty introduced by each variable was summed to create a total estimated maximum additional uncertainty caused by occupancy. This value was added to the previously estimated measurement uncertainties for heat input, temperature and solar gain calculation to produce a total uncertainty boundary for the HLC measurement by the LIUHB. This uncertainty boundary was then used to compare the results of the full synthetic occupancy test with the baseline co-heating test measurement. The selection of the behaviour synthesised for each variable and the methods used to estimate its impact on the measured HLC are described in section 4.1.4.

3.2.5. Pre and Post-Retrofit Testing

One likely application for the LIUHB is to evaluate the change in the thermal performance of a house that result from retrofit measures. An experimental comparison between the LIUHB and a standard co-heating test was carried out to investigate the suitability of the in-use method in such an application. The comparison was undertaken as part of a project carried out in conjunction with PRP Architects and funded by the Energy Technologies Institute (ETI), who required a non-invasive method to measure the effect of a novel retrofitting method being demonstrated in occupied homes. The commissioning and testing work for this project was carried out by the author in conjunction with David Allinson and Stephen Porritt, of the Building Energy Research group at Loughborough University, while all analysis was carried out by the author.

The testing was carried out in the Holywell test house; it involved measuring the HLC of the house before and after a retrofit had been carried out. The pre and post-retrofit performance was measured by the LIUHB and by a co-heating test in order to provide benchmark HLC measurements. For both the pre and post-retrofit cases, the in-use test was carried out and analysed before the completion of the co-heating test, so that the result of the in-use test was calculated before the benchmark measurement was known. The schedule of tests is shown in Table 3-5, each co-heating test was carried out over a period of two weeks and the in-use tests over a period of three weeks. Delays in commissioning the project led to tests being completed during the spring and early summer months, resulting in higher ambient temperatures and levels of solar irradiation than are ideal for such testing. Nethertheless, adaptations to the testing methods (described in section 7.5) allowed the comparison to be successfully completed.

Activity	Start Date	End Date	Duration
Pre-retrofit LIUHB test	11/4/2014	2/5/2014	3 weeks
Pre-retrofit co-heating (and blower door) test	5/5/2014	19/5/2014	2 weeks
Retrofit measures applied	19/5/2014	21/5/2014	2 days
Post-retrofit LIUHB test	26/5/2014	16/6/2014	3 weeks
Post-retrofit co-heating (and blower door) test	16/6/2014	1/7/2014	2 weeks

Table 3-5: Schedule of works for the pre and post-retrofit tests.

In order to produce a significant difference between pre and post-retrofit performance (greater than the level of accuracy of the testing methods) the loft insulation installed in the house was removed to create the pre-retrofit configuration. The retrofit included the installation of 300mm of new mineral wool loft insulation, together with clay impregnated boards fastened to the inside of walls and partitions (shown in Figure 3-3). The clay boards were procured from Eco Building Boards Ltd (Eco Building Boards, n.d.), a total area of 37.5m^2 of boards was installed and the manufacturer's reported properties are given in Table 3-6.

Property	Value
Weight	18.8 kg/m^2
Thickness	0.022 m
Specific heat capacity	1.3 kJ/kg
Heat capacity as per SAP 2009 Table 1e	35 kJ/m^{2}K
Thermal conductivity	0.47 W/mK

Table 3-6: Manufacturer's reported physical properties for the clay boards that were fitted to external and internal walls.

Figure 3-3: Edge view of two of the clay boards that were installed on internal walls (left) and picture of the boards installed in the living room (right).

The clay boards were installed as a part of the retrofit to cause an increase in the thermal mass of the house, in addition to the reduction in the HLC provided by the added loft insulation. This was considered to be important to evaluate whether the LIUHB was capable of distinguishing between changes in these two characteristics. A change in the effective thermal mass of a house is a common result of a retrofit measure, particularly in the case of adding internal wall insulation. The effect of the retrofit was estimated using the Reduced Data Standard Assessment Procedure (RDSAP) 2009 (BRE, 2011). The RDSAP calculation predicted a reduction of 43% in the HLC of the house and an increase of 29% in its thermal mass parameter (Table 3-7).

SAP prediction	Pre-retrofit	Post-retrofit	% change
Heat Loss Coefficient (W/K)	155	88.6	-43%
Thermal Mass Parameter (kJ/m^{2}K)	54.3	70.2	+29%

Table 3-7: Thermal properties of the Holywell test house before and after the applied retrofit as predicted by a 2009 RDSAP assessment (BRE, 2011)**.**

An elevated set-point temperature of 24°C was chosen for the in-use tests to ensure a significant positive internal-external temperature difference given that the testing was carried out in late spring/early summer. The temperature set-point would not usually be stipulated for occupied homes if the LIUHB is applied during the winter heating season as recommended, but was necessary in this case due to the delay in starting the monitoring period. A single heating period heating profile was applied with the heating operating between 06:00 and 21:00 each day at the request of the ETI. No synthetic occupancy was applied during the tests.

The accuracy of the LIUHB was analysed by comparison with the benchmark co-heating results for the pre and post-retrofit tests. The ratio between pre and post-retrofit performance as measured by the two tests was also compared. The results of the pre and post-retrofit testing are presented in section 7.5.

3.2.6. Occupied House Case Study

One of the great challenges of carrying out any post-occupancy analysis is the infinitely varied and unpredictable behaviour of the occupants. It is recognised that this cannot be completely replicated with synthetic occupancy in test houses; clearly tests must be carried out in real, occupied homes to provide confidence in the results of the LIUHB method. There is a significant practical constraint with this aim which is that the co-heating test is the only method currently available to define a baseline measurement of a house's HLC. The invasive nature of the co-heating test makes it difficult to find houses in which a comparative study with the LIUHB test can be carried out. However, a single, case study, comparison between a co-heating and LIUHB test was carried out in a three bedroom, semi-detached house built around 1950, with cavity wall construction.

The co-heating test for the occupied house case study was carried out over a 14 day period during December 2012 and January 2013. The data collection and analysis methods for the co-heating test are described in full in chapter Chapter 4. The intention was to carry out the monitoring for the LIUHB test immediately after the co-heating test; however an equipment failure of the electricity meter reader meant that incomplete data was collected during the remaining winter months at the beginning of 2013. Therefore the monitoring for the in-use test was carried out the following winter, beginning in November 2013 and continuing until March 2014 over a period of 117 days. No retrofit measures were carried out between the co-heating and in-use tests, so the thermal performance of the house was assumed to have remained unchanged between the co-heating and in-use tests. An extended monitoring period was applied for the in-use test (the method recommends a minimum period of 3 weeks) in order that data would be collected during a wide range of weather conditions.

Activity	**Start Date**	**End Date**	**Duration**
Co-heating test	23/12/2012	5/1/2013	2 weeks
LIUHB test	5/11/2013	1/3/2014	117 Days

Table 3-8: Testing dates for the occupied house case study.

There were no secondary heating sources present in the house, though cooking was carried out using gas hobs which will introduce an extra uncertainty into the measurement as the consumption for this use was not measured specifically. During the monitoring period, no requests were made of the occupants to adjust their use of the house, they were simply informed that their energy consumption would be monitored and they should behave as normal. The measurements made during the monitoring period included the air temperature in each room, relative humidity at one location on each of the two storeys, electricity and gas consumption. Due to the proximity of the house to the Loughborough University campus (less than 1 km) it was possible to source weather condition measurements from a weather station located on campus; these included external air temperature, global solar irradiation, net solar irradiation and wind speed and direction. Full details of the measurement equipment are given in section 4.3.1.

The installation and decommissioning of the monitoring equipment was carried out during two visits to the house, the first of several hours duration and the second of less than an hour. In addition, one supplementary visit of approximately one hour was carried out in order to download data from the installed loggers. No qualitative data regarding the experience of the occupants during the testing was collected.

Following the completion of the co-heating and LIUHB tests, the HLC value resulting from each was calculated and the results compared. In addition, the extended dataset of monitored in-use data was separated into a series of 3-week-long samples so that the effect of internal and external conditions during the samples on the calculated HLC could be investigated. These analyses were used to assess the accuracy of the LIUHB method in comparison to the baseline HLC measured by the co-heating test.

3.3. Summary

This chapter has described the empirical work that was carried out in pursuit of the research aims of this research and the reasoning for its design. In the next chapter a technical description of the methods that were used for each of the tests is given.

Chapter 4 Data Collection and Analysis Method

This chapter builds upon Chapter 3 giving a technical description of the facilities, equipment and methods used to collect and analyse data for the experiments that were described in the previous chapter. In section 4.1 the test house facilities that were used are described, including the Holywell test house, 209 Ashby Road and buildings 50.3 and 50.4 at the BRE's Garston site. In section 4.2 the selection of the synthetic occupancy conditions, and the method used to apply them, are described. In section 4.3 the method used to carry out co-heating tests and analyse the data is described, including a description of the new 'facade solar gain estimation' method developed in this study to quantify the solar gains to a house. In section 4.4 the data collection and analysis methods for the Loughborough In-Use Heat Balance test are described. This is a non-invasive test developed during this study which offers a significantly reduced cost measurement of a house's HLC without disrupting the occupants and at much reduced cost. Finally, in section 4.5 the method used to carry out RdSAP assessments is given.

4.1. Testing Facilities

As described in Chapter 3, experimentation was primarily carried out in a set of 'test houses', this phrase simply describes a house that is specifically used for experimentation and is not normally occupied. The test houses used in this research were the Holywell test house and 209 Ashby Road, located at Loughborough University, and buildings 50.3 and 50.4 located at BRE's Garston site (near Watford, UK). In addition testing was carried out in one occupied house also located very close to the Loughborough University campus. In this section each of these houses is described in order. The majority of the measurement equipment used for the LIUHB and co-heating tests is mobile so that it can be transferred between houses; it is described in section 4.1.4.

4.1.1. The Holywell Test House

The Holywell test house is a small, timber framed, detached building, with a total floor area of 59.8m^2 and an envelope surface area of 166.1m^2. A photograph of the house is shown in Figure 4-1 and floorplans in Figure 4-2. It is located on the Loughborough University campus and was built in 2000 to the contemporary building regulations; it has been used solely as a test house since its construction. The house has uninsulated suspended floors, insulated cavity walls and during the majority of testing had 200mm of loft insulation installed. The air tightness of the house was measured regularly throughout the testing period using the blower door method (ATTMA, 2010). The average air tightness was 14.5m^3/h.m^2 (surface area) at 50 Pascals pressure difference between the inside and outside of the house (see Table 4-1 for the full set of results), significantly higher than the upper limit of $10m^3/h.m^2$ set out for new buildings in the 2013 building regulations (H.M. Government, 2013).

Test Date	**Air Tightness ($m^3/h.m^2$ (surface area) at 50 Pa)**
8/12/11	14.9
6/6/12	13.3
14/11/13	13.9
14/11/13	14.0
18/11/13	15.2
18/11/13	14.9
19/11/13	15.1
MEAN	*14.5*

Table 4-1: Results of all blower door tests carried out in the Holywell test house during this study.

An RdSAP assessment (BRE, 2011) of the house was carried out which gave an estimated total HLC (including ventilation heat loss) of 180W/K.

Figure 4-1: The Holywell test house.

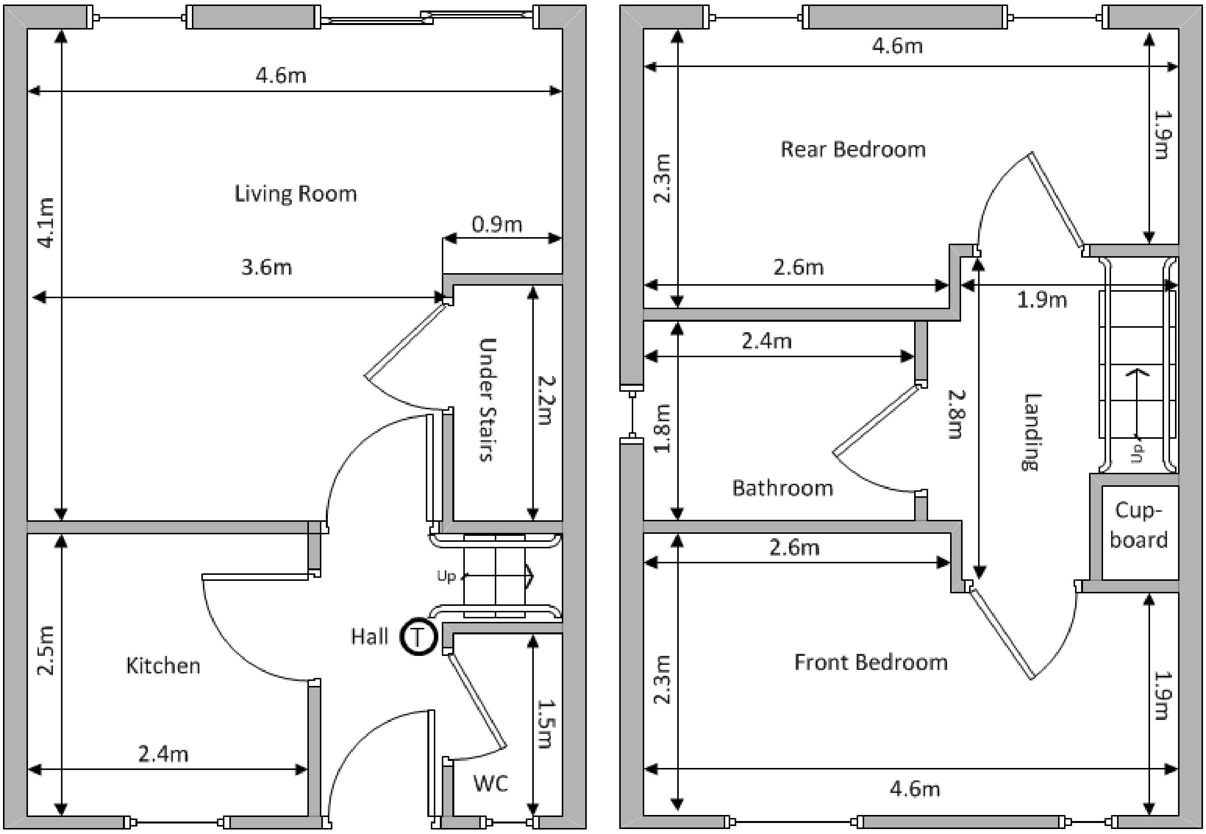


Figure 4-2: Floor plans of the Holywell test house ground floor (left) and first floor (right). The thermostat is shown by circled T in the hall.

Both space and hot water heating in the test house are supplied by an Ideal Classic He9 condensing gas boiler which has a listed Annual Boiler Efficiency of 86.4% according to the SAP database(BRE, 2014b). The space heating is distributed by a traditional radiator system, and there is a hot water tank installed in a cupboard in the front bedroom which can deliver hot water to taps in the bathroom, WC and kitchen. The boiler is controlled by a programmable timer unit which allows separate heating schedules to be applied for space and hot water heating, with up to three heating periods per day and different schedules each day. The air temperature is controlled by a single bi-metallic strip thermostat located in the hall.

The total heat output of the boiler was measured at 10Wh resolution using a Sontex Supercal 531 heat meter, with the flow measured by a SuperStatic 440 flow meter and the flow and return temperatures measured using two Pt500 RTD temperature sensors. The flow meter and RTD sensors were installed directly adjacent to the boiler so that any distribution or storage losses were not included in the measurement. The pulse output of the gas and electricity service meters (where 1 pulse was equal to 0.01m^3 of gas consumption and 1Wh of electricity consumption, respectively) were logged using Enica Opti-pulse pulse loggers; the logged values were compared with regular meter readings throughout testing and showed 100% agreement. The measurement of the gas input and total heat output of the boiler was used to measure the efficiency of the boiler (this is possible as the boiler is the only gas-consuming appliance used during the tests as no gas was used by the cooker hobs during testing).

The house is installed with equipment to allow opening and closing of blinds and windows and hot water use according to pre-set schedules. Tubular motors were used to actuate roller blinds located in each window reveal in the house. The blinds were controlled remotely by a bespoke unit that allowed up to 6 operations per day according to a pre-set schedule. Hot water was released into the bathtub in the bathroom by a motorised valve; the valve could be operated up to five times per day according to a pre-set schedule controlled by an in-built unit. Five windows in the house can be opened remotely; they are located in the kitchen, living room, bathroom and one in each of the bedrooms. The windows are top hung and are actuated by motors which push the bottom edge of the window out via a chain (as shown in Figure 4-3); the actuators are controlled remotely from an adjacent control shed.

Figure 4-3: Extended chain actuator in the front bedroom window.

Internal gains heat gains in the house, from electrical and metabolic heat generation, were synthesised using heaters of various sizes of power output chosen to match the designed magnitude of the gain in each room. The heat emitters varied in power output from 3kW fan heaters to 60W light bulbs in order to match the designed heat gains profile. The heat emitters were controlled using a Plogg smart meter plug system that can be used to apply a daily on/off schedule with up two three operations per day as well as logging the energy consumption. The definition of the schedules for all of the synthetic occupancy equipment is given in section 4.2. A full list of the synthetic occupancy equipment is given in Table 4-2.

Synthetic Occupancy Equipment	Component Name
Window actuators	Mingardi Magnetic Micro 92 linear electric actuator
Timer plugs for window actuators	Timeguard 7 day general purpose time switch
Hot water release timer	Silverline 868719 Electronic Water Timer
Window blind actuators	Somfy 24V tubular motor
Heaters for internal gains	60W & 120W Tubular greenhouse heaters Dimplex DXFF30TS 3kW flat fan heater 60W light bulbs
Control for internal gains	Energy Optimizers Plogg smart meter plug system

Table 4-2: List of synthetic occupancy equipment.

4.1.2. 209 Ashby Road

209 Ashby Road is one of a pair of semi-detached test houses owned by Loughborough University, located adjacent to the main University campus. They were built in the 1930s and have uninsulated cavity walls with a solid partition wall, at the time of testing 209 Ashby Road had no loft insulation installed. The house is single glazed throughout, with wooden window frames and external doors. The house has suspended timber floors on the ground floor, with the exception of the kitchen which has a tiled solid floor. The airtightness of the house was measured before and after all testing was completed by a blower door test (ATTMA, 2010), the average measured air-tightness was 17.7$m^3/h.m^2$ (surface area) at a 50 Pascal pressure difference across the house. An RdSAP assessment (BRE, 2011) of the house was carried out, which resulted in an estimated total HLC (including ventilation heat loss) of 384W/K. A photograph of the house and floor plans are given in Figure 4-4 and Figure 4-5, respectively.

Figure 4-4: The semi-detached Ashby Road test houses, 209 Ashby Road is on the right.

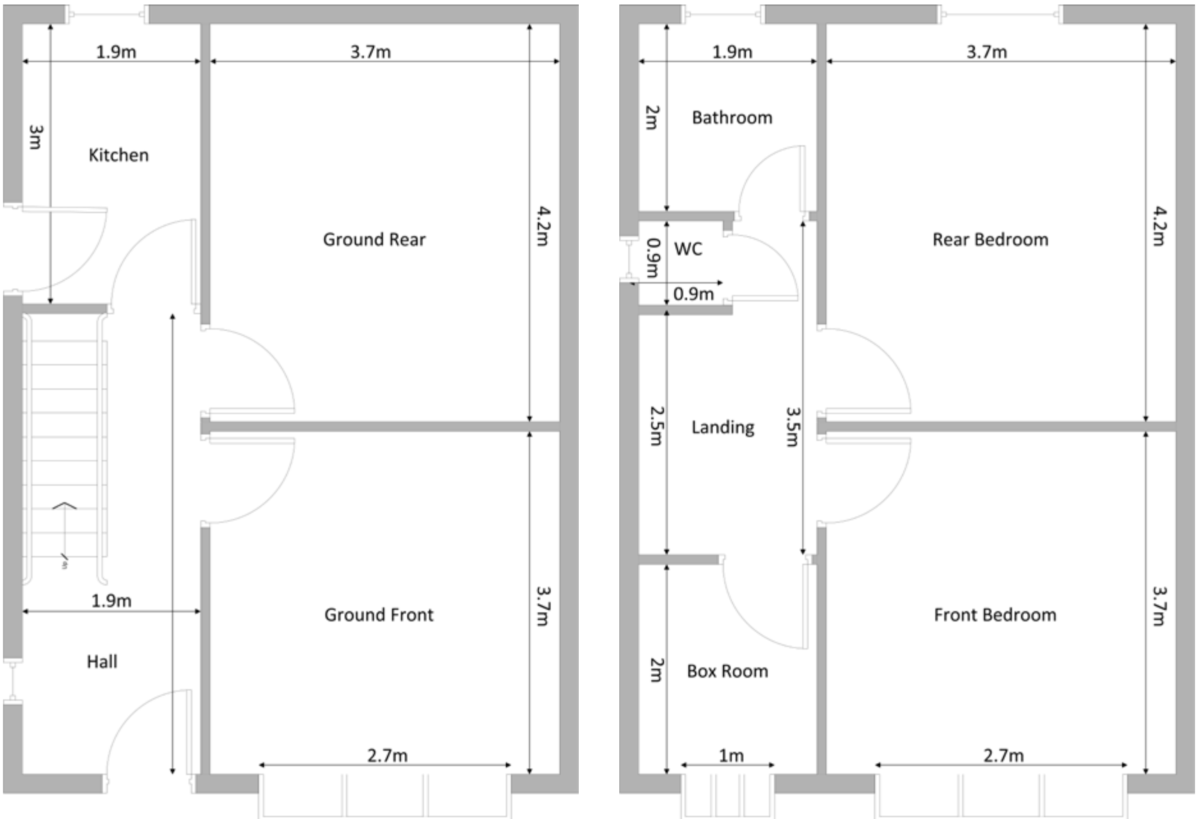


Figure 4-5: Floor plans of 209 Ashby Road ground floor (left) and first floor (right).

Both houses have a gas central heating system installed, with the heat distributed by radiators. However, in this project the houses were used for co-heating tests only and the central heating system was therefore not used.

4.1.3. Buildings 50.3 and 50.4 at BRE Garston

Buildings 50.3 and 50.4 are identical purpose-built test houses located at BRE's Garston site. They were both used in the NHBC co-heating project, as described in section 3.1.1. Photographs and floor plans of the houses are given in Figure 4-6 and Figure 4-7.

Figure 4-6: South facing front (above) and north facing rear (below) facades of the matched pair of test houses used in the NHBC co-heating project. In the upper photograph, House 50.3 (which was used for the long-term test) is to the left and house 50.4 (which was used for the round robin test) is to the right.

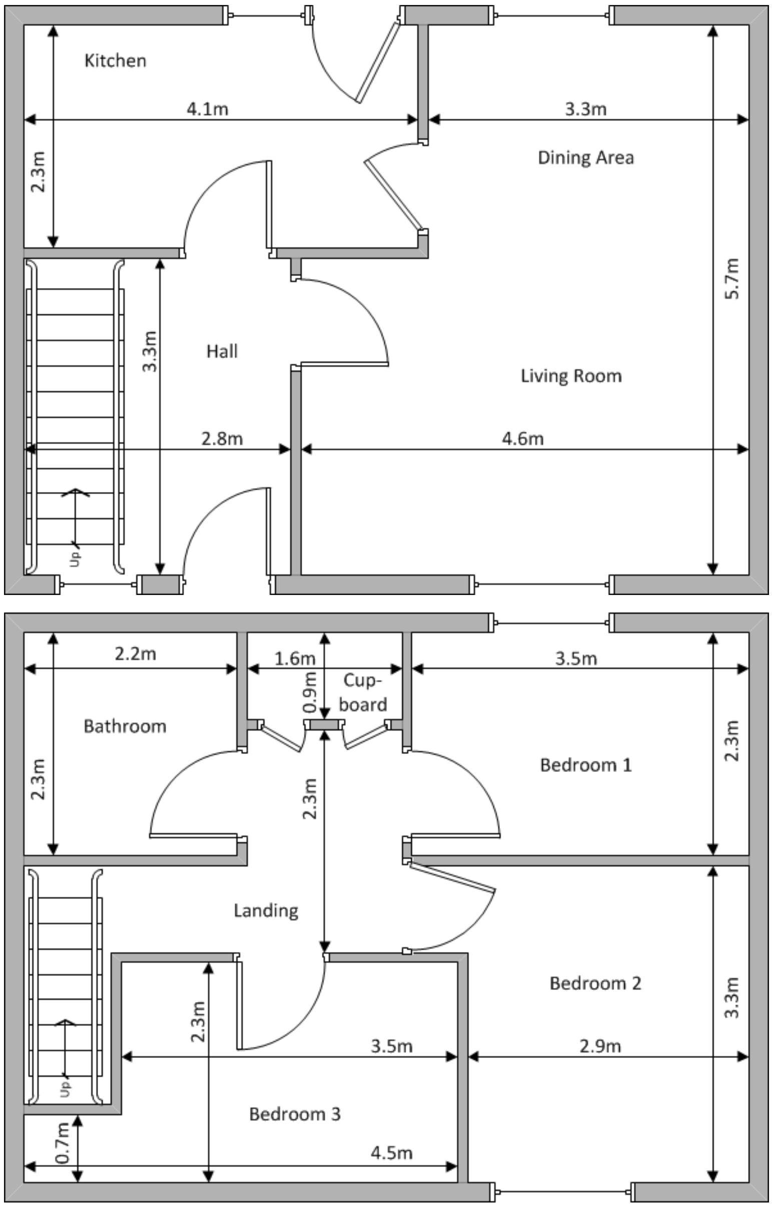


Figure 4-7: Floor plans for buildings 50.3 and 50.4 (they are identical) ground floor (top) and first floor (bottom).

The houses were built in 1995 to contemporary Swedish building standards. The walls are constructed of an outer leaf of bricks, followed by a 50mm air gap, 13mm of fibreboard, 170mm of Rockwool insulation, 9mm of plywood, 45mm of Rockwool insulation and finally 13mm of plasterboard on the internal surface. The houses are triple glazed, with 240mm of loft insulation installed and 220mm of insulation installed beneath the suspended ground floor. An elemental summation of the performance of the building elements results in an estimated fabric HLC of 65.92W/K (BRE, n.d.).

The design performance of each of the major building elements is given in Table 4-3; for reference, the limiting (maximum allowable) U-values according to the 2013 edition of the UK Building

Regulations are also given (H.M. Government, 2013). It can be seen that the test houses meet the limiting performance standards of the 2013 building regulations for each building element. However, compliance with the current building regulations is based upon a calculation of the thermal performance of the whole house rather than individual elements. This means that in practice, some or all of the building elements must have a lower U-value than the limiting values in order to comply with the whole house regulations. The building regulations provide a 'notional dwelling specification' with a set of example U-values for each building element which, if used in a building of the same dimensions as the notional dwelling, would meet the whole house regulation. The specification for this notional dwelling is also shown in Table 4-3; a comparison with the design U-values suggests that the test house would fall slightly below the 2013 whole-house performance standard.

Building Element	**Design U-value (W/m^2K)**	**2013 Building Regulations Limiting U-value (W/m^2K)**	**2013 Building Regulations Notional Specification (W/m^2K)**
External Walls	0.21	0.30	0.18
Floor	0.21	0.25	0.13
Roof	0.16	0.20	0.13
Windows	1.85	2.00	1.40
External Doors	1.00	2.00	1.00

Table 4-3: Comparison between design U-values for the test houses used in the NHBC co-heating project and those stipulated in the 2013 edition of Part L of the Building Regulations (H.M. Government, 2013)**.**

The air tightness of building 50.4 was measured before and after Loughborough University's co-heating test using the blower door method (ATTMA, 2010). The house proved to be very airtight with an average measured air-tightness of $1.49m^3/h.m^2$ (surface area) at a 50 Pascal pressure difference across the house. The infiltration rate was also measured twice daily during the co-heating test using the tracer gas decay method (Roulet and Foradini, 2002), the mean air tightness as measured by this method was 0.0763 air changes per hour (ACH) with a standard deviation of 0.01ACH. This can be compared with the value measured by the blower door test by applying the Kronvall and Persily (K-P) method (Sherman, 1987), where the air changes/hour at 50Pa is divided by 20 to give an estimate of the air change rate at normal pressure difference. Application of the K-P method on the mean results of the blower door tests gives an air change rate of 0.0757ACH, which agrees very closely with the mean measurement according to the tracer gas decay method (it is recognised that both values have been quoted to an inappropriately high number of decimal places, however they were necessary to demonstrate that the figures didn't agree exactly).

4.1.4. Occupied House Case Study Building

The occupied house case study was carried out in a semi-detached, masonry building, constructed in the 1950s, with a total floor area of 73.4m^2 and an envelope surface area of 121.8m^2 The house is double glazed with loft insulation installed and uninsulated cavity walls. Space and water heating is provided by an Alpha CB28 mains gas combination boiler, with space heating distributed by a standard radiator system. The airtightness of the house was measured before testing by a blower door test (ATTMA, 2010), the measured air-tightness was 9.63m^3/h.m^2 (surface area) at a 50 Pascal pressure difference across the house. A photograph and floorplans of the house are given in Figure 4-8 and Figure 4-9.

Figure 4-8: The house in which the occupied house LIUHB case study was carried out.

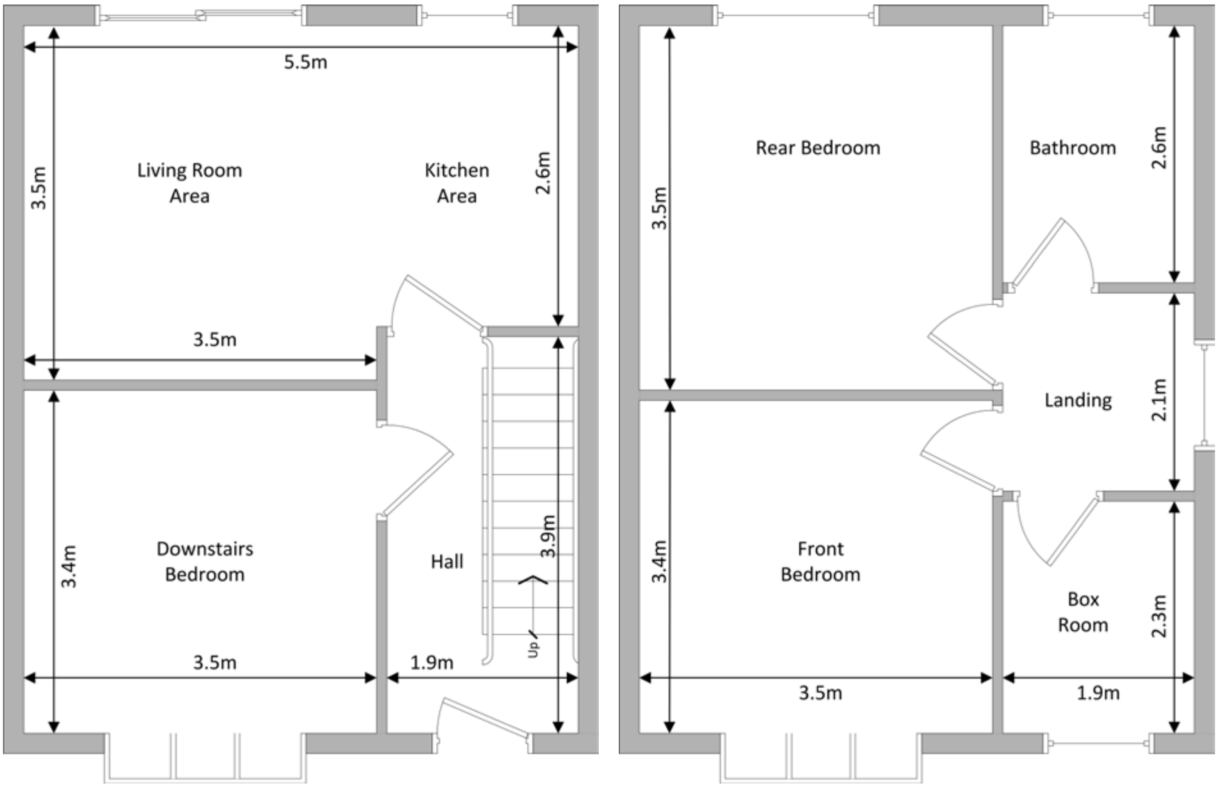


Figure 4-9: Floorplans (ground floor to the left, and 1st floor to the right) of the building in which the occupied house case study was carried out.

At the time of measurement the house was occupied by four adults, with one of the downstairs reception rooms converted to use as a bedroom. The house is located in Loughborough, within one kilometre of to the Loughborough University campus.

4.2. Synthetic Occupancy

In this sub-section the synthesis of each of the occupancy variables is described, including both the selection of timings for their application and the experimental method. As described in section 3.2.4, the general approach was to apply extreme examples of realistic behaviour. This approach was adopted in order to determine the largest possible additional uncertainty in the HLC measurement by the LIUHB that each occupancy variable could cause.

4.2.1. Window Opening

There is a paucity of literature describing window opening behaviour in houses. For this reason, it was difficult to select a realistic, well referenced, window opening profile to apply in the synthetic occupancy tests. In order to represent a realistic 'worst case' scenario, evidence which suggested that windows were opened less during the winter (Fabi et al., 2012) was ignored, with the same opening profile applied regardless of weather or internal conditions. This is in line with the approach of applying extreme examples of realistic behaviour. The little literature that is available regarding the time of use of windows suggests that window opening is most likely in the morning, with very little in the afternoon and a little more in the evening (Fabi et al., 2012; Fox, 2008; Johnson and Long, 2005). These times of peak use are linked to the positive observed relationship in these studies between occupancy and window opening. It was also observed that the rooms in which the windows were opened most frequently were the bathrooms, bedrooms and kitchen (Fox, 2008). This evidence informed the window opening schedule selected for use in the synthetic occupancy tests:

- Kitchen window, open 18:30-18:45.
- Bathroom window, open 07:30-08:00.
- Bedroom windows (front and rear facade), open 08:00-08:15.

The control of the actuators used to open the windows in the synthetic occupancy tests can only open the windows to one position, which is defined by the maximum travel of the actuator. This results in a large opening area during the period that the window is open; as an example, the front bedroom window is shown in its open position in Figure 4-10. The size of the opening area for each of the windows operated during the synthetic occupancy tests is given in Table 4-4.

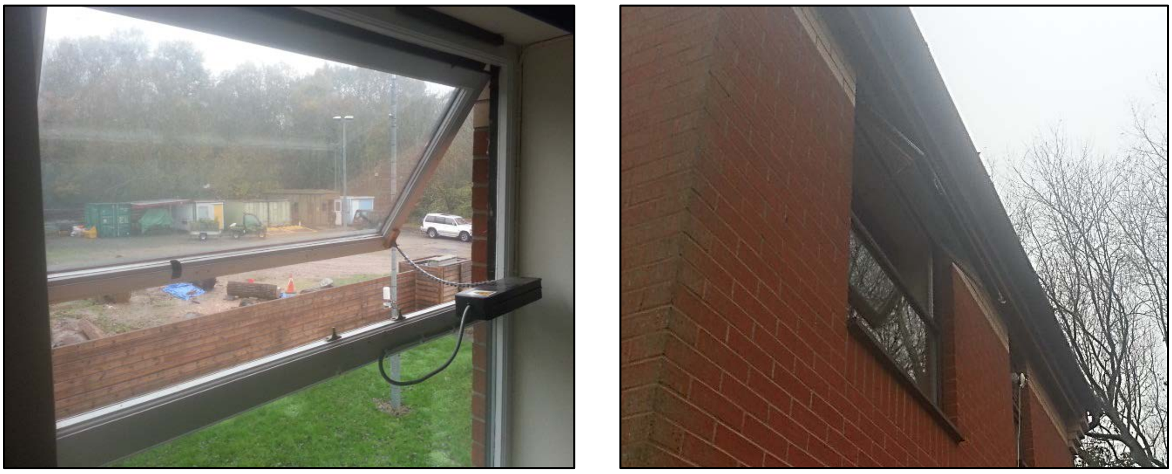


Figure 4-10: Internal and external views of the front bedroom window when open.

Window	Opening Area (m^2)	Facade (Orientation)
Kitchen	0.43	Front (WNW)
Bathroom	0.33	Side (NNE)
Front Bedroom	0.59	Front (WNW)
Rear Bedroom	0.46	Rear (ESE)

Table 4-4: Window opening area for each of the windows actuated in the synthetic occupancy tests.

Blower door tests were used to measure the effect of window opening on the air permeability of the Holywell test house (ATTMA, 2010). This was achieved by a series of repeated blower door tests carried out with different windows around the Holywell test house opened to different extents; the results of the tests were used to establish a relationship between window opening area and additional air infiltration. This relationship was used to estimate the additional heat loss due to the additional ventilation, so that the additional heat loss due to the window opening profile applied in the synthetic occupancy tests could be estimated. The additional heat loss was added to the baseline heat loss from the house, and the resulting estimated HLC incorporating the effect of window opening was compared with that measured in the synthetic occupancy test.

4.2.2. Hot Water Use

In a typical domestic heating system, a boiler provides both space heating and domestic water heating. It is possible that the efficiency at which the heat is generated for each use (space or water heating) could differ, and furthermore the heat will be delivered in different ways (i.e. via radiators and taps). This introduces a potential source of uncertainty to the LIUHB, in which the heat input from the boiler is calculated by simply multiplying measured fuel consumption by the stated efficiency. The additional uncertainty has several sources: transmission losses in pipework, storage loss, differing boiler efficiency when used for space or water heating, and heat lost to warm water going to the drain. For these reasons, hot water used was chosen as an occupancy variable to be applied in the synthetic occupancy tests so that the possible additional uncertainty caused in the HLC measurement could be investigated.

The total hot water demand for the Holywell test house was estimated according to the method described in SAP which is based upon the floor area of the house. This resulted in an estimated daily total hot water demand of 84 litres (BRE, 2011). The findings of an Energy Savings Trust (EST) study which monitored hot water use in 120 homes was then used to define the schedule over which the hot water would be delivered (Energy Savings Trust, 2008). The schedule was applied in five releases of hot water throughout each day, as shown in Table 4-5, with the length of each release timed so that the total calculated daily hot water demand of 84l was delivered. The findings of the EST study were also used to define typical hot water heating periods during the synthetic occupancy tests; these were 07:00-09:00 and 17:00-19:00.

Time of Release	Volume of Water (litres)
3:00	6
9:00	30
14:00	12
18:30	24
22:30	12
TOTAL	*84*

Table 4-5: Water release schedule for the synthetic occupancy in-use test with the hot water use occupancy variable.

In order to simplify the experimental equipment required, all water was delivered at the hot tap in the bath. The temperature of the water as it was released to the drain was measured so that the heat loss due to the remaining warmth in the water being released to the drain could be estimated. This additional heat loss was added to the baseline measurement to estimate the effect on the HLC measurement. The distribution and storage heat losses were assumed to provide a useful heat gain to the house and thus excluded from the estimated additional heat loss. The estimated effect of heat loss to warmed drained water on the measured HLC was then compared with the HLC measured in the synthetic occupancy test.

4.2.3. Internal Heat Gains

Internal heat gains to a house from electricity use and metabolic heat generation of occupants occur as a direct result of carrying out an 'in-use' test, and gains from both sources could have an impact on the uncertainty of the HLC measurement. The electrical gains are easier to account for in the heat balance as they can be measured simply at the service meter, but metabolic heat generation is harder to measure and is therefore likely to introduce an unaccounted-for heat gain into the heat balance. Both sources of heat gains could also increase the temperature variation throughout the house. A synthetic occupancy test was designed and applied to investigate the effect of these internal heat gains; the gains were synthesised using heaters which supplied heat according to a pre-determined schedule in different rooms around the house (a description of equipment used is given in section 3.2.4).

Occupancy profiles derived by Porritt (2012) from the United Kingdom Time of Use Survey were used to define the size and timing of the internal gains in the synthetic occupancy experiment. The profiles define the hours during which the house is occupied, and the associated electrical and metabolic heat gains that result from the occupation. Two profiles are given; a family profile, including two working adults and two school age children, and a second for two elderly residents.

The profiles define different periods during which the occupants are present in the house; in the family profile the house is empty for large parts of the day due to time spent at work and school, while in the elderly profile occupants are present at all times (Porritt, 2012). As for the other occupation variables, the approach of synthesising extreme versions of realistic behaviour in order to determine the greatest possible uncertainty was followed. With this in mind two profiles of internal gains were applied, the family profile and a hybrid of the two profiles defined by Porritt, to synthesise a household of two elderly residents and two children, referred to as 'elderly + children' in this thesis. The fact that the occupants are defined as 'elderly' in the second profile does not affect the heat loads applied; it simply means that they are applied for the whole period of the day. Both profiles represent a higher level of occupancy than that estimated by SAP for a building of this floor area (2.4 people) (BRE, 2011), and hence both could be considered to give high, yet reasonable, estimates for the internal gains in the house. The timing and size of the gains for both profiles are shown in Figure 4-11, while further details of the specific activities and their associated heat gains represented in each of occupancy profile are given in Table 4-6.

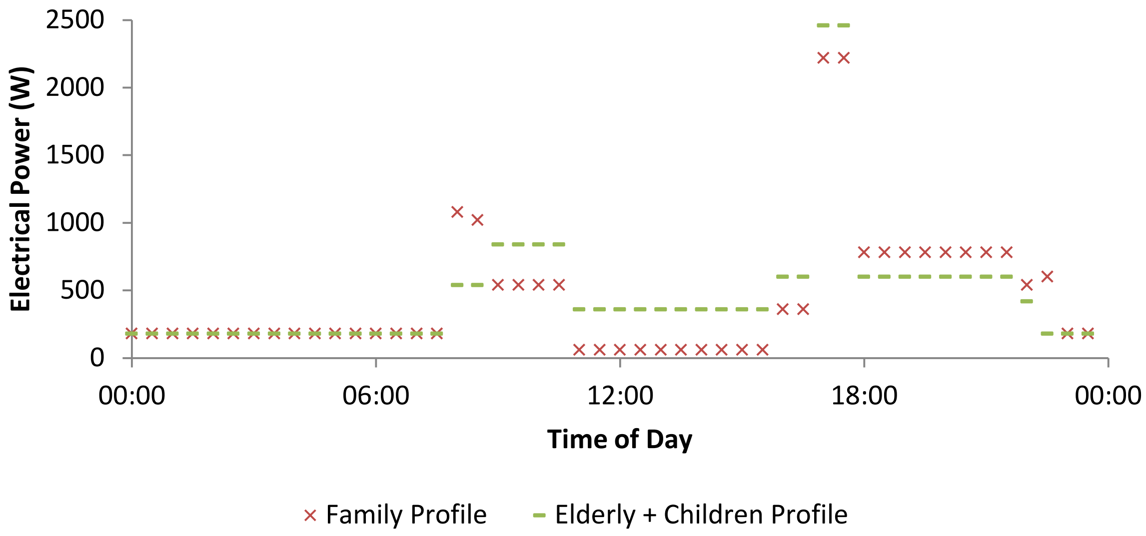


Figure 4-11: The size and timing of the heat gains due to the family and elderly + children internal gain profiles used in the synthetic occupancy tests.

		Time of Use	
Room - Activity	**Heat Gain (W)**	**Family**	**Elderly + Children**
Living Room - General	318	1800-2300	0900-2230
Kitchen - Morning Cooking	409	0730-0830	0800-0900
Kitchen - Washing Machine	500	0900-1100	0900-1100
Kitchen - Evening Cooking	1849	1700-1800	1700-1800
Kitchen - Fridge	50	24hrs	24hrs
Front Bed - Sleeping	72	2230-0730	2230-0800
Back Bed - PC & Occupancy	210	1600-2200	1600-2200
Back Bed - Sleeping	54	2200-0800	2200-0800

Table 4-6: Occupancy profiles for the internal gains synthetic occupancy experiments.

Three analyses were carried out on the results of the internal gains synthetic occupancy tests. Electrical heat gains to the house are likely to change the proportion of the total heat input contributed by electrical sources and other fuels (most commonly gas boilers). This will affect the uncertainty in calculating the heat balance, as electrical inputs can be measured more accurately because they are not affected by the variable efficiency of devices such as boilers. For the first analysis, the effect of the applied internal gains profiles on the relationship between electrical and gas inputs to the Holywell test house during the synthetic occupancy tests was calculated, and the resulting effect on the uncertainty in the HLC measurement estimated. For the second analysis, the temperature variation between rooms during the internal gains synthetic occupancy tests was compared to that during LIUHB tests in an empty house to test whether the gains caused an increased temperature variation between rooms. Finally, the heat input due to metabolic gains, which is likely to be unknown when the LIUHB is applied in actual occupied homes, was compared to the total heat input to the house and the additional uncertainty caused to the measurement of the HLC calculated.

4.2.4. Window Covering

The fourth occupation variable to be included in the synthetic occupancy tests was window covering, in this case using standard roller blinds installed at the edge of the window reveal. In order to investigate the maximum possible effect of window covering, LIUHB tests were carried out with all windows covered and all windows uncovered. Window covering could impact the LIUHB test in two ways:

- By causing a change in the effective thermal resistance of the window assembly by introducing a volume of trapped air between the window and the blind

- By changing the way in which heat gains occur in the house due to solar irradiation.

An RDSAP model of the Holywell test house was used to estimate the change in thermal resistance of the window system caused by the blinds. The Siviour method was used to analyse the effect of window covering on the solar gains to the house. The results of the LIUHB test with the windows covered were then compared to those with the windows uncovered to compare the estimated and measured effects.

4.3. Co-heating Test Method

The history and basis of the co-heating test was described in detail in section 2.6.1, in this section the specific co-heating method which has been applied during this study is described.

4.3.1. Data Collection

Before each co-heating test was carried out the house was prepared for testing by: closing all of the external openings (windows, door, trickle vents etc), ensuring that all water traps are filled, opening all internal doors, ensuring that all equipment not associated with carrying out the test is turned off and ensuring that the in-situ central heating system is also turned off. A survey of the house was undertaken to measure its dimensions, the measurements included: the volume of each room (in order that the volumetrically weighted internal temperature could be calculated), the area of each glazed element, and the volume, surface area and floor area of the whole house. The orientation of the building was measured afterwards using the Google Earth software. An infiltration rate measurement was then carried out using a blower door test (ATTMA, 2010) so that the fabric and infiltration heat loss can be separated during data analysis. In early co-heating tests the infiltration rate was also measured daily using the tracer gas decay method (Roulet and Foradini, 2002), using a solenoid valve controlled by a programmable timer plug. The CO_2 outlet was placed centrally in the house, immediately adjacent to a mixing fan so that an even CO_2 concentration was achieved throughout the contained volume. The settings for the time and extent to which the release valve of the CO_2 bottle was opened were adjusted to ensure a significant increase in the CO_2 concentration after a release, with a release time of 10 minutes eventually settled upon. This method proved a cheap and easy way to measure air-tightness; however as the measurements agreed very closely with those of the blower door test ,tracer gas decay measurements did not provide additional information and were not carried out during later tests.

Following the preparation of the house the co-heating equipment was installed; service meter readings were taken at this time to provide assurance that no gas was consumed during the test and to compare to the logged electricity consumption to check its accuracy. The purpose of the co-heating equipment is to provide an evenly distributed elevated internal temperature; this was usually 25^{o}C but was sometimes increased when testing was carried out during warmer weather (the chosen internal temperature is reported with the results of each test). The temperature was controlled using digital PID controllers and RTD temperature sensors which provide closer control of the internal temperature profile than simple switching thermostats. Heat was provided by fan heaters. In order to ensure an even temperature distribution, an air mixing fan was installed along with each heater (an example is shown in Figure 4-12). As far as possible, a heater and mixing fan were placed in each room of the house being tested, positioned so that the airflow was not aimed directly at wall surfaces in order to avoid increased convective heat exchange at the surface. In this study eight set of heaters and fans were used, which generally allowed one set per room, 3kW fan heaters were used at a setting to provide a 1.5kW power output. A greater number of heaters providing a lower heat output each helps to provide a more even temperature distribution. The energy consumption of each set of heating equipment was measured and logged at a five minute interval using Plogg smart meter plugs which were check calibrated against a known electrical load before use. This allowed an analysis of which room the most energy consumption occurred in, and also provided a back-up for the total energy consumption measurement. The Plogg plugs are accessed via a Zigbee link so that their measurements can be checked outside the house without interrupting the test. The whole house electricity consumption was also measured at the service meter using a pulse logger connected to the pulse output of the meter, with the measurements compared to meter readings to ensure accuracy.

Figure 4-12: Example co-heating set-up in the Holywell test house, including heater, temperature controller, mixing fan, electricity consumption logger and shielded thermistor for internal temperature measurement.

The temperature was measured at the midpoint of each room using a thermistor connected to a central data logger, the temperature was sampled every 10 seconds and mean values logged every five minutes. For the tests carried out in the Holywell test house, wired access to the data logger was connected to the adjacent control shed so that the conditions inside the house could be remotely monitored. Remote monitoring in general was found to be a useful function to check that all equipment was functioning correctly, preventing excessive data loss due to sensor failure. Secondary stand-alone HOBO temperature pendant loggers were also installed in order to provide back-up temperature measurements. The temperature sensors were protected by screens to prevent them being affected by direct sunlight (as shown in Figure 4-12). The temperature sensors were check calibrated against each other before and after each set of co-heating tests, and calibrated using a calibration bath following testing. Relative humidity was also measured on each storey to check that significant drying out had not occurred during the tests.

The weather conditions during each of the tests carried out in Loughborough were measured at the weather station located on the university campus, operated by Dr Richard Hodgkins of the Geography Department. The weather station is manufactured by Campbell Scientific and logs measurements of global solar irradiation, net radiation, ambient air temperature, relative humidity, wind speed and direction, barometric pressure and rainfall at a 15 minute interval, a full list of the equipment used in the weather station is given in Table 4-7.

Weather Station Measurement	**Component Name**	**Accuracy**
Temperature & relative humidity	CS215 temperature and relative humidity probe	±0.4°C, ±4% (RH)
Rainfall	ARG100 tipping bucket raingauge	±0.2mm
Net radiation	Kipp & Zonen NR-Lite net radiometer	±5%
Global solar radiation	SP-Lite silicon pyranometer	±10%
Wind speed and direction	Windsonic ultrasonic wind sensor	±2%, ±3°
Data logger	CR1000 measurement and control system	N/A

Table 4-7: List of weather station equipment (all equipment manufactured by Campbell Scientific).

In addition to these measurements, solar irradiance measurements were carried out by the author in the plane of each wall that contained glazing using Kipp and Zonen MP3 pyranometers; an example installation is shown in Figure 4-13 and Figure 4-14. These pyranometers were connected to a central data logger located within the house, with the mean irradiance sampled at a 10 second interval and logged at a 5 minute interval.

Figure 4-13: Example installation of a pyranometer in plane with the wall (left) and the weather station and south facing pyranometer at BRE Garston (right).

Figure 4-14: Close-up of an example installation of a pyranometer on the external surface of a window.

Secondary external temperature sensors were used during each of the tests to collect back-up measurements, they were located close to, but out of the temperature field of, each house and shielded from direct solar radiation. For the test carried out at the BRE Garston site weather conditions were measured by a weather station mounted at a height of 5m on a mast erected in front of the house which measured air temperature, wind speed and direction, relative humidity, rainfall and barometric pressure. A south facing vertically-mounted pyranometer was used to measure total solar irradiance; both the pyranometer and weather station are shown in Figure 4-13.

A list of the equipment used for the co-heating tests is given in Table 4-8.

Co-heating Equipment	Component Name	Accuracy
Fan	18" high velocity FGDB-18" Pro Elec Fan	N/A
Fan heater	Dimplex DXFF30TS 3kW flat fan heater	N/A
Temperature controller	Instcube 3215L	N/A
Electricity kWh meter	Energy Optimizers Plogg smart meter plug system	<0.5%
Electricity meter reader and logger	Enica Opti-Pulse logger + LED sensor cable	N/A
CO_2 bottle		N/A
CO_2 solenoid valve	D-D solenoid valve	N/A
Timer plug (to operate CO_2 valve)	Masterplug indoor power TE7-MP timer	N/A
CO_2 sensors	Telaire 7001	±50ppm
Thermistors	U-type thermistor w/10m cable	±0.2°C
Pyranometers	Kipp & Zonen MP3	±10%
Data logger	Squirrel SQ2040 Wi-Fi	N/A
Secondary temperature sensors	HOBO UA-001-64	±0.53°C
RH sensors & CO_2 data logger	HOBO U10	±3.5%
Weather station (for wind speed, direction, external temperature)	Davis Vantage Pro2 Plus	±1m/s, ±3°, ±0.5°C

Table 4-8: List of co-heating equipment.

4.3.2. Data Analysis

The data analysis for the co-heating tests was carried out using Microsoft Excel. The first step in the analysis was to calculate the volumetrically weighted mean internal temperature based upon the temperature sensors in each room, which was carried out for each five minute time step. Mean daily values were then calculated for the internal and external temperature, total electrical power consumption, weather conditions (wind speed, solar irradiance, net radiation, relative humidity, rainfall and barometric pressure). The daily mean internal-external temperature difference was calculated by subtracting the external from the internal measurements on a daily basis. For every analysis carried out in this study a day is defined as a 24-hour period between 0600-0600, labelled by the day on which the period started. This is to incorporate a daily diurnal cycle of warming and cooling of the building's thermal mass, so that as far as possible the weather conditions occurring during a single day impact upon that day alone. This is particularly aimed at allowing as much time as possible for the solar gains occurring during a sunny day to dissipate overnight. On the few occasions when temperature or energy data was not collected by the primary sensors due to logger failure or other such problems it was replaced with the data collected by the secondary sensors.

Following this data processing the HLC was calculated by the multiple regression, Siviour and Siviour plus regression methods, which were described in the literature review (section 2.6.1). A multiple regression technique was also used to attempt to account for variations in heat loss occurring due to differences in wind speed during the measurement period. This involved carrying out a multiple regression with total heating power (electrical + solar by each of the data analysis methods) as the independent variable, and internal-external temperature difference and wind speed as the dependent variables. The correlation coefficient between total heating power and wind speed is then multiplied by the wind speed each day to calculate the additional heat loss relative to a day with zero wind speed which is then subtracted from the total heating power. However, after several co-heating tests had been carried out it was found that there was rarely a clear relationship between the daily total heat input and wind speed, and that it was usually a much more nuanced relationship related to co-correlations between wind speed, wind direction and external temperature. Therefore, although the multiple regression analysis to correct for the effect of wind speed often led to a closer relationship between total heating power and internal-external temperature difference, there was not a clear physical reasoning for this. Furthermore, the relationships between the solar, temperature and wind speed data contravene the underlying assumptions of a multiple linear regression analysis in the same way that was described in section 3.1.1 in relation to the calculation of solar gains. Therefore this analysis method was not used and the co-heating results in this thesis are reported with no correction for differing wind speeds applied.

4.3.3. The Facade Solar Gain Estimation Method

The facade solar gain estimation method (abbreviated to the 'facade' method throughout this thesis) is a new technique, developed in this study, for quantifying useful solar gains to a building. It has been applied during the data analysis of both co-heating and LIUHB tests. The principle of the method is to attempt to directly measure solar gains, and thereby overcome the risk of depending upon a statistical analysis that is undermined by questionable assumptions and may produce inaccurate results due to an over-simplification of a complex process (as described in section 3.1.1). The facade method incorporates both new data collection and data analysis processes.

The data collection involves the use of pyranometers to measure the solar irradiation reaching each vertical surface including a glazed element; practically this involves mountings in the plane of walls which include glazed elements as described in the data collection section (section 4.3.1). However, it is recognised that this data collection method may be expensive and impractical on a widespread scale due to issues connected with securing the expensive pyranometers, and connection with a data logger located within the house. Therefore a second variant of the method has also been applied, where the solar irradiance reaching each facade is calculated based upon a translation of global solar radiation, which is available from many weather stations. The first and second variants are described as 'measured' and 'translated' respectively in this thesis. The advantages of the data collection method of the 'measured' variant are that the uncertainty inherent in translating global solar irradiance into irradiance on vertical planes is avoided, and that the effect of overshading will be included in the measurement to some extent.

In the facade solar gain estimation method the solar gains are calculated using (EQ 4-1), which is based upon equation 6 from SAP2009 (BRE, 2011):

$$Q_S = 0.9\ A_W\ S\ g_{\perp} \qquad \text{(EQ 4-1)}$$

Where: Q_S is the average solar heat input to the house (W); 0.9 is the factor representing the ratio of typical average transmittance to that at normal incidence; A_W is the area of glazing in an opening (i.e. not including the area of the frame) in m^2; S is the solar flux on that facade in W/m^2; and $g_{\perp}$ is the total solar energy transmittance factor of the glazing at normal incidence. The solar gains are calculated separately for each facade and then summed. The transmittance factor ($g_{\perp}$) is dependent upon the type of glazing that is used, and values for the factor are sourced from table 6b in SAP (BRE, 2011). For the facade method it is assumed that all solar gains occur through the glazed elements, and solar gains through non-glazed elements are not calculated.

The solar flux term (S) in (EQ 4-1) is simply measured directly by the pyranometers positioned on each facade in the 'measured' variant. In the 'translated' variant an additional term to account for overshading is included, again after the approach adopted in SAP (BRE, 2011):

$$Q_S = 0.9\ A_W\ S\ g_{\perp}\ Z \qquad \text{(EQ 4-2)}$$

Where Z is the solar access factor, which varies depending upon the percentage of sky which is blocked by surrounding obstacles; values of Z are sourced from Table 6d in SAP (BRE, 2011). For each of the analyses carried out the degree of overshading was considered to be 'average or unknown', resulting in a Z value of 0.77 for most of the year and 0.9 during the summer months (June, July and August) (BRE, 2011).

The calculated total solar gain (the sum of the solar gains falling on each facade) is then added to the electrical heating power to calculate the total heat input (electrical plus solar) to the house. The HLC is then calculated using the same co-heating plotting procedure as for the Siviour plus regression method, described in section 2.6.1. The internal-external temperature difference is plotted on the x-axis and the total heating power (from the heating system + solar gains) on the y-axis, the HLC then being the gradient of a linear line of best fit forced through the origin.

Initially, the translation of global solar radiation to vertical irradiance falling on each facade was carried out using the method given in SAP 2009 (table 6a, page 187) (BRE, 2011). However, this was found to be unsuitable as it is based upon monthly averaged solar declination figures, which is particularly problematic when a measurement period spanned two different months; in this case, the translated irradiance values change suddenly from one month to the next. This effect is carried into the calculated total heat input which is used in the regression analysis carried out to determine the HLC; the daily total heating power values collected during days in different months do not align directly and cause a miscalculation of the HLC. Therefore, a method was required to carry out the translation on a shorter time interval. An hourly horizontal-vertical translation using the method given by Duffie and Beckman in their book Solar Engineering of Thermal Processes (Duffie and Beckman, 1991) was settled upon. The Duffie and Beckman data analysis method is significantly more complicated and time consuming than the SAP method, but this was a one-off process; once a spreadsheet had been created to carry out the analysis it was simply a matter of inputting the global solar radiation data for the appropriate location and time.

In order that the facade method can be applied by the reader, a full description of the translation method sourced from Duffy and Beckman is given here (Duffie and Beckman, 1991). Global solar irradiance data measured within 20km (ibid) of the test site is required in order to accurately calculate the translated vertical irradiance. More local variations in irradiance (due to movement of clouds for example) are not considered to introduce a large error within this range, particularly as the translations are averaged over an hour-long period. The total irradiance reaching each facade is comprised of three elements; beam, diffuse and reflected radiation; which are calculated separately and summed. In preparation for this summation, a series of steps are taken in order to calculate the properties that are used in calculating each element. The first step in the translation is to account for the way in which the sun moves across the sky in a particular location, at a particular time of year. To do this the ‘solar time’ must be calculated, which is based upon the apparent angular motion of the sun across the sky and does not coincide with standard local time. Two corrections are used to convert local time to solar time; the first is a constant correction for the difference in longitude between the observer's meridian (longitude) and that upon which the local time is based (EQ1.5.2 in (Duffie and Beckman, 1991)).

Solar time = 4 (L_{ST} + L_{LOC}) + E + Standard Time (EQ 4-3)

Where L_{ST} is the standard meridian of the local time zone (zero in the UK), L_{LOC} is the longitude of the location of the house (longitudes must be in degrees west), E is the 'equation of time' (in minutes) and the standard time is in hours (i.e. 23:00 is inputted to the equation as 23). The equation of time (E) is calculated using (EQ 4-4) (EQ1.5.3 in (Duffie and Beckman, 1991)):

$$E = 229.2\,(0.000075 + 0.001868\cos B - 0.032077\sin B - 0.014615\cos 2B - 0.04089\sin 2B) \qquad \text{(EQ 4-4)}$$

Where B is calculated using (EQ 4-5) (EQ1.4.2 in (Duffie and Beckman, 1991)), in which n is the day of the year (between 1 and 365):

$$B = (n-1)\ \ 360/365 \qquad \text{(EQ 4-5)}$$

The next step is to calculate the beam irradiance falling on each facade. Beam radiation is that received from the sun without having been scattered by the atmosphere. In order to calculate the amount falling on each facade a number of variables specific to the location of the house and the time at which the measurement was taken must be calculated. The first is the declination (δ), which is the angular position of the sun at noon relative to the celestial equator; it is calculated using (EQ 4-6) (EQ1.6.1a in (Duffie and Beckman, 1991)):

$$\delta = 23.45 \sin (360\ (284 + n / 365)) \qquad \text{(EQ 4-6)}$$

Next the cosine of the angle of incidence (Θ), which is the angle between the beam radiation on a surface and the normal to that surface, is calculated using (EQ 4-7) (EQ1.6.4 in (Duffie and Beckman, 1991)):

$$\cos \Theta = -\sin \delta \cos \phi \cos \gamma + \cos \delta \sin \phi \cos \gamma \cos \omega + \cos \delta \cos \gamma \sin \omega \qquad \text{(EQ 4-7)}$$

Where ϕ is the latitude of the house; γ is the surface azimuth angle (which is the direction in which the vertical surface (i.e. each facade of the house) is facing, where due south is zero, east negative and west positive); and ω is the hour angle (which is the angular displacement of the sun east or west of the local meridian due to the rotation of the earth on its axis at 15^{o} per hour, where the morning is negative and the afternoon is positive). ω is calculated using (EQ 4-8):

$$\omega = 15 * (\text{Local solar time} - 12) \qquad \text{(EQ 4-8)}$$

Now the cosine of the zenith angle (Θ_Z) is calculated using (EQ 4-9) (EQ1.6.5 in (Duffie and Beckman, 1991)); Θ_Z is the angle between the vertical and the line of the sun, effectively the angle of incidence of beam radiation on a horizontal surface.

$$\text{Cos}\ \Theta_Z = \cos\phi \cos\delta \cos\omega + \sin\phi \sin\delta \qquad \text{(EQ 4-9)}$$

The next step is to calculate the geometric factor (R_b), R_b is the ratio of beam irradiance on a tilted surface to that on a horizontal surface at any time, and is calculated using (EQ 4-10) (EQ1.8.1 in (Duffie and Beckman, 1991)):

$$R_b = \cos\Theta \ / \cos\Theta_Z \qquad \text{(EQ 4-10)}$$

At this stage the information required to calculate the beam radiation has been generated; now the diffuse element is addressed, diffuse radiation is the solar radiation reaching the facades after its direction has been changed by scattering in the earth's atmosphere. The diffuse element is calculated by comparing the theoretically possible radiation that would be available if there was no atmosphere and comparing it to what is measured. To carry out this comparison it is necessary to calculate the extraterrestrial radiation falling on a horizontal surface for each hourly time step (I_0), extraterrestrial irradiation is the amount of solar radiation reaching the edge of the Earth's atmosphere. This is calculated using (EQ 4-11) (EQ1.10.4 in (Duffie and Beckman, 1991)):

$$I_0 = (12 \times 3600/\pi)\, G_{SC}\, (1 + 0.033 \cos 360n / 365)\ X \qquad \text{(EQ 4-11)}$$
$$(\cos\phi \cos\delta\, (\sin\omega_2 - \sin\omega_1) + (\pi\, (\omega_2 - \omega_1)/180) \sin\phi \sin\delta)$$

Where G_{SC} is the global solar constant, and ω_1 and ω_2 are the hour angles at the start and end of the hour in question. Next the 'clearness index' (k_T) is calculated, this is to take account of how clear the sky was during each hour, and is the ratio of the measured global radiation (I) to the calculated extraterrestrial radiation during each hour. It is calculated using (EQ 4-12) (EQ2.9.3 in (Duffie and Beckman, 1991)):

$$k_T = I / I_0 \qquad \text{(EQ 4-12)}$$

The diffuse radiation reaching a horizontal surface can now be calculated using an empirically defined correlation between the fraction of hourly global radiation which is diffuse (I_d/I) and the clearness index (k_T). Several very similar correlations have been defined, but Duffie and Beckman recommend using the Erbs et al correlation (Duffie and Beckman, 1991) for this calculation, which is given in (EQ 4-13) (EQ2.10.1 in (Duffie and Beckman, 1991)):

$$I_d/I = \begin{cases} 1 - 0.09k_T & \text{for } k_T <= 0.22 \\ 0.9511- 0.1604k_T + 4.388k_T^2 - 16.638k_2^3 + 12.336k_T^4 & \text{for } 0.22< kT <=0.80 \\ 0.165 & \text{for } k_T > 0.80 \end{cases} \qquad \text{(EQ 4-13)}$$

As these values are for a horizontal surface there is no reflected element, therefore the beam irradiance (I_b) can easily be calculated using (EQ 4-14):

$$I_d = I - I_b \qquad \text{(EQ 4-14)}$$

At this stage the amount of beam irradiance reaching the facade and the amount of diffuse irradiance reaching a horizontal surface at the location of the house have been calculated. Now the direction from which the diffuse radiation (including diffuse and ground reflected radiation) is received is calculated so that the total irradiance reaching the facade can finally be determined. First the anisotropy index (A_i) is calculated using (EQ 4-15) (EQ2.16.3 in (Duffie and Beckman, 1991)). It is a function of the transmittance of the atmosphere for beam radiation and is used to determine the proportion of the horizontal diffuse radiation which can be treated as 'forward scattered', and hence is considered to arrive at the facade at the same angle as the beam radiation.

$$A_i = I_b / I_0 \qquad \text{(EQ 4-15)}$$

Finally, a correction is applied to the calculation of total irradiance reaching the facade to account for horizon brightening. The correction uses a modulating factor (f) which is calculated using (EQ 4-16) (EQ2.16.6 in (Duffie and Beckman, 1991)):

$$f = \sqrt{(I_b / I)} \qquad \text{(EQ 4-16)}$$

The necessary preparatory calculations have now been carried out and the total solar irradiance (I_T) (beam + diffuse + reflected) reaching each vertical facade can now be calculated using the HDKR model (Hay, Davies, Klucher, Reindl), as shown in (EQ 4-17) (EQ2.16.7 in (Duffie and Beckman, 1991)):

$$I_T = (I_b + I_d A_i) R_b + I_d\,(1 - Ai)\,(1 + \cos\beta / 2)\,(1 + f \sin^3(\beta/2)) + I\rho_g\,(1 - \cos\beta / 2) \qquad \text{(EQ 4-17)}$$

Where ρ is the ground reflectance and β is the orientation of the surface (which is 90^o for vertical walls). For all calculations in this thesis a ρ-value of 0.2 was applied, this being chosen based upon the measured ρ of common material surrounding the houses tested (IBPSA-USA, 2012). In order to provide confidence in the results of the Duffie and Beckman translation a second similar translation method sourced from *Solar Radiation and Daylight Models* by Tarek Muneer was also applied (Muneer, 2007). A comparison between the two translation methods using the same source data successfully showed almost identical results for a variety of facade orientations and house locations.

The translated irradiance calculated using the Duffie and Beckman method was then used in the same way described for the measured irradiance values to calculate the solar gains for each facade. The solar gains for each facade are summed and the HLC calculated using the same method as the measured variant.

4.4. The Loughborough In-Use Heat Balance

The Loughborough in-use heat balance (LIUHB) is a non-invasive test method to determine the HLC of a house which has been developed as a part of this study. The test has a similar basis to the co-heating test, using an energy balance where the total heat input to the building (heating system, electricity use and solar gains), and the air temperature difference between inside and outside, are measured in order to calculate the HLC. The major advance of the method is that it is carried out using monitored data which is collected while a house is ‘in-use’, without major disruption to the occupants. The method is based on the energy balance shown in (EQ 4-18):

$Q_h + Q_e + Q_s = HLC \times \Delta T$ (EQ 4-18)

Where Q_h is the daily average heating power from the heating system (W), Q_e is the daily average heating input due to electricity use within the heated volume (W), Q_s is the daily average heating power supplied by the sun (W) and ΔT is the daily average air temperature difference between inside and outside (K).

Daily averages of these values are used in order to minimise the influence of the thermal mass of the building, which will store and release heat energy over a diurnal cycle. It is assumed that the net energy storage over each 24 hour period is close to zero. At present, the minimum required monitoring period to effectively account for variable weather conditions, variations in occupant behaviour and additional temperature variation in the house compared to a co-heating test is estimated to be three weeks.

Although the recommended minimum sample is longer than that of the co-heating test, the in-use heat balance is significantly cheaper and simpler to carry out and can be undertaken while the house is in use. In this way, the monitoring approach effectively acts to remove many of the practical difficulties that a long testing period introduces. The only restriction that is placed upon the occupants is that they are asked not to use unmetered secondary heating, such as gas fires and solid fuel combustion, as the heat output of these cannot be easily measured and accounted for in the energy balance. The holistic nature of the in-use heat balance, which measures the performance of the whole house, allows significant simplifications when considering heat transfer in the house. All electricity use is simply accounted for as a useful heat gain to the internal space, distribution and storage heat losses in the central and hot water heating systems are also assumed to provide a useful heat gain to the house and hence do not need to be individually estimated or measured (as they are included in the total estimated heat input). A limitation of this assumption is that the boiler must be located within the heated envelope of the building being tested (as it was for each of the houses in which testing took place in this study).

There are three stages to completing an LIUHB test: a building survey, a monitoring and data collection period, and finally the data analysis. The building survey comprises:

- Measurement of a house’s dimensions, including the volume of each room to determine the volumetrically weighted mean internal temperature, and the size of every window and orientation of the house to allow the calculation of solar gains using the facade solar gains estimation method.

- Visual identification of the heating system to determine the rated efficiency to allow calculation of heat from fuel input. For gas boilers this is sourced from the SAP boiler efficiency database (BRE, 2014b).
- A blower door test to measure the infiltration rate of the house so that the total heat loss can be broken down into fabric and infiltration components.

4.4.1. Data Collection

During the monitoring period, measurements must be taken of the whole house electricity and gas (for the majority of houses which use gas as fuel for their heating system) consumption and the internal temperature in each room. Measurements are also required of the local weather conditions, in particular the external temperature and the global solar radiation. Measurements of other weather conditions such as wind speed and direction, rainfall, net radiation and relative humidity can be useful additional pieces of information but are not essential to the data analysis in its present form. In general, this information can be sourced from local weather stations, providing that there is a station within approximately 20km of the test site (Duffie and Beckman, 1991). All LIUHB tests reported in this thesis were carried out either on or very close (within 1km) to the Loughborough University campus; therefore all weather condition measurements were sourced from the university's weather station, as they were for the majority of the co-heating tests. All measurements must be logged on a daily basis at least, though logging on a shorter time step is preferable to allow investigation of dynamic effects. During all testing carried out in this study the electricity, gas and internal temperature measurements were logged on a 5-minute time step, and the university weather station logs values on a 15-minutely basis.

Electricity and gas usage should be measured at the service meter so that all heat inputs to the house are accounted for. Placement of internal temperature sensors is likely to be compromised by practicalities associated with carrying out the test while houses are in-use, though this isn't usually too onerous as typical sensors are small (the HOBO pendant loggers used in the occupied house case study are approximately the same size as a matchbox) and can be placed discreetly on shelves and other surfaces. Crucially, a temperature sensor must be located in each room in the house, out of direct sunlight and the immediate influence of heat emitters, and at approximately mid-height in the room. The measurements must be taken using sensors that have an accuracy of at least $\pm 0.5^{o}C$. Relative humidity is also measured at a central location in the house to identify any drying out in recently built or refurbished houses. Drying can adversely affect the results as heat transfer is affected by vapour movement.

The application of the LIUHB is normally limited to the heating season, so that there is a significant positive temperature difference between the inside and outside of the house (>10°C). No heating schedule, temperature set-point, or domestic hot water usage is prescribed; the occupants simply continue to heat the house as they would normally do.

A list of the equipment used for the LIUHB tests is shown in Table 4-9.

Sensor	**Measurement(s)**	**Accuracy**
HOBO pendant temperature logger (UA-001-64)	Internal air temperature	±0.53^{o}C
HOBO U10-003	Internal air temperature and relative humidity	±0.53^{o}C, ±3.5%
Elster IN-Z61 pulse block	Gas consumption at utility meter	N/A
Enica Opti-Pulse LED pulse meter logger	Electricity consumption at utility meter, plus data logging for gas consumption	N/A

Table 4-9: List of equipment for the LIUHB tests.

4.4.2. Data Analysis

The accuracy of the monitored gas and electricity data is verified by comparison with meter readings taken at the beginning and end of the monitoring period. The total heat input from the gas central heating system is then calculated by multiplying the gas consumption (in m^3) by the average calorific value of gas for the area in which the dwelling is located (East Midland for all cases in this study) during the period of the tests (10.92kWh/m^3 (National Grid, 2014)) and the efficiency of the boiler. The mean daily total heat inputs (excluding solar gains which are added in a later analysis step) are then calculated by summing the heat input from the heating system and the electrical consumption.

The volumetrically weighted mean daily internal temperature is then calculated based upon the measurements from the temperature sensors and the building survey. When temperature measurements were collected in occupied houses they were visually inspected to ensure that sensors had not been placed in direct sunlight, as evidenced by large temperature spikes. The hourly global solar radiation translation process described in section 4.3.3 is then used to calculate the total solar gain reaching each facade which includes a glazed element. The mean daily global solar radiation is then calculated so that all data necessary for the calculation of the HLC have been collected.

For each of the LIUHB tests carried out, the reported HLC was calculated using the ‘translated’ variant of facade solar gain estimation method used in co-heating tests, described in section 4.3.3. The HLC was also calculated by each of the statistical approaches used in co-heating tests (Siviour, Siviour + regression and multiple regression) described in 2.6.1, so that the results by each analysis type could be compared.

4.5. Blower Door Tests

All blower door tests were carried out by the author using The Energy Conservatory’s Minneapolis Blower Door System, which was calibrated before the start of testing and after the completion of the testing programme. All tests were carried out according to ATTMA Technical Standard 1 (ATTMA, 2010).

4.6. Reduced Data Standard Assessment Procedure (RdSAP) Assessments

RdSAP assessments were carried out using a Microsoft Excel based analysis tool developed by Dr David Allinson at Loughborough University, which is based upon the 2009 SAP (BRE, 2011). All RdSAP assessments were carried out according to SAP 2009, which was current at the time that they were carried out. It should be noted that an updated version, SAP 2012 (BRE, 2013), has been published since that time. The method used to calculate the HLC of a building did not change between SAP 2009 and SAP 2013, however, which is the sole purpose of the RdSAP assessments carried out in this work. Similarly, as only the estimated HLC was required, the RdSAP method could be used rather than the full SAP assessment because the calculation method for the HLC is the same for both. The RdSAP method was also thought to be most appropriate in this study as all testing was carried out on existing houses, rather than new-builds.

4.7. Chapter Summary

This chapter has given a technical description of the testing and analysis methods used in this project, building upon the methodology overview given in Chapter 3 to provide define the scope of the thesis.

Chapter 5 Establishing a Baseline – Empirically Defining the Uncertainty in Co-Heating Tests

The co-heating test represents the current most commonly used method to measure whole-house heat loss coefficients. Therefore, a better understanding of this test was developed as the first step in this investigation. While the co-heating test has been reasonably widely used in the research field, the literature review showed that the uncertainty of the test has yet to be defined. Understanding the uncertainty of the test is crucial to developing confidence in its use. It would also be a vital part in the development of an alternative testing method, as the uncertainty of the current most-widely used method would make a natural benchmark for the accuracy of any alternative method.

The author's involvement in the NHBC co-heating project, described in section 3.1.1, provided a uniquely suitable dataset for estimating the uncertainty of the co-heating test. The dataset provided an opportunity to test the reproducibility of co-heating tests given variations in both the external conditions and the methodology applied to carry out and analyse the results. The round-robin test, where 7 different teams carried out a co-heating test in the same building over the course of one winter, provides the information for a comparison of the methodological and data analysis approaches adopted. Meanwhile, the long-term co-heating test, carried out continuously by BRE over a six month period in an adjacent building, provides the data for a sensitivity analysis investigating the effects of measurement uncertainty on the calculated HLC.

A basic reporting of the results of the NHBC co-heating project is presented in section 5.1 to give context to the more detailed sensitivity and comparative analyses that follow. In section 5.2, a sensitivity analysis of the effect on the calculated HLC of uncertainty in each constituent measurement of a co-heating test was undertaken. The results of this analysis were then used to estimate the total uncertainty of the HLC measurement by the co-heating test, given a constant data collection method. This analysis is completed for each of the most typical data analysis methods used in co-heating.

A comparative analysis was used to quantify the reproducibility of the test given varying weather conditions, different methods of applying the test and different methods of analysing the test data, the results of this analysis are reported in section 5.3. This could be considered as a measure of the robustness of the test to the natural variability that occurs across different bodies applying the same test, and of course to the all-important weather conditions. It is important to note however, that all of the co-heating tests were carried out in the same building, which removes one potentially significant source of uncertainty. This comparative analysis has been used to inform a set of recommendations on the best practise methods for co-heating testing and analysis, which are presented in section 5.4.

The results of these two analyses are then considered in the chapter's summary, section 5.5, to make an estimate of the practical accuracy with which co-heating results can be reported.

5.1. Results of the NHBC Co-heating Project

The NHBC co-heating project involved the serial testing of a single detached house by seven teams from both academia and industry, between December 2011 and May 2012. Each team completed their test independently and according to their own method, the project was fully described in section 3.1.1. The HLC values reported by each team are shown in Figure 5-1. For this data set, the mean value for the HLC is 66.95W/K, with a standard deviation (for small data sets) of 4.22W/K, a standard error of the mean of 1.60W/K, and hence the 'population' mean expressed as 66.95±3.2W/K at the 95% confidence level and 66.95±4.8W/K at the 99.75% confidence level. Five teams come within the 95% confidence interval, but team G are out of range even at the 99.75% level, suggesting a systematic error in their results.

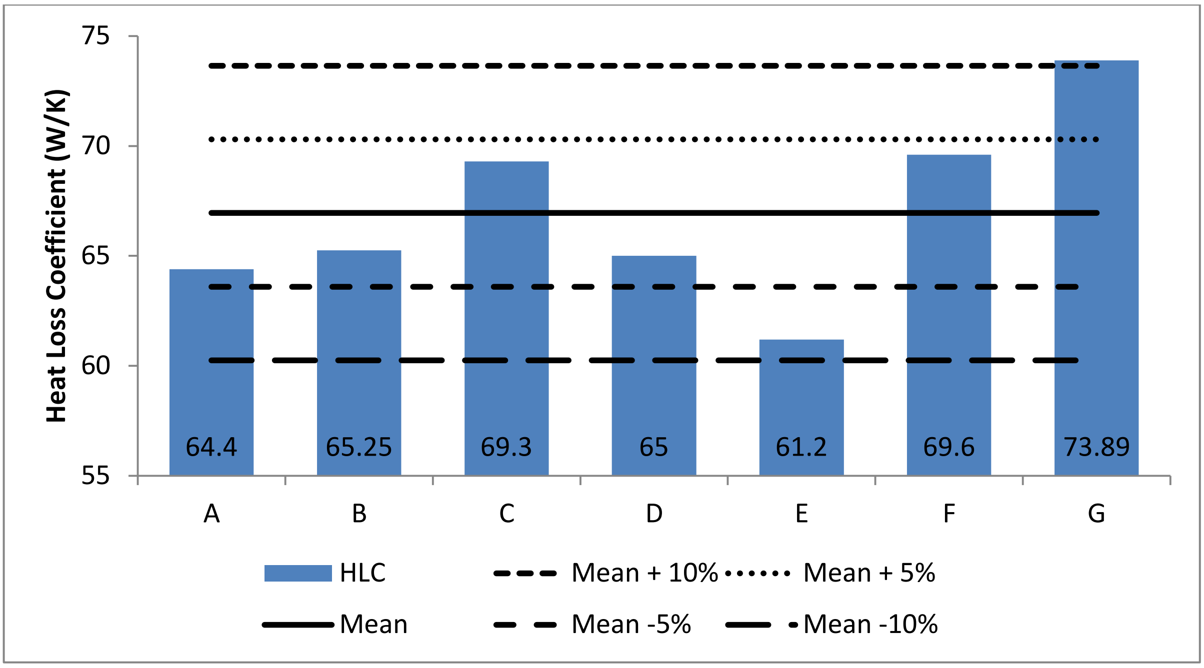


Figure 5-1: Reported heat loss coefficient by each testing team in the NHBC co-heating project.

Despite variations in weather, in the individual team testing procedure and in the data analysis technique, the reported HLC values of five of the seven teams fall within a 5% margin of the mean result. Even where results lie outside of the 99.75% confidence interval, the range of the HLC is approximately ±10%. This could therefore be considered as a practical range around the mean with which to report such a result.

Energy meter failures experienced by team G meant that energy consumption data was not collected for the majority of the testing period. Rather, it was interpolated based on an assumption that the distribution of heat supplied during the first day of the test would remain constant throughout (described fully in section 5.3.1). Given this unfortunate event, team G's result was excluded from further analysis.

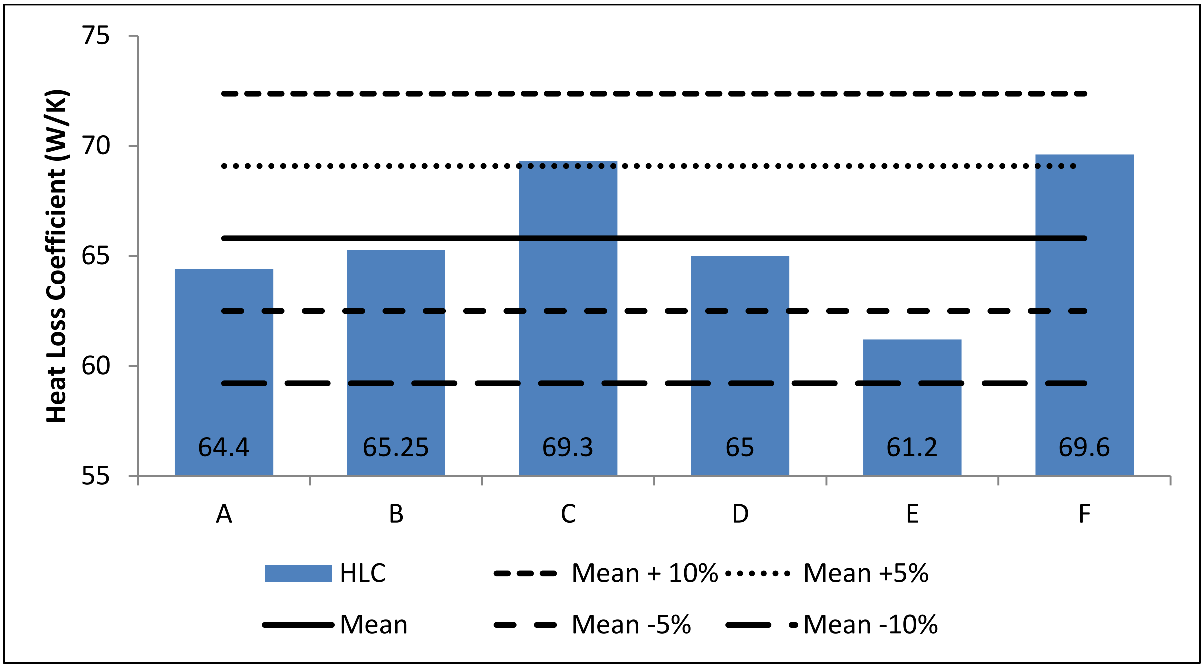


Figure 5-2: Reported HLC by each team, excluding the statistical outlier (G).

The updated set of results, excluding the result of team G, is shown in Figure 5-2. For this reduced dataset, the mean HLC value is 65.79W/K, with a standard deviation of 3.19W/K, a standard error of the mean of 1.30W/K. The HLC can therefore be given as 65.79±2.55W/K at the 95% confidence interval, and 65.79±3.65W/K at the 99.75% confidence interval. As shown in Figure 5-2, all of the results fall comfortably within a ±10% boundary of the mean. The largest differences between reported result and the mean in this dataset are -7.0% and +5.8%, for the results of team E and F, respectively.

Two teams, C and F, reported the heat loss coefficient due to infiltration; the results were 5W/K and 4.8W/K, respectively.

5.2. Sensitivity Analysis of the HLC to Measurement Uncertainties in Co-heating

A differential sensitivity analysis was carried out to investigate the sensitivity of the HLC to variations in the key measurements that comprise the co-heating test. The measurements considered are internal-external temperature difference (section 5.2.1), electrical power consumption (section 0) and estimation of solar gains (section 5.2.3).

The analysis was carried out using the data from the co-heating test carried out continuously by BRE between 23rd December 2011 and 11th September 2012, in building 50.4, as part of the NHBC Co-heating Project described in section 3.1.1. The purpose of the analysis was to gain an insight into which elements of the co-heating test contribute the largest uncertainty to the measured HLC value, and to estimate the total uncertainty of the test (section 5.2.4).

The sensitivity to each measurement was estimated according to four data analysis methods, these were the multiple regression, Siviour and Siviour plus regression methods (described in section 2.6.1), and the facade method (developed in this study and described in section 4.3.3). The original plots (co-heating and Siviour) for each method, before the sensitivity analysis was carried out, are shown below.

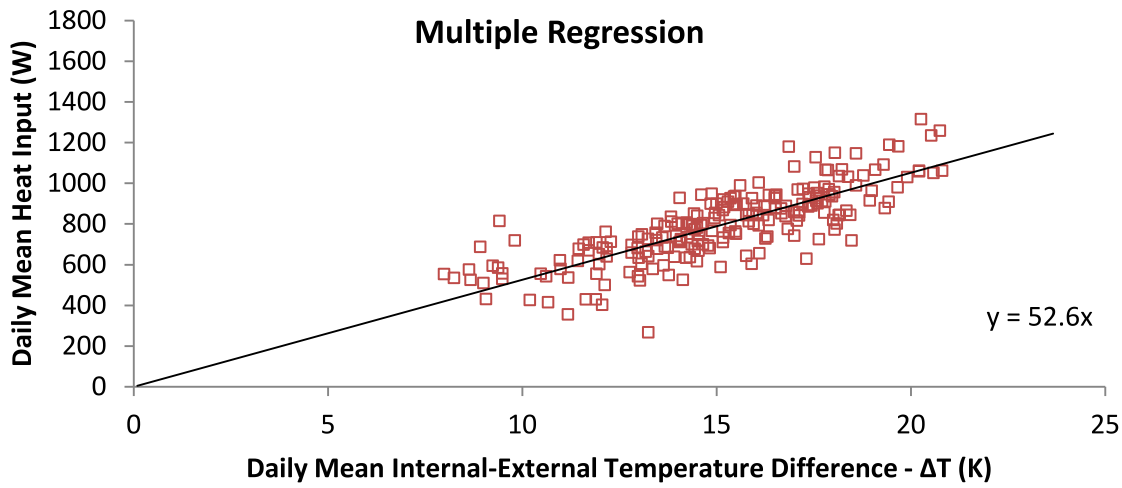


Figure 5-3: Co-heating plot for the long-term co-heating test carried out as part of the NHBC co-heating project, solar gains calculated by the multiple regression method.

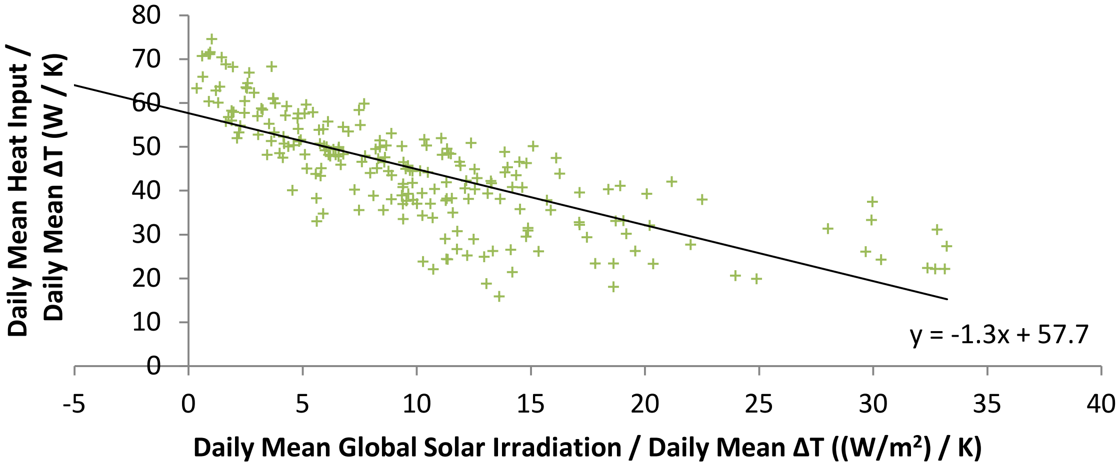


Figure 5-4: Siviour plot for the long-term co-heating test carried out as part of the NHBC co-heating project.

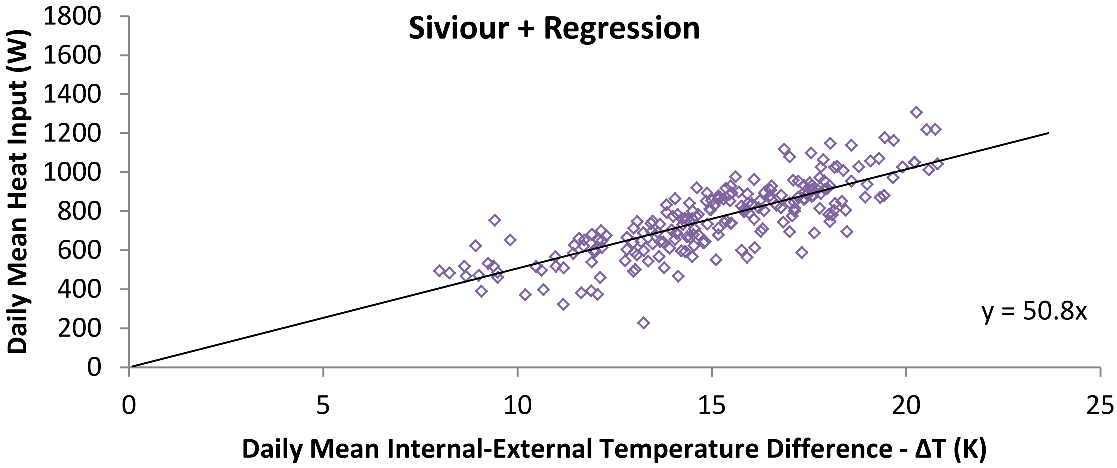


Figure 5-5: Co-heating plot for the long-term co-heating test carried out as part of the NHBC co-heating project, solar gains calculated by the Siviour plus regression method.

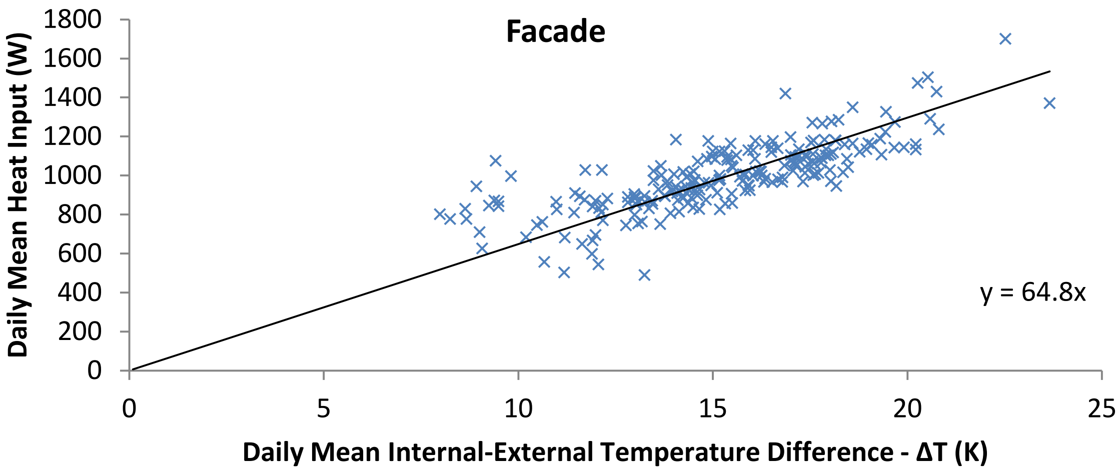


Figure 5-6: Co-heating plot for the long-term co-heating test carried out as part of the NHBC co-heating project, solar gains calculated by the facade method.

5.2.1. Internal-External Temperature Difference

Measurement of the internal-external temperature difference (ΔT) is one of the key parts of the co-heating test. Temperature sensors such as thermistors offer an accuracy of ±0.2°C (Omega, n.d.), while the placement of sensors can introduce an added (systematic) uncertainty. The internal-external temperature difference value is generated by two measurements, both prone to these uncertainties. The placement of the sensor can also cause additional uncertainty, which will be further investigated in section 7.2. Taking into account the sensor accuracy and the effect of sensor placement, the sensitivity of the HLC to an uncertainty of ±1°C in the measurement of internal-external temperature difference has been calculated.

The sensitivity was estimated by adjusting the daily average internal-external temperature difference by 1°C for each day during the testing period, then calculating the HLC with this new dataset using the four data analysis methods (multiple regression, Siviour, Siviour plus regression and facade). The sensitivity is reported (Table 5-1) as the resulting change in the HLC and, in brackets, the percentage difference in the HLC compared to the value calculated using the original dataset.

		Sensitivity of HLC to Change in ΔT (W/K)	
Analysis Method	**HLC (W/K)**	**ΔT -1°C**	**ΔT +1°C**
Multiple Regression	52.6	+2.7 (+5.0%)	-4.0 (-7.5%)
Siviour	57.7	+2.8 (+4.9%)	-2.6 (-4.6%)
Siviour + Regression	50.8	+1.9 (+3.7%)	-1.8 (-3.6%)
Facade	64.8	+3.7 (+5.7%)	-3.4 (-5.2%)

Table 5-1: Sensitivity of HLC to a 1°C change in daily average internal-external temperature difference (ΔT).

These results (Table 5-1) show that the sensitivity of the HLC to a variation of ±1°C in the ΔT measurement is approximately 5% on average, across all analysis methods. There is a small amount of variation in the sensitivity between different analysis methods, with a total range of -7.5% to +5.7%; the Siviour plus regression method resulted in the lowest sensitivity, of -3.6%, +3.7%.

5.2.2. Electrical Power Consumption

The same sensitivity analysis method applied for internal-external temperature difference, was used for the measurement of electrical power consumption, this time with a variation of ±5%. This value was chosen to reflect a reasonable estimate of the accuracy with which this measurement can be made. Current regulations require that an electricity service meter has an accuracy of at least ±3.5%

(H.M. Government, 1998); a further uncertainty of ±1.5% was added to account for the accuracy of the sensor and logger used to monitor the service meter.

Table 5-2 shows that the uncertainty in measurement of power consumption causes an uncertainty of approximately ±5% in the HLC on average, across all data analysis methods.

		Sensitivity of HLC to Change in Electrical Power Consumption (W/K)	
Analysis Method	**HLC (W/K)**	**-5%**	**+5%**
Multiple Regression	52.6	-2.3 (-4.3%)	+3.1 (+5.8%)
Siviour	57.7	-2.9 (-5.0%)	+2.9 (+5.0%)
Siviour + Regression	50.8	-2.5 (-5.0%)	+2.5 (+5.0%)
Facade	64.8	-2.0 (-3.0%)	+2.0 (+3.0%)

Table 5-2: Sensitivity of HLC to a ±5% change in the measured electrical power consumption

As for the internal-external temperature difference, there is a small variation between analysis methods, with a total range of -5% to +5.8%. The facade method had the lowest sensitivity to the variation in electrical power consumption (±3%).

5.2.3. Estimation of Solar Gains

The uncertainty associated with the calculation of solar gain is more difficult to quantify due to the complex data analysis methods used. Here, the total uncertainty is a combination of that entailed in the measurement of irradiance, which is approximately ±5% for a pyranometer of reasonable quality, and that introduced by the assumptions inherent in each analysis method, which is more difficult to estimate.

An estimate of the uncertainty inherent to the data analysis process has been generated by a comparison of the solar gain as calculated by each method. The mean daily solar gain, as calculated by each analysis method, is shown on a monthly average basis in Table 5-3.

	Mean Daily Solar Gain (W)		
Month	**Facade**	**Regression**	**Siviour and Siviour + Regression**
February	273	92	78
March	376	170	145
April	349	203	173
May	405	258	220
June	394	252	214
July	417	267	227
August	404	247	211
September	485	246	209
Whole Period	*371*	*211*	*180*

Table 5-3: Mean daily solar gain to building 50.3 calculated by each analysis method (note that the Siviour and Siviour pus regression methods result in the same size solar gain).

As co-heating tests are usually limited to the heating season (defined as the start of October – end of April (BRE, 2011)), only data from this period will be used to estimate the uncertainty in the estimation of solar gains. To estimate the largest possible uncertainty during this period, the mean difference for the period between the largest and smallest values for the solar gain resulting from the four analysis methods has been calculated (they result from the facade and Siviour/Siviour plus regression methods respectively). Over the heating season this mean difference between the two estimates of the solar gain is 39%. In addition to the uncertainty of ±5% contributed from the measurement of solar irradiance, the maximum likely total uncertainty in the estimation of solar gains is therefore calculated to be 44%. Clearly, this is a very large level of uncertainty, and further reflects the importance of carrying out further research into the best method for calculating solar gains.

In order to estimate the effect of this uncertainty on the calculation of the HLC, the relative size of the solar gains and electrical heat input from the co-heating equipment was calculated. Table 5-4 shows the monthly averaged percentage of the total heating input contributed by solar gains according to four different data analysis methods.

	Average % Total Heat Input Solar		
Month	**Facade**	**Multiple Regression**	**Siviour + Regression**
February	24%	11%	9%
March	37%	23%	21%
April	32%	23%	21%
May	45%	38%	35%
June	42%	37%	34%
July	44%	36%	33%
August	49%	39%	36%
September	51%	37%	33%
Whole Period	*39%*	*30%*	*27%*

Table 5-4: Monthly average percentages of total heating input resulting from solar gains for each data analysis type

During the months which fall within the heating season (February – April), the mean percentage of the total heat input that is provided by solar gains is 22%. The estimated uncertainty for estimating solar gains (44%) was then multiplied by this value (22%), to calculate the uncertainty introduced into the measurement of the total heat input caused by the uncertainty in the solar gains, which is ±10%. The sensitivity of the HLC to a variation of ±10% in the total heat input (from both electrical and solar sources), and therefore the estimated uncertainty due to the estimation of solar gains, is ±9% on average across all analysis methods (Table 5-5). There is a small difference in the uncertainty between the analysis methods, with a total range of -10.7% to + 10.8%. The facade method has the lowest uncertainty of all the analysis methods.

		Sensitivity of HLC to Change in Total Heat Input (W/K)	
Analysis Method	**HLC (W/K)**	**-10%**	**+10%**
Regression	52.6	-4.9 (-9.3%)	+5.7 (+10.8%)
Siviour	57.7	-5.8 (-10.00%)	+5.8 (+10.00%)
Siviour + Regression	50.8	-5.4 (-10.7%)	+5.4 (+10.7%)
Facade	64.8	-4.3 (-6.6%)	+4.3 (+6.6%)

Table 5-5: Sensitivity of HLC to a ±10% change (the estimated uncertainty of the calculation of solar gains) in the total heat input (electrical + solar).

It should be noted that the uncertainty will vary with the weather and season, depending upon the proportion of the total heat supply to the building caused by solar gains. The uncertainty will be higher during sunnier periods, such as those likely to occur outside of the heating season, due to increased levels of solar gains. Conversely, it can also be observed that the uncertainty may be reduced by the application of the facade data analysis method.

5.2.4. Sensitivity Analysis Summary

This analysis has shown that reasonable estimates of the measurement uncertainty associated with internal-external temperature difference and electrical power consumption each lead to an uncertainty in the calculated HLC of ±5% on average across all data analysis methods. The uncertainty associated with estimating solar gains is larger, ±9% on average across all data analysis methods; this provides further evidence for the importance of research to establish the most accurate method of accounting for solar gains in co-heating.

In a differential sensitivity analysis an approximation of the total uncertainty in the HLC caused by the summation of these factors can be calculated from the quadrature sum of the influence of each (Lomas and Eppel, 1992). Quadrature summation is used to add uncorrelated uncertainties, rather than simple addition. This reflects the probabilistic nature of the uncertainties, simply adding the uncertainty contributed by each of the measurements in the sensitivity analysis would result in the largest possible uncertainty boundary in the final HLC. This range would be very unlikely to occur, however, as that would require each of the constituent measurements to have been at the extreme end of their expected range (Harvard University, 2007). Summing in quadrature allows the total uncertainty, in this case in the HLC, to be estimated at the same point in the probability distribution as each of the constituent uncertainties was (Lomas and Eppel, 1992). The total calculated uncertainty in the HLC measurement by a co-heating test according to each of the analysis methods studied was calculated by quadrature sum (Table 5-6). In addition, the mean uncertainty over all analysis methods was calculated; this gives an indication of the general uncertainty of the co-heating test, including the additional uncertainty caused by the variation in data analysis approaches used. The mean calculated uncertainty across all analysis methods, and hence the estimated general uncertainty in the HLC measurement by a co-heating test, was -11%, +12%.

	Sensitivity of HLC to Uncertainty in Variable							
	ΔT		Electrical Power		Solar Gains		Total HLC Uncertainty	
Analysis Method	**-**	**+**	**-**	**+**	**-**	**+**	**-**	**+**
Regression	5%	-8%	-4%	6%	-9%	11%	-13%	13%
Siviour	5%	-5%	-5%	5%	-10%	10%	-12%	12%
Siviour + Regression	4%	-4%	-5%	5%	-11%	11%	-12%	12%
Facade	6%	-5%	-3%	3%	-7%	7%	-9%	9%
MEAN	5%	-5%	-4%	5%	-9%	10%	-11%	12%

Table 5-6: Results of the sensitivity analysis, showing the measurement uncertainty according to each data analysis method.

It can also be seen that there was a variation in the total uncertainty, depending upon which analysis method was used. The regression method gave the highest level of uncertainty, of ±13%, and the facade method the lowest, of ±9%.

It should be noted that all of the testing for this project was carried out in a single detached building. In order to comprehensively confirm the robustness of the co-heating test, further testing is required that in buildings with other built forms and constructions.

5.3. Comparison of Reproducibility of Different Co-Heating Data Analysis Methods

Analysis of the data collected in the NHBC Co-heating Project offered a unique opportunity to investigate the reproducibility of the co-heating test, given different weather conditions and methodological approaches. As several different groups carried out their test on the same building, a direct comparison could be drawn between the results.

The comparison reported here was based upon the method and results reported by each of the seven participants in the project (the participants have been anonymised and randomly assigned the letters A-G in this thesis). It includes a comparison of the method used to carry out the test – sensors chosen, sensor placement, internal set-point temperature choice, heating equipment and placement – and the method used to analyse the data collected. The methodological and data analysis comparisons have been considered separately, followed by a summary that combines the insights of both.

Given the wide variation in approach, it was not possible to separate the influence of each variable on the eventual resulting HLC. However, lessons drawn from the comparative analysis have been used to generate a set of recommendations on the best practice method for carrying out and analysing a co-heating test. These recommendations build upon the most commonly used existing set (Johnston et al., 2012), and in particular give clearer guidance on how to best analyse co-heating data.

5.3.1. Methodological Comparison

Each testing organisation involved in the NHBC project used a testing method that was based upon that published by Leeds Metropolitan University (Johnston et al., 2012), but with a rather large variation in the detail of each application, given that each party was following ostensibly the same method.

Table 5-7 summarises each approach for ease of comparison, with further detail in the accompanying text.

Team	Temp-erature Control	No. of Heaters & Fans	Electricity Measuring Point	Internal Temp Set-Point	Internal Temp Sensor Placement	Infiltration Rate Measurement	Additional Tests
A	PID control	Not reported	Meter	25°C	Each room	Pre & post blower door	None
B	On/Off Thermo-stat	5	Plug	25°C	Each room	Pre & post blower door	Heat flux & IR
C	PID control	5	Plug	25°C	Each room	Daily tracer gas	Heat flux & IR
D	On/Off Thermo-stat	5	Meter	24°C	Each room	One off tracer gas	Heat flux
E	On/Off Thermo-stat	3	Plug	27°C	Unheated rooms	Post blower door only	None
F	PID	8	Meter & plug	25°C	Each room	Pre & post blower door & daily tracer gas	IR
G	On/Off Thermo-stat	6	Plug	26°C	Heated rooms	Post blower door only	IR

Table 5-7: Methodological comparison table for the NHBC Co-heating Project

All of the teams used electric heating and fans to ensure good air mixing around the house, but there were differences in both the number and type of heaters and fans employed. Six of the seven teams used electric fan heaters to provide the heat input, with the remaining team using convector heaters without an in-built fan.

Each team distributed their heaters around the house according to their own regime, with the majority placing a heater in each large room of the house to the extent that their number of equipment items would allow. All teams placed a circulation fan adjacent to each heater to distribute the warmed air, effectively creating a ‘heating and mixing station’. As shown in Table 5-7, there was a large variation in the number of heaters used.

Two different control systems were used to control the heaters; teams B, D, E and G used switching thermostats, while teams A, C and F used proportional-integral-derivative (PID) controllers.

Teams B, C, E and G measured energy consumption using in-line plug meters only, team D measured the energy consumption of the whole house at the service meter, and team F measured energy consumption with both in-line plug meters and at the service meter.

During the test conducted by team G, two of the five in-line plug meters used failed during the first day of their testing. This was not discovered until the end of the testing period, as access to the building was strictly controlled. In order to complete their analysis, team G interpolated the power consumption at these two meters for the period of malfunction. This was carried out using an assumption that the percentage of total power consumption occurring at these meters, when all meters were functioning correctly, would be maintained during the whole period of the test. This load fraction was calculated relative to the functioning meters, and then applied to estimate the power during the period of logger failure.

The equipment failure experienced by team G highlights a practical difficulty in performing co-heating tests remotely, which is common due to access restrictions and the location of test sites. The value of a back-up measurement system is clear and especially pertinent given the time-consuming and invasive nature of the co-heating test. Remote monitoring would further alleviate this problem in wider practice.

Four teams (A, B, C and F) chose 25°C as their set point temperature, as suggested in the Leeds Metropolitan method (Johnston et al., 2012), while teams D, G and E used a value of 24°C, 26°C and 27°C, respectively. Teams G and E selected a higher internal temperature in an attempt to achieve an indoor / outdoor temperature difference of more than 10K, as recommended in the Leeds Metropolitan method, during periods of unusually high external temperatures.

Different methods were used to measure internal temperature; teams A, B, C, D and F each used a solar-shielded sensor at the centre of each room. Team E used five temperature sensors, three on the ground floor and two on the first floor, placed adjacent to the walls. Team G installed temperature sensors in only the five rooms with heating and mixing stations.

The measurement of weather conditions, in particular external temperature, solar irradiance and wind speed, forms an important part of the co-heating test method. The project provided the opportunity to investigate the effect of sensor placement on recorded weather conditions, as those measured by the testing teams could be compared to those recorded by the BRE's on-site weather station.

In practice, external sensor placement must often be a compromise. A typical house does not provide a secure, easy-to-access location, free from shading, wind obstructions and heat sources in which to temporarily mount valuable weather monitoring equipment. In co-heating testing this issue is most critical in the measurement of temperature, solar radiation and wind speed, as these are the measurements used in the subsequent data analysis. Therefore, a compromise must be sought between accurate measurement and on-site practicalities. For the test house in this project, the most common location chosen for external monitoring equipment was on the hand rails adjacent to the south facing facade of the building, shown in Figure 5-7.

Figure 5-7: The hand-rail used as mounting point for weather monitoring equipment on the south facing side of the test building can be seen in adjacent to the front door, a pyranometer has been mounted on it in the photograph.

The method recommended by Leeds Metropolitan University (Wingfield et al., 2010) for estimating infiltration is to use the blower door method (BSI, 2001b) to measure air leakage rates prior to, and following, a co-heating test. This is because the co-heating procedure may affect the air-tightness of a building by causing cracking or drying out of seals.

In this project, a variety of approaches were used. Pre and post blower door tests were carried out by teams A, B and F, while teams E and G carried out just one blower door test following their co-heating period. Teams C and D measured the air infiltration rate using the tracer gas decay method (Roulet and Foradini, 2002), with team C carrying out daily measurements and team D a single measurement. Teams B and F also carried out tracer gas decay measurements, but used the measurements from the blower door tests in calculating the heat loss due to infiltration. The format of the project had an influence on the choice of the air-tightness measurement method adopted, as teams considered that as the house had already undergone a sustained period of co-heating, and indeed a long history of testing in general, the air-tightness was therefore unlikely to be altered by their co-heating test.

In addition to the core measurements required when conducting the co-heating test, some teams chose to make additional measurements. Teams B, C and D carried out measurements of the in-situ U-value of external walls at various points using heat flux meters, team C also carrying out measurements on ceiling elements. Teams B, C, F and G carried out an infra-red (IR) thermal imaging survey of the test house. These measurements do not form an essential part of the calculation of the HLC in the co-heating method. However, they are necessary in order to carry out any diagnostic analysis of the causes of heat loss in the case of an unexpectedly high measured value for HLC. The constant, raised indoor air temperature used in the co-heating test is beneficial for both U-value measurements and IR surveys.

5.3.2. Results of the Methodological Comparison

In the previous section the methods used by each team to complete their co-heating tests were described and compared. In this section the effect of these variations in methodology on the result of the test are considered. As the analysis was carried out using only the information that each team chose to include in their project report, it was not possible to investigate the effect of every change in method.

Three teams: C, E and F, chose to report the degree of air mixing during their tests, as represented by the variation in temperature throughout the house. Team C, employing five heating stations, observed a slightly lower temperature in those rooms without heating and mixing stations. Team F used eight stations, enough to place one in each room, and observed good mixing throughout the space, with a temperature variation of less than 0.5^{o}C throughout the interior of the house. The level of mixing during team E's test, using only three stations, was not as great, with a variation of approximately 2^{o}C between the warmest and coolest rooms during the testing period. Close internal temperature control is vital in co-heating to ensure a measurement of the whole building's performance. It is clear that this is best achieved through the use of many heaters and mixing fans, with at least one in each large room, inputting heat evenly throughout the space. This finding supports that of Mangematin et al, and echoes the advice given in the latest LMU co-heating method statement (Johnston et al., 2012; Mangematin et al., 2012b).

These findings show the importance of supplying sufficient, evenly-distributed, heat to maintain an elevated internal temperature that is as uniform as possible throughout the house. Team C's observation of a lower temperature in rooms without heaters, whilst not particularly surprising, is significant. It is clear that in order to accurately measure the average internal temperature it is particularly important to measure temperature in *all* rooms when it is not possible to install a heater in each room, which is common due to equipment or other logistical restraints. In this project this has particular relevance to the results of teams E and G, who measured temperature in only the unheated and heated room respectively, which is likely to have led to an underestimate of internal temperature for team E, and an overestimate for team G. The impact on the final calculated HLC caused by an error in the measurement of internal temperature was shown in the sensitivity analysis in section 5.2 (around 5% per degree Kelvin), further highlighting the importance of an adequate and well-positioned measurement regime.

As described in section 5.3.1, four different internal set-point temperatures were used across the testing teams. The HLC values obtained using the various internal temperatures were plotted, but no statistically significant relationship was observed between internal set point temperature and the HLC values measured in this work.

As described in section 5.3.1, teams chose to install weather monitoring equipment in a range of locations around the house. Comparison of the temperatures measured by the testing teams with those measured by the on-site weather station shows good agreement, with an average difference of less than 5%. There was no observed bias towards a higher or lower value of temperature at any particular external location.

The location of weather monitoring equipment in close proximity to the house resulted in a particularly sheltered location for the measurement of wind speed and direction. The impact on the recorded wind speeds was clear, with the BRE weather station, which was mounted on a mast adjacent to and well above the test houses, gave wind speed measurements ranging from 12-71% higher than those of the testing teams. The difference shows the error that is likely to result from taking wind speed measurements in close proximity to obstructions.

There was not enough information available to take into account the accuracy and type of weather sensors used or the exact location and height that they were placed. However, it does suggest that sensor placement in this work had a significant impact on the recorded values of wind speed, but little impact on the recorded values of external air temperature. In all cases, each team used its own recorded weather data, as opposed to that of the BRE weather station.

5.3.3. Data Analysis Comparison

As shown by the methodological comparison, the experimental co-heating method published by Leeds Metropolitan University (LMU) (Wingfield et al., 2010) was generally adopted as the basis for the team's experimental method. However, this method does not include a detailed explanation of how to analyse the data collected to calculate the HLC of a house (a more recent LMU method statement (Johnston et al., 2013), published well after the completion of the project, does give data analysis guidance). In fact, at the time that the project was carried out, there was very little published guidance how to carry out the data analysis.

For that reason the data analysis carried out for this project varied more fundamentally than the experimental method. The main aims of the data analysis are to separate the infiltration and fabric heat loss, and to factor out the influence of varying weather conditions which affect the measured heat loss rate, such as solar heat gains and wind speed.

5.3.3.1. Calculation of Infiltration Rate

Two different methods were used to measure the infiltration rate, namely blower door tests and the tracer gas decay method (Roulet and Foradini, 2002). The infiltration rate as measured by both methods was very similar, though there was more variation in the results measured by the tracer gas decay method, as shown by the higher standard deviation (Table 5-8). This is to be expected as the blower door test applies a high pressure difference across the house in order to negate the influence of different wind speeds and external temperatures. In contrast, the tracer gas decay method measures the infiltration rate for the conditions that occur during the test.

Test Method	Mean (1/h)	Standard Deviation (1/h)
Blower Door	0.076	0.002 (3 measurements)
Tracer Gas Decay	0.076	0.01 (18 measurements)

Table 5-8: Infiltration rate as measured by blower door test and tracer gas decay methods. Blower door results converted to air change rate at ambient pressure difference according to the 1/20 rule of thumb (Sherman, 1987)**.**

Infiltration rate measurements can be used to disaggregate the HLC of the whole house into fabric and infiltration heat losses. However, despite each team carrying out some sort of infiltration rate measurement, only three teams; C, E and F; chose to report a disaggregated HLC.

5.3.3.2. Calculation of Solar Gain

The greatest variation in data analysis method was in accounting for solar gains occurring in the house. The techniques used to attempt this can be broadly categorised into five groups: i) multiple regression, ii) Siviour analysis, iii) Siviour plus regression, iv) analysis using measurements taken during the night or early morning only, and v) direct estimation of the solar gains through the glazed elements. As shown in Table 5-9, several teams chose to apply more than one data analysis method before selecting one method to calculate their final reported HLC; the analysis method finally selected by each team is highlighted with an asterisk (*).

	Data Analysis Method				
Team	**Regression**	**Siviour**	**Siviour + Regression**	**Night Only**	**Window Estimation**
A	✓	✓	✓*		✓
B	✓*				
C	✓	✓	✓*		
D		✓*		✓	
E	✓*				
F	✓	✓			✓*
G		✓		✓*	✓

Table 5-9: Summary of data analysis methods employed by each team, the method chosen by each team to calculate their final reported HLC is highlighted with an asterisk (*).

The 'multiple regression', 'Siviour' and 'Siviour plus regression' approaches have been described in detail in section 2.6.1. Three variants of solar gains through glazing estimation were employed (the facade method has been included in this category); each variant assuming that all solar radiation passing through the windows was an effective heat input to the building, and that solar gain through opaque elements could be ignored.

In the 'simple window model' method used by Team A, the measured global horizontal irradiation was translated into the irradiation falling on each facade containing glazing, according to the method set out in CIBSE guide A (CIBSE, 2006).The standard G-value (a measure of total solar energy transmittance – the proportion of incoming solar energy transmitted into the building) for wood framed, triple glazing and the measured glazed area were then used with this value for vertical irradiation to calculate the total solar gain passing through on an hourly basis (BRE, 2011). No account was made of shading from trees or other buildings.

Team G used a computer model of the building and surroundings, in the 'Ecotect' software, with the aim of more accurately taking into account window properties such as admittance value and solar energy transmittance factor, overshadowing, and the sun path at the time of year. As in the method of Team A, the standard G-value for the glazing type was used in the model. Team G considered that the building had no significant shading from foliage or other buildings, so this was ignored.

The 'facade solar gain estimation' method of Team F was described in detail in section 4.3.3, and is examined in more detail in Chapter 6.

Teams D and G reported the results of a data analysis method using data gathered only during the night or early morning. The stated aim of these methods was to remove the requirement for complex calculation of solar gains by simply using data during periods with no solar input. The night data approach of Team G used a time period from 22:00-04:00 hrs, which was selected in order to allow sufficient time for heat built up from solar gains during the day to dissipate. The early morning approach of Team D used data from 06:00-08:00 hrs, with the aim of finding data as far removed from the previous day's solar gains as possible while also preceding the gains of the current day.

The period chosen by teams to define the start and end of each day also varied, with periods of 00:00-00:00, 06:00-06:00, 09:00-09:00 and 18:00-18:00 hrs being used. Where the day definition varied from 00:00-00:00, the stated aim was to base the definition of the day around a completed diurnal cycle, allowing solar gains occurring during daylight to be released into the house during the night. This should help to contain the effect of solar gains to the day in which they have been accounted for.

5.3.3.3. Calculation of the Effect of Wind Speed

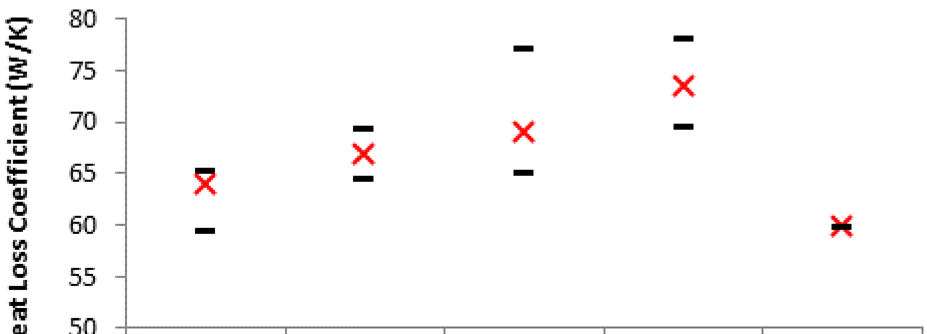
The effect of varying wind speed on the reported HLC value was accounted for by six of the seven teams using a multiple regression analysis, as described in section 2.6.1. Team C did not carry out an adjustment to their reported value, as they observed a weak correlation between average daily wind speeds and heating power, which they considered made an adjustment unnecessary.

5.3.3.4. Reporting of Measurement Uncertainty

Only two teams, C and D, reported their HLC result with a stated uncertainty range, in each case defined as one standard error in the average daily internal-external temperature vs. heating power regression, to either side of the reported HLC. This could reflect the difficulty in accurately defining the measurement uncertainty of the test, particularly due to the contribution of solar gains. The margin of uncertainty in the test results is therefore associated not only with the accuracy of the equipment used, but also the data analysis methods employed to translate measurements of irradiance, infiltration rate and wind speed into effects on the heat loss coefficient.

5.3.4. Calculated HLC and Data Analysis Method

As shown in Table 5-9, several teams applied more than one data analysis method before selecting one as their chosen method for their reported 'headline' HLC value. The extended set of results is summarised in Figure 5-8, where 'sample size' refers to the number of teams applying the particular method in question.



	Multiple Regression	Siviour + Regression	Siviour	Window Estimation	Night Only
Max (W/K)	65.3	69.3	77.1	78.0	59.9
Mean (W/K)	63.9	66.9	68.9	73.4	59.9
Min (W/K)	59.4	64.4	65.0	69.6	59.9
Standard Deviation (W/K)	3.8	3.5	5.0	4.3	N/A
Sample Size	5	2	5	3	1

Figure 5-8: Comparison of calculated HLC disaggregated by data analysis method. The mean result is shown with an 'X', and the range of results is shown by horizontal lines. Note that the y-axis has been truncated to allow the differences to be observed, this may artificially increase the appearance of the variation between results.

Figure 5-8 suggests that there was a systematic difference in the calculated HLC values resulting from the analysis approach used (though this could also be caused by the variation in data collection methods and weather conditions during the tests). The 'window estimation' method resulted in the highest HLC, and the 'multiple regression' resulted in the lowest HLC, with the 'Siviour plus regression' and 'Siviour' methods giving values between these two. There was only one application of the 'night only' method, after the removal of Team G's result from the analysis, which gives the lowest estimate of the HLC for these tests.

No statistically significant relationship was found between the times chosen to delineate the start and finish of a day and the calculated HLC value.

It is clearly not possible to definitively state the 'correct' value for HLC and therefore announce which of the analysis methods is the most accurate. Given the relatively small sample of applications of particular methods, neither is it possible to be completely certain about the relationship suggested between data analysis method employed and the HLC value obtained. What is important, however, is that Figure 5-8 shows that, even with this extended set of reported results, the range of variation in HLC values obtained is ±15% from the mean HLC, which was 67.9W/K (this is the mean of all calculated HLCs, by every data analysis method). This is a small variation in comparison with the previously measured difference between predicted and in-situ performance of up to 120%, which the co-heating test is likely to be used to detect. This implies that the co-heating test is reasonably robust to different measurement methods and weather conditions, and also to different data analysis techniques. It is therefore reasonable to suggest that, if standardised testing and data analysis approaches were defined and employed, then an even better degree of reproducibility than that observed in these tests could be achieved in HLC testing.

5.4. Recommendations for Best Practise Co-Heating Testing and Data Analysis Method

As well as providing the evidence to estimate the accuracy of a co-heating test, this study has considered a wide range of approaches to carrying out a co-heating test. Therefore, based on the findings, the following recommendations are made for the experimental method and data analysis techniques for use in co-heating testing. These recommendations are intended as additions to the current standard practice (Johnston et al., 2012). In particular, alongside the description given here, they provide clearer guidance on how best to approach the data analysis element of co-heating

- To ensure an even temperature distribution throughout the house under test, it is recommended that electric fan heaters are used in each room as far as possible, with additional fans used to mix the air. These should be positioned so that the airflow is not aimed directly on wall surfaces in order to avoid increasing convective heat exchange at the surface.

- PID control of the electrical heaters is recommended, with an internal set point temperature chosen to achieve a mean daily internal-external temperature difference of at least 10^{o}C at the time of the test.

- Back-up sensors or remote monitoring is recommended for all key measurements, in order to reduce the risk of data loss, and the consequent extension in the testing period that would be caused, in what is already a long and invasive test.

- Whenever possible, external air temperature should be measured on site, using a shielded temperature sensor located a short distance from, and beyond the influence of, the building. An unshaded south facing pyranometer mounted on a vertical plane should also be included if practicable.

- Infiltration should be measured at the start and end of the test in order to calculate infiltration heat loss. By blocking vents, as is standard practice in carrying out the blower door method (ATTMA, 2010), the building is not operating normally. It is therefore recommended that vents remain unblocked during the infiltration rate measurement in order to ensure a measurement of the performance of the house as it will be used. If vents are blocked during the blower door test, this should be considered when using the results to predict energy demand (i.e. ventilation heat loss should be calculated and added).

- The elevated and stable indoor air temperature during a co-heating test offers an ideal opportunity for additional measurement of wall U-values by the heat flux method, and for conducting IR surveys to identify thermal bridges and thermal bypasses.

- It is recommended that each data analysis type described in this thesis is applied, and the full set of results reported when completing a co-heating test. This would allow direct comparison between tests carried out by different organisations and does not require any additional measurements or significant further data analysis to be undertaken.

5.5. Summary

The purpose of this chapter is to empirically develop an estimate of the uncertainty of the measurement of HLC by the co-heating test. In practise this task breaks down into two parts:

a) Defining the measurement uncertainty.
b) Estimating the reproducibility of the test.

The measurement uncertainty is defined by the accuracy with which each of the constituent measurements of the energy balance that underpins the co-heating test can be taken. As the heat loss is not measured directly, but rather inferred by measurement of the heat input to the house, defining the measurement uncertainty is not a simple matter.

A sensitivity analysis has been applied to investigate the influence of what are thought to be the three most significant measurements; the internal to external temperature difference, the electrical heat input, and the heat input due to solar gains. The analysis found that a reasonable estimate of the uncertainty associated with both the internal-external temperature difference and the electrical heat input resulted in a change in the calculated HLC of approximately ±5%, across the four most common analysis types. The uncertainty associated with estimating solar gains was found to be slightly higher, ±9%, reflecting the requirement for further research into the best method to account for this heat input. The final result of the sensitivity analysis is an estimated measurement uncertainty in the HLC by a co-heating test of -11%, +12%, for the building in question.

It is important to note that this estimated uncertainty is related to the building and conditions in which the data was collected. While these factors will not affect the uncertainty in the measurement of temperature or energy consumption, they could impact upon the measurement of solar gain as there is a set of shading and window conditions which are specific to the building and location. In order to build confidence in the estimated uncertainty it would be desirable to repeat this analysis on data collected in different buildings, and in particular in buildings of different forms, although that could introduce an additional source of variation derived from the set-up of the testing equipment. The fact that this data was collected continuously using the same equipment is seen as a strength of this analysis. As the data was collected over a period which included summer months, which have typically been thought unsuitable for co-heating, it is likely that -11%, +12% is a rather large estimate of the uncertainty in the HLC measurement. The uncertainty may be reduced if testing was restricted to the winter months.

The *reproducibility* of the test refers to the precision of the measurement given variations in location, operators and equipment across several tests (BSI, 2000), and hence incorporates both the measurement uncertainty and variation which could be introduced by changes in experimental method, data analysis, or the conditions during the testing period. This could be regarded as a more practical metric than the theoretical measurement uncertainty. The reproducibility of co-heating tests was investigated using a methodological comparison of each of the participating teams in the NHBC co-heating project, and a statistical analysis of the reported results. This analysis showed a reproducibility of the test, again in this particular building, of ±10%, despite significant variations in the methods used to collect and analyse data used by the various teams. This agrees closely with the estimated uncertainty derived from the sensitivity analysis (-11%, +12%). Taking both the observed reproducibility and the results of the sensitivity analysis into account, an estimated uncertainty in the co-heating test of approximately ±10% seems reasonable.

The range in the results presented here may appear lower than that reported in the NHBC report of the project (Butler and Dengel, 2013). This is because a different method of reporting the range in the results has been used in the two analyses. In this thesis, each measured result has been compared to the mean of all measured results, while in the NHBC report the HLC as calculated by SAP (BRE, 2011) is used as the benchmark for comparison. A method of benchmarking based upon a predicted HLC was considered inappropriate for this project, given the evidence for a performance gap between predicted and in-situ performance.

The lessons learnt through the methodological comparison have led to the recommendations for a best practise co-heating method set out in section 5.4. Clearly, if all results were collected according to a more rigidly defined testing methodology, it is likely that the observed reproducibility would be improved. In general, the recommendations are based upon good experimental procedure, designed to allow closer control of internal conditions, and provide methods to ensure that data is successfully collected during the testing period. This is particularly important for co-heating due to the invasiveness of the test and the limitations on testing period which are therefore likely to be applied.

The 'Siviour plus regression' data analysis method appeared to give the most consistent results in this project, and a result which was similar to the mean result of all methods. However, due to the structure of the project, it is not possible to state conclusively which method is most accurate. It is therefore recommended that the analysis method used in a co-heating test is clearly stated to allow direct comparisons to be carried out. Ideally, each data analysis method should be carried out, and all results reported, to further facilitate this. This is not thought to be overly onerous, as the time and effort required is extremely limited in comparison to that required to collect the data.

Although the 'night data only' analysis approach significantly simplifies the calculation of the HLC, it relies upon the definition of a steady-state period, independent of the influence of the preceding day's solar gain. This state seems unlikely given the high thermal time constant of many typical constructions; indeed, the lack of steady-state condition is the reason that co-heating tests are carried out over an extended period. In infra-red thermography, it is recommended that testing is not carried out for a period of 12 hours after a surface has been exposed to direct sunlight (BSI, 1999), this stipulation leaves a very small time window in which to carry out a co-heating test. Even when proposing an approach using only data collected in the early morning, with mean values between 06:00-08:00, team D considered that this would assume a very thermally lightweight building. Furthermore, this approach would have to be adapted for much of the typical co-heating season, where sunrise occurs before 08:00 hrs.

The work presented in this chapter has led to a reasonable estimate of the uncertainty to be expected of co-heating tests in their present form, of ±10%. It has also added to confidence in the method used to define the benchmark measurements which are used throughout the rest of the project. Both are vital in providing a benchmark against which alternative methods can be compared.

Chapter 6 Solar Gains in Co-Heating

Traditionally co-heating has only been applied during the winter months. This approach is adopted for two reasons:

- To enable a sufficiently large temperature difference between inside and out.
- To reduce the 'noise' introduced into the test through difficult to quantify solar gains. By testing in the winter months the proportion of the total heat input to the building from the accurately measured electrical heating input is maximised, and the contribution from solar gains minimised.

Though these measures are likely to improve the accuracy of the test, they apply significant practical limitations to its widespread use. For example, it seems difficult to legislate for a compliance test for newly built houses that can only be carried out during seven months of the year (the length of the typically defined heating season, October-April (BRE, 2011)). It is clear then that addressing this issue of seasonality would be a significant step towards addressing concerns surrounding co-heating's widespread application.

The issue of achieving a significant internal-external temperature difference can be simply dealt with through the application of a higher internal set-point temperature, as it is the temperature difference which is important in heat transfer calculations (though this does raise the possibility of damaging the building's fabric by rapid drying, particularly in new builds).

It is the issue of noise generated by solar gains which represents the greatest difficulty at present. This issue can be further broken down into two parts: i) accurately accounting for the amount of heat introduced to the building through solar gains, and ii) understanding how the HLC is affected by charging and discharging of the house's thermal mass due to significant solar gains.

In this chapter, the development of a new data analysis method which seeks to address the first part of the issue, accurately accounting for the heat input due to solar gains, is presented. The aim of the *facade solar gain estimation method* (referred to as the 'facade' method for the sake of brevity) is to improve the estimation of solar gain through more accurate measurement of the solar irradiation incident on each facade of the building being tested.

The data from the long-term continuous co-heating test carried, out as a part of the NHBC Co-Heating Project, allowed a comparison between the facade method and other, currently commonly-used testing methods, over a wide range of weather conditions occurring over a seven-month period. For this comparison, a range of analysis methods were applied to two-week subsets of the dataset, and the results compared. This dataset allows a picture to be drawn of how the results of a co-heating test, according to each data analysis method, can vary throughout the year as external conditions change. The analysis of the long-term co-heating test dataset is reported in section 6.1.

In order to further trial the new method, repeat co-heating tests were carried out in two test houses in Loughborough. For each house three tests were carried out according to the same experimental method; the tests were spaced such that one was carried out in winter, one in the summer and one in a transitional period (spring or autumn). As for the long-term co-heating test dataset, the data was analysed according to the new 'facade' method and the most common current methods, and the results compared. The results of these inter-seasonal, repeated tests are reported in section 6.2.

The facade method has two variants, the first of which uses measurements of solar irradiance taken on each vertical facade with glazing, and a second which uses translated values for irradiance incident on each facade calculated from a measurement of global solar irradiance (as described in detail section 4.3.3). A comparison between the performance of these two variants of the facade method is reported in section 6.3.

The chapter is completed by a summary (section 6.4).

6.1. Long Term Co-Heating Testing (NHBC co-heating project)

The data from the long term co-heating test, carried out continuously over a period of seven months as a part of the NHBC co-heating project, was used in an investigation into the reproducibility of the co-heating test, given a varying set of weather conditions during the measurement period. The data from the long term test was broken down into a series of 14-day subsets, with the HLC then calculated for each subset using four different methods to account for solar gains. This allows a picture to be developed of how the measured HLC would have varied over the period of the test depending upon the chosen start date, given that the minimum recommended measurement period for the test (14 days) was used, after the method described by Johnston et al. (2012). The four data analysis methods for calculating solar gains were applied to allow a comparative evaluation of the success of each. The methods applied were the multiple regression, Siviour, Siviour plus regression and facade methods.

In order to show the variation in calculated HLC at the highest possible resolution the two-week sample periods overlap; where each sample represents a moving two week window on the data, with the window moving forward by one day for each time. The application of this moving window is shown in Table 6-1, which also shows that this approach results in a total of 164 14-day samples.

Sample Number	**Sample Period**	**Position on x-axis**
1	12/2/2012 – 25/2/2012	25/2/2012
2	13/2/2012 – 26/2/2012	26/2/2012
3	14/2/2012 – 27/2/2012	27/2/2012
↓ Sampling method applied in the same way across sample ↓		
163	28/8/2012 – 10/9/2012	10/9/2012
164	29/8/2012 – 11/9/2012	11/9/2012

Table 6-1: An example of the 14 day sampling periods and where each sample is located on Figure 6-1.

As there is no agreed method of defining the HLC, it is not possible to define the 'correct' value, and analyse the variation in results by each data analysis method with respect to this point. However, it can be seen that where the conditions are most suited to co-heating – with low external temperature and solar irradiance – the results of the three analysis methods converge to an HLC of approximately 63W/K (as shown in Figure 6-1). Therefore this is considered the best estimate of the HLC of the house and is shown in the plot of the results of the investigation (Figure 6-1).

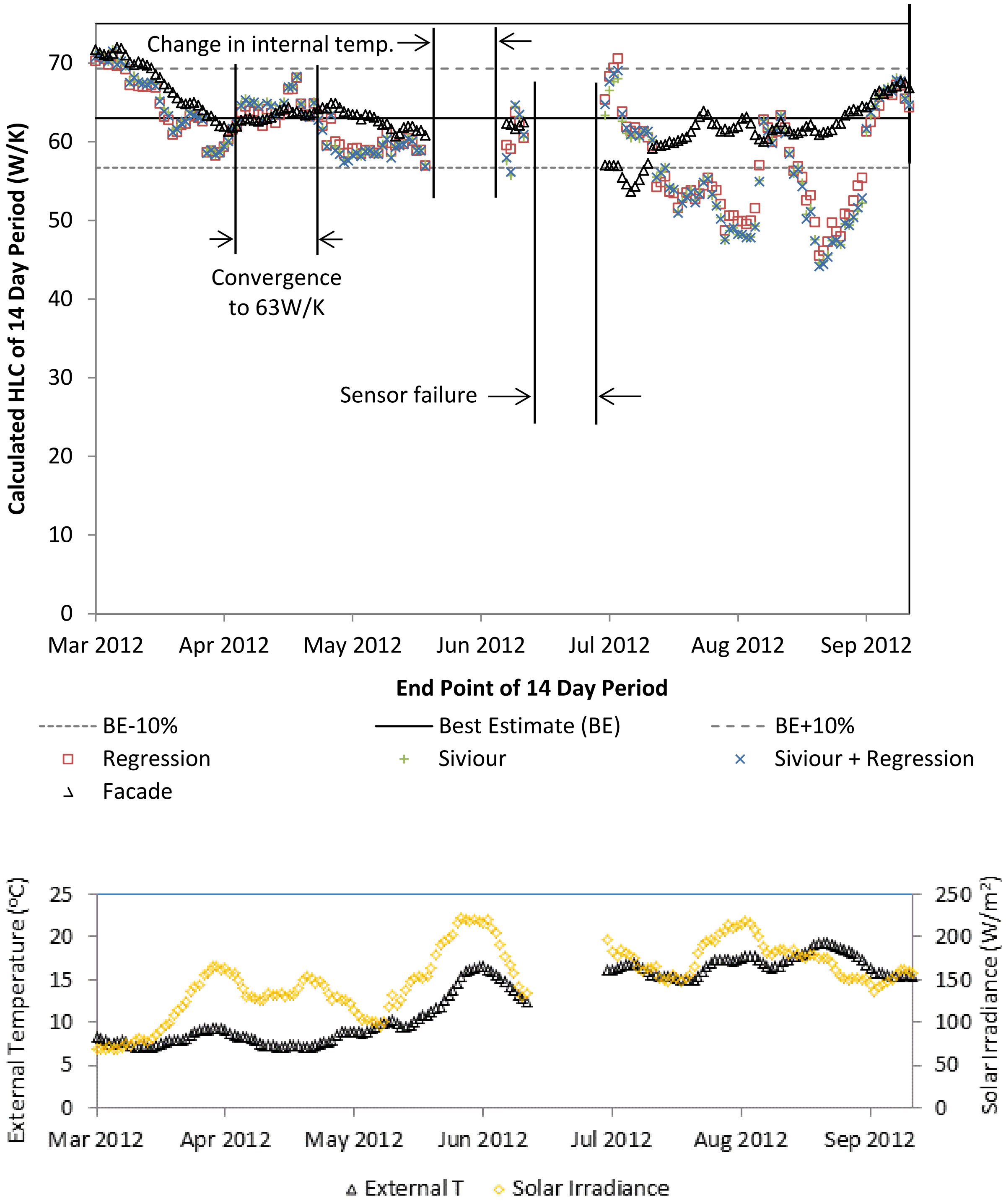


Figure 6-1: A comparison of the results of long-term co-heating in test house 50.3 at the BRE Garston site using each data analysis method. The mean external temperature and global solar irradiance over the entire corresponding 14 day sample period are shown in the lower chart.

There were two periods in the test when the HLC could not be calculated, 22/5/2012-8/6/2012 and 14/6/12-1/7/12; these were caused by a change in internal temperature (from 25°C to 30°C) and logger failure respectively. All data collected after the transition in internal temperature was collected at the increased level of 30°C.

It should be noted that the weather data displayed in Figure 6-1 represents mean measurements taken over a fourteen day period. This approach allows a direct comparison between the HLC measurements calculated by different analysis methods during periods of different prevailing weather conditions. This approach cannot be used to investigate the effect of changes in weather conditions on a shorter time basis though, i.e. two data points in Figure 6-1 could have the same mean external temperature and solar irradiance and yet represent two-week periods with significantly different day to day weather patterns. This could explain some of the variation shown in the calculated HLC values in Figure 6-1. For example, the regression-based methods require a variety of different conditions to occur to allow a regression to be accurately applied, as described in section 2.6.1 (Bauwens et al., 2012; Butler and Dengel, 2013). This effect cannot be identified by using the mean values taken over a fourteen day period, as in Figure 6-1.

Initial inspection of Figure 6-1 shows that the facade calculation method seems to offer the most repeatable estimation of the HLC. This is particularly noticeable during the period outside the traditional heating season - between May and September 2012, which are the summer months with higher external temperatures and levels of solar irradiance. During this period the HLC as calculated by the other analysis methods varies wildly (up to 50%) from that measured during the winter. In addition to the large variation from the winter value, there is also a large scatter between data points, so that although a value close to the best estimate is reached in some samples, adjacent samples often differ considerably. This shows a lack of both accuracy and reproducibility in the results. In contrast, the facade data analysis method results in a much more consistent and repeatable HLC value.

A statistical investigation of the results supports these observations (detailed in Table 6-2). The mean result of the facade method is closest to that of the best estimate and also has a significantly lower standard deviation. Furthermore, despite much of the testing being completed outside of the usual co-heating season, the result of the facade method falls outside of a ±10% tolerance band (compared to the best estimate of the HLC of 63W/K) in only 20 of the 155 samples, and is within ±15% for all 155 samples. This compares favourably with the results of the other three methods, which fall outside of a ±10% zone in around a third of all samples, and outside of a ±15% zone in 17-19% of all samples.

Analysis Method	Regression	Siviour	Siviour +Regression	Facade
Mean of all samples (W/K)	60.1	59.9	58.8	63.2
Standard deviation (W/K)	5.9	6.5	6.5	3.5
Samples outside ±10%	49	50	51	20
% outside ±10%	32%	32%	33%	13%
Samples outside ±15%	27	29	30	0
% outside ±15%	17%	19%	19%	0%

Table 6-2: Summary statistics of the results presented in Figure 6-1; the tolerance bands of ±10 and ±15% are around the best estimate of the HLC – 63W/K. Total sample size 155 for each analysis method.

This initial analysis shows that the facade method offers the most repeatable results in this situation. However, it is clear in Figure 6-1 that even using this analysis method there is a variation in the calculated HLC over the samples. Further statistical analysis was attempted to investigate the causes of the variation in calculated HLC using each analysis method.

Due to the cross-correlations between variables (e.g. between higher external temperature and global solar irradiance), and the lack of independence in the samples due to their overlapping, it is not possible to analyse this data using statistical tests for correlation. An alternative graphical approach was therefore adopted. The HLC calculated for each 14 day sample, by each of the four data analysis methods, was plotted against a range of mean conditions over the sampling period. The conditions were internal-external temperature difference (delta T), solar irradiance, wind speed and electrical heating power. This approach allows the over-arching relationships between the conditions during the tests and the results of each of the analysis methods to be clearly illustrated (Figure 6-2) (though it does not allow investigation of the effect of changing weather conditions over shorter time periods).

Ideally, co-heating tests should be able to be carried out in any weather conditions and result in the same answer. Therefore, when looking at the following plots (Figure 6-2), the best possible pattern would be a tight cluster of results along a horizontal line, indicating that there is no relationship between the calculated HLC and the condition being considered, and hence that the effect of the condition has been perfectly accounted for by the analysis method.

This comparison is designed specifically to investigate different methods of accounting for solar gains during co-heating tests. Therefore, no further correction to account for wind speed (as described in section 2.6.1) was carried out.

As each of the conditions considered in this analysis use different units and are of different scales, the regression coefficients of each condition versus the HLC could not ordinarily be compared. A direct comparison would be useful to observe which condition variable has the strongest impact on the calculated HLC. Therefore, to enable direct comparison, the averaged conditions for each 14 day sample have been standardised using (EQ 6-1) (Ravid et al., 2010).

$$z = (x - \mu) / \delta \qquad \text{(EQ 6-1)}$$

where z is the standard score, x is the raw score (i.e. the original measurement), μ is the mean of all samples, and δ is the standard deviation of all samples. By using a standardised version of the condition variable, the linear regression coefficient gives a measure of the change in the HLC per standard deviation increase in the condition variable being considered. As all of the standardised condition variables are compared to the same property, the HLC in this case, it is not necessary to also standardise this value.

The four comparisons are shown graphically in Figure 6-2. Linear mean regressions have been taken, with the lines of best fit shown in the Figure and the statistics summarised in Table 6-3. Due to the lack of independence in the samples, the regressions give a clear visual impression of the general trend of the results, but are not statistically significant.

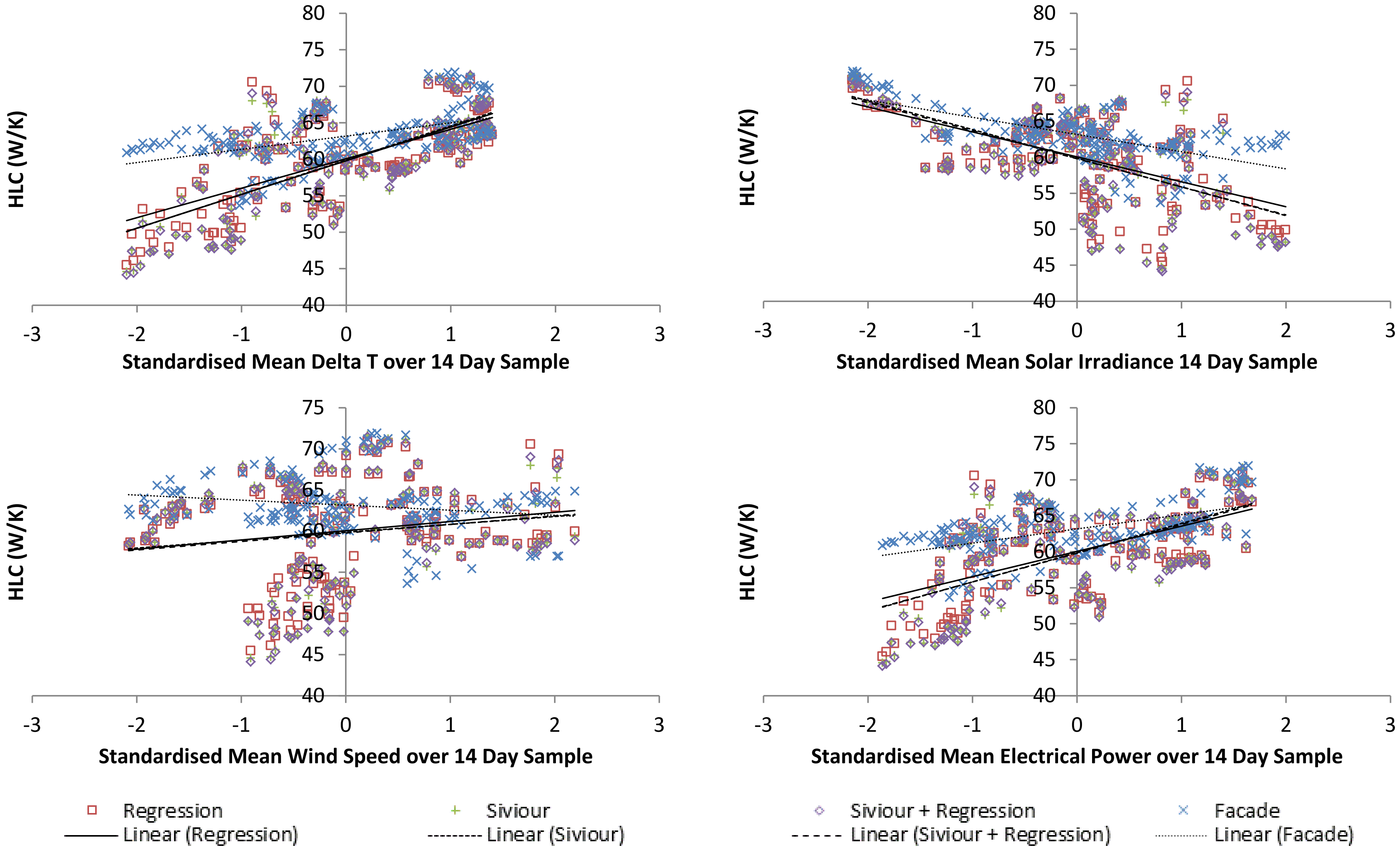


Figure 6-2: Calculated HLC by four data analysis methods vs. four condition variables, where each data point represents the standardised mean of the condition for one 14 day sample.

	Analysis Method	Regression	Siviour	Siviour + Regression	Facade
Delta T	Regression Coefficient	4.04	4.68	4.62	1.82
	Constant	60.1	59.9	59.8	63.2
	R^2 Value	0.473	0.524	0.508	0.267
Solar Irradiance	Regression Coefficient	-3.47	-3.99	-3.91	-2.39
	Constant	60.1	59.9	59.8	63.2
	R^2 Value	0.349	0.380	0.364	0.456
Wind Speed	Regression Coefficient	1.12	0.958	1.04	-0.612
	Constant	60.1	59.9	59.8	63.2
	R^2 Value	0.037	0.021	0.026	0.03
Electrical Power	Regression Coefficient	3.51	4.06	3.99	1.97
	Constant	60.1	59.9	59.8	63.2
	R^2 Value	0.357	0.394	0.379	0.311

Table 6-3: Results of the linear regression analyses shown graphically in Figure 6-2.

A visual inspection of Figure 6-2 provides some reasoning for the observation made from Figure 6-1, where the facade method appeared to offer the most consistent results throughout the year. In each of the charts shown in Figure 6-2 the facade method has the weakest relationship with the condition variable it is plotted against. This visual conclusion is supported by the regression coefficients presented in Table 6-3, though it should be noted that the R^2 value for many of the regressions is rather low, indicating a low level of fit with the data.

A comparison of the regression coefficients for each of the condition variables shows that mean wind speed seems to have the smallest effect on the calculated HLC, across all analysis methods. Furthermore, the extremely small R^2 values for the regressions confirm the visual impression that there is no clear relationship between wind speed and HLC for any analysis method. Given that a correction for solar gains has been applied when calculating these HLCs, it can be said that the wind speed during this co-heating test had no clear impact on the measurement of the HLC.

The regression coefficients for the other three condition variables considered are of rather similar magnitude when considered for each analysis method in turn – e.g. for the Siviour method the regression coefficients for solar irradiance and electrical power are similar.

Looking in more detail at Table 6-3 it can be seen that the regression, Siviour and Siviour + regression methods all display a similar relationship to the four condition variables considered. This is perhaps unsurprising given that they are based upon similar statistical premises. Of all of these methods, the regression method shows a slightly weaker relationship with the conditions variables than the Siviour or Siviour + regression. This provides evidence for why the mean HLC across all samples calculated using the regression method was closer to the 'best estimate' for the HLC of the house of 63W/K, with lower standard deviation than for the Siviour and Siviour + regression methods.

Using the standardised regression coefficients for the comparison; the mean internal-external temperature difference proved to be the most powerful explanatory variable, followed by the mean electrical power consumption, the mean solar irradiance and finally the mean wind speed. However, given the issues of co-correlation already discussed and the minute differences in the coefficients it is not possible to draw any really firm conclusions as to which condition variables have the most effect on measured HLC from this data.

Applying the same comparison metric to the results of the facade method, it can be seen from the data in Table 6-3 that solar irradiance seems to have the biggest impact on the measured HLC. This is clear to see graphically in the charts presented in Figure 6-2. However, this relationship is still weaker for the facade method than for the other three.

A particular issue when considering these relationships is the strong co-correlation between condition variables. For instance, it is likely that a relatively high internal-external temperature difference (caused by a low external temperature difference), will occur at the same time as a high solar irradiance – this is a rather convoluted way to say that it is sunnier and warmer in the summer than it is in the winter! Therefore, the relationship between calculated HLC and solar irradiance and internal-external temperature difference could be considered together (the top left and top right charts in Figure 6-2). There is a clear positive correlation between HLC and temperature difference, and a clear negative correlation with solar irradiance for all analysis methods; combined, this suggests that co-heating tests carried out in warmer, sunnier periods will result in a lower calculated HLC. The relationship between HLC and electrical heating power also shows this finding, there is a positive correlation for all analysis methods, so that when a higher heat input is required a higher HLC results. This would be the situation in cold weather, with low solar gains, where more heat is required to maintain a constant internal temperature.

However, typically, 'scratch a little deeper' and the story is not quite as simple as that. The calculation of solar gains, that is the effective heating load to the house in Watts caused by the sun, are very closely, *but not directly*, linked to the global solar irradiance during the test. That is because global solar irradiance is measured on a horizontal plane, but the larger part of the solar gains into a house occur through the glazed elements of the house (indeed, the facade method assumes that all solar gains occur through the glazed elements), which are most commonly vertically orientated on the facades of the house. This means that the angle of the sun at any particular time has a significant impact on the amount of solar gains. During the winter, the sun is at a lower angle for a longer part of the day, and hence shines more directly on the vertical facades in which the glazed elements are located. The effect is that the solar gains are relatively higher during winter, when compared to the level of global solar irradiance. This could be further complicated by shading from trees, which changes size with leaf growth in the summer months, and varying cloud cover. The variation in solar gain, as calculated by each of the analysis methods being considered, is shown in Figure 6-3. The solar gain as calculated by the Siviour and Siviour + regression methods are the same, and are shown by a single trace.

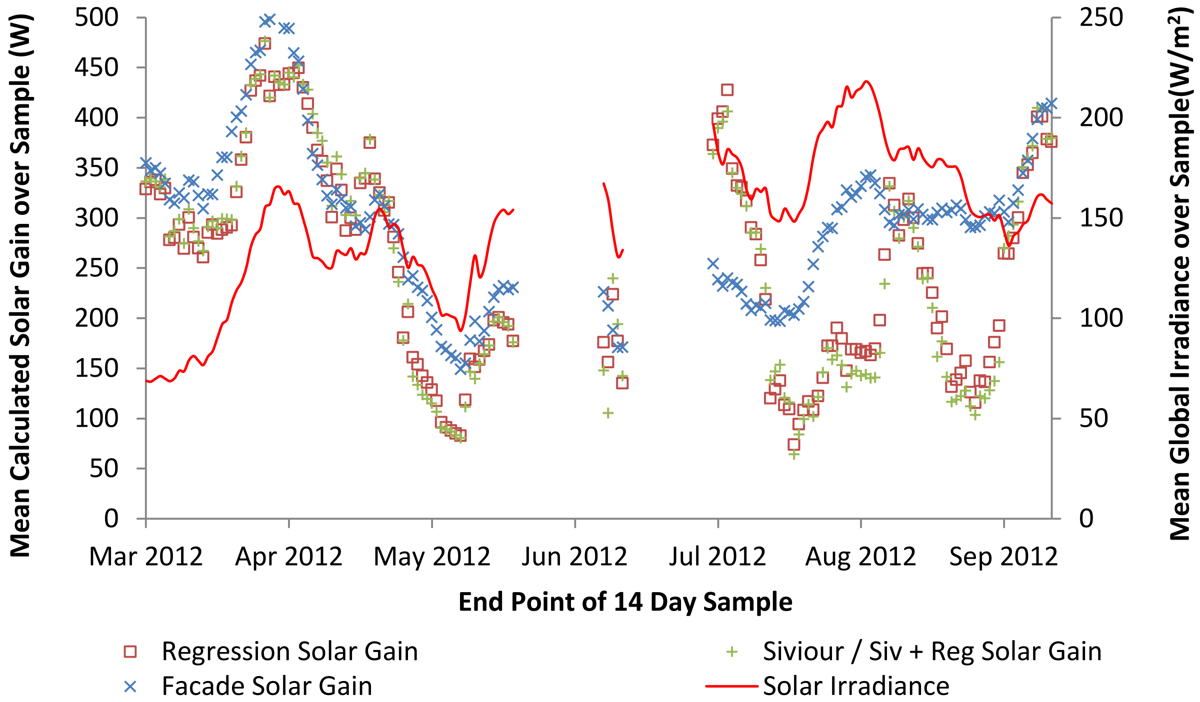


Figure 6-3: Variation of calculated solar gain by each of the data analysis methods compared to mean global irradiance over the corresponding 14 day sample.

This disconnect between global irradiance and calculated solar gain can be seen clearly in Figure 6-3, when one considers that a similar level of irradiance in April results in a significantly higher solar gain than in July, across all analysis methods. Indeed it can be seen that there is not a large difference in the solar gain occurring across the whole period of the test.

It is interesting to note that there is a closer agreement between the solar gains calculated by each of the analysis methods during the months which have been traditionally used for co-heating (March and April, at the left hand side of Figure 6-3). While during the summer months (in the centre of Figure 6-3) there is generally a significant difference between the solar gain as calculated by the façade method and that calculated by the regression, Siviour and Siviour plus regression methods. This observation could be explained by the statistical issues associated with applying multiple regression techniques to co-heating data, which were described in section 3.1.1. When applying multiple regression it is assumed that the independent variables, in this case internal-external temperature difference and global solar irradiance, are not correlated. While this may be true in most cases during the winter, it is likely that the assumption will be violated during the summer months when external temperature and global solar irradiance are more closely linked. Indeed, this is an issue highlighted in Leeds Beckett University's method statement, in which multiple regression is suggested as a suitable data analysis method (Johnston et al., 2013).

As has been noted throughout this section, each condition variable has a relation to the others. In Figure 6-4 the percentage of total heating power (electric + solar) that is caused by solar gains is shown for the most common data analysis methods. This relationship is important as the calculation of solar gains has been shown to be a significant source of uncertainty for all data analysis methods. Therefore, if a greater proportion of the total heat input to the house is due to solar gains rather than accurately measured electrical heating the uncertainty of the measurement of the HLC will be increased.

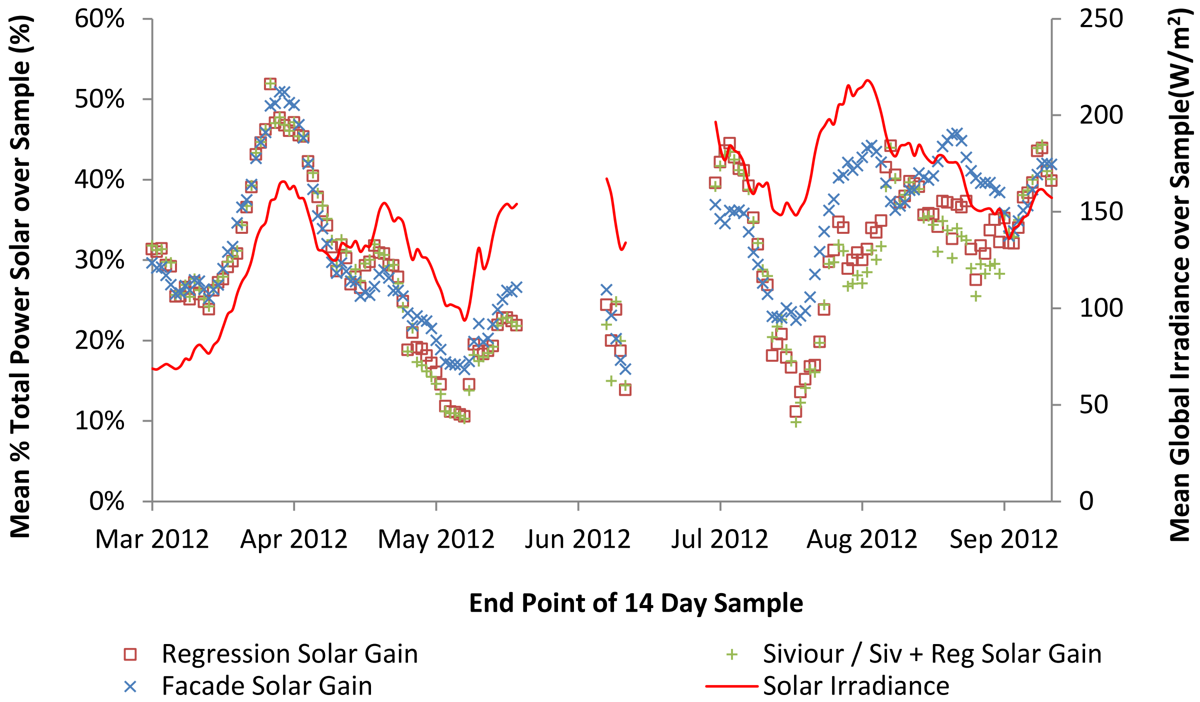


Figure 6-4: Variation of the mean percentage of total heating power caused by solar gains over each 14 day sample, by each of the data analysis methods compared to mean global irradiance over the corresponding sample.

It can be seen in Figure 6-4 that the percentage of total power that is contributed by solar gains generally increases in the summer months towards the right of the graph. This is due to a complex interaction of the condition variables. Higher external temperatures result in a lower internal-external temperature difference and hence total heating demand, while higher irradiance may also lead to a higher solar gain – though not in a simple manner as has been discussed. This higher fraction of total power caused by solar gains in turn leads to a decrease in the electrical power consumption, which was shown to be associated with a decrease in the measured HLC in Figure 6-2. This effect is likely to be more pronounced in highly performing (better insulated) houses where there is a lower heat loss rate. One possible solution to this would be to use a higher internal temperature set point; this would ensure that the electrical heat input remained higher, meaning that the uncertainty in the energy balance would be reduced. The disadvantage of this approach is the possibility of damage to the house caused by such high temperatures, especially by rapid drying in new-build properties.

The risk of this could be mitigated by reducing the amount of time at a raised internal temperature; as can be seen in Figure 6-5, the internal-external temperature difference is rarely lower than the suggested minimum of 10°C, even during the summer months. (It should be noted here that the internal set-point temperature was raised to 30°C in late May to ensure a higher temperature difference over this period.)

This change does not, however, reach the heart of the issue. As has been shown in this chapter, it is the combination of all external conditions that affects the measurement of the HLC. Figure 6-6 further illustrates this observation. Comparison with Figure 6-5 shows that the electrical heating load, while closely related to the temperature difference, is not completely dependent upon it. It is this electrical heating load which is key in defining the uncertainty in the energy balance which is used to calculate the HLC. The electrical heating power is the 'signal' which is inputted to allow the measurement of HLC, and can be thought of as a proxy for the combined effect of external temperature, solar irradiance and other variables which may affect the energy balance. Therefore, perhaps the most effective control strategy would be to apply a minimum electrical heating load which would override the set point temperature, thus ensuring a strong enough 'signal' to ensure that the energy balance can be applied with the desired level of certainty.

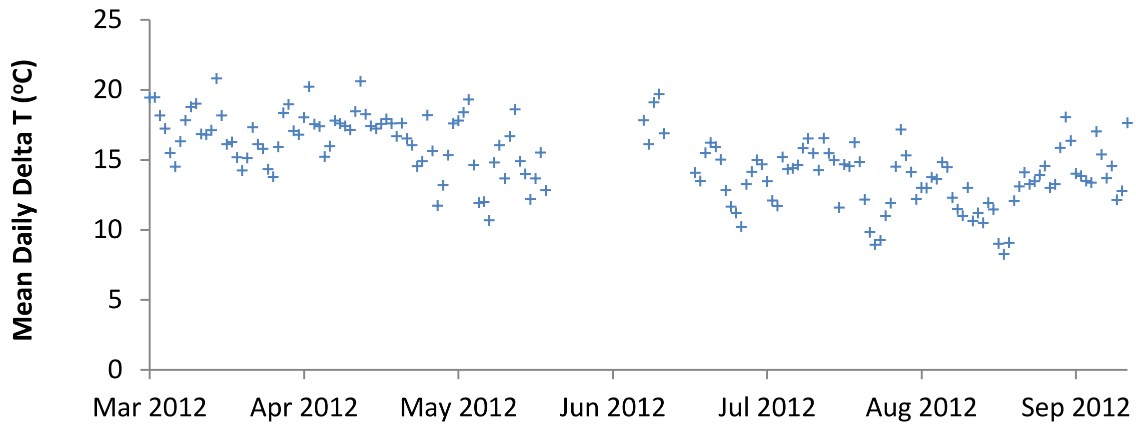


Figure 6-5: Variation of mean daily internal-external temperature difference (delta T) across the testing period.

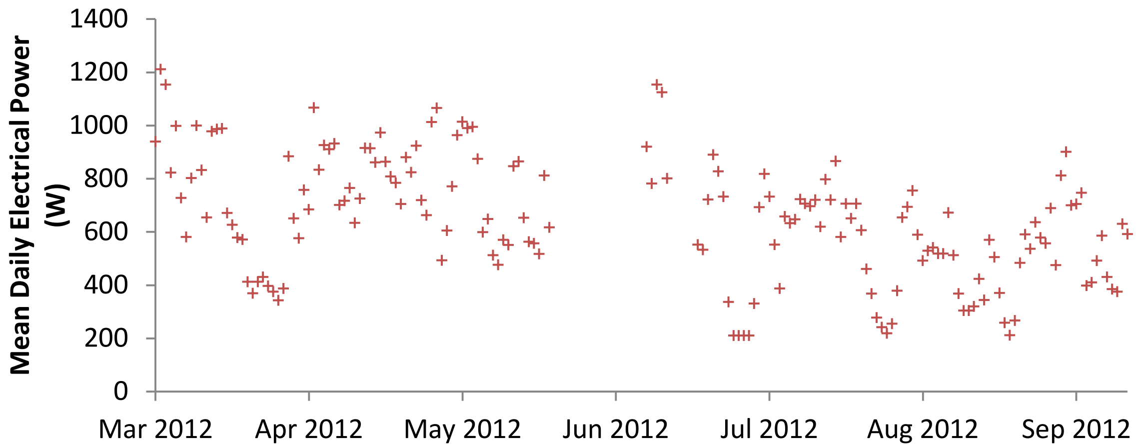


Figure 6-6: Variation of mean applied electrical heating power across the testing period.

The investigation presented in this section has shown that there is not yet a perfect method to account for solar gains in co-heating. Each of the four data analysis methods considered here show a residual relationship with various condition variables after the solar correction has taken place, in particular solar irradiance and internal-external temperature difference. However, the facade solar gain estimation method, developed as a part of this research, has been shown to provide the most repeatable results. Furthermore, in the house that this test was applied, the method resulted in an HLC within ±15% of the best estimate for every 14 day sample taken, including many from summer months previously thought unsuitable for co-heating. The method also resulted in an answer within ±10% of the best estimate for 87% of all samples.

Figure 6-7 shows the monthly mean HLC according to each of the four methods, and shows perhaps most clearly of all the consistency in the result as calculated by the facade method, when compared to the other methods.

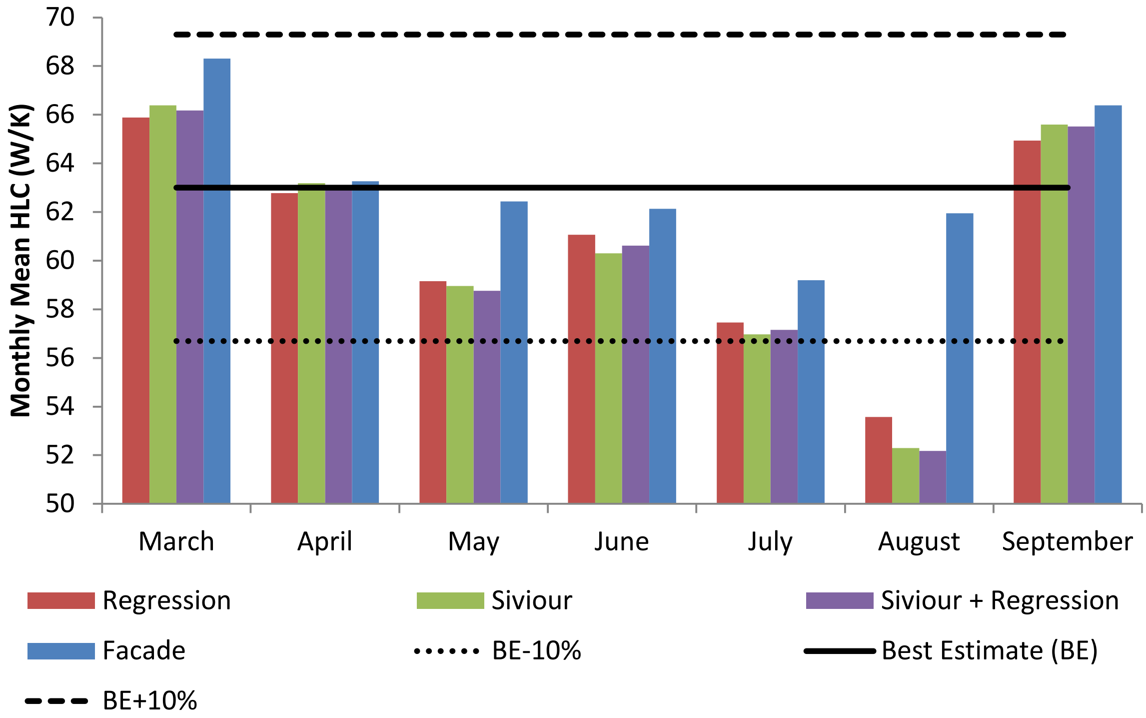


Figure 6-7: Monthly mean HLC according to each of the four data analysis methods considered. The mean result is taken from each of the 14 day samples that finish in that month.

It can be seen in Figure 6-7 that the facade method resulted in demonstrably more consistent estimates of the HLC during the entire period of the test. It is also likely that this level of consistency could be improved upon with more detailed measurements of solar gain, taken at the facade of each building. This hypothesis was further investigated using repeated co-heating tests applied in the same house in different seasons, the results of which are reported in section 6.2.

This is positive evidence that the facade method may provide not only a more accurate method of accounting for solar gains, but also may open up a larger period of the year for co-heating tests. This addresses the issue of seasonality that was identified as a crucial impediment to the co-heating test's use as a test for compliance check of as-built performance against building regulations. It should be noted however, that these results are all collected in the same detached building; the next step is to carry out comparative tests of the methods in more buildings of different forms and performance levels. It should be possible to do this retrospectively, on data that has already been collected, using the method outlined in this section. Further tests in two other buildings were carried out and the results of these are presented in the next section.

6.2. Inter-Seasonal Repeat Co-Heating Tests in Loughborough Test Houses

The results of the analysis on the data collected during the long-term co-heating test carried out at the BRE have been used to show the potential of the facade solar gain estimation method to allow co-heating during the summer months. As was noted in the concluding remarks of the previous sub-section, this result would need to be repeated in other buildings and locations to gain confidence in the facade method. Therefore further tests were carried out in two test houses located at Loughborough University.

For each house three co-heating tests were carried out; each test was carried out according to the same experimental method, but independently, with the equipment installed and removed before and after each test. For each house a test was carried out in winter, summer and a transitional period (spring/autumn), with the aim of testing over a range of external conditions. The HLC was calculated for each test using the multiple regression, Siviour, Siviour plus regression and facade methods. The results of the 'facade' method presented in this section have been calculated using the first variant of the method, using irradiance measurements taken on each facade.

The repeated tests consisted of two sets of three measurements of the HLC in a house, each measured by the co-heating test. It is not possible to define a baseline measurement which could be considered the 'correct' HLC for the building; therefore the amount of variability in the results is considered. If each of the results falls within an acceptable level of variation when considered in relation to the others, it is considered a successful demonstration of the data analysis method in question. Given the theoretical uncertainty, ±11%, and reproducibility, ±10%, of the co-heating test found from the data collected at BRE (section 5.2), an acceptable tolerance band of ±10% has been chosen. A tighter optimal tolerance of ±5% is also displayed.

6.2.1. Inter-Seasonal Tests in the Holywell Test House

The tests in the Holywell test house were carried out in November-December 2012, June-July 2013 and October 2013; representing the winter, summer and transitional period (in this case autumn) tests respectively. The dates over which each of the tests was carried out are shown in Table 6-4, with the mean conditions during each test presented in Table 6-5.

Test	Start Date	End Date
Winter (November 2012)	24/11/2012	6/12/2012
Summer (June 2013)	26/6/2013	15/7/2013
Autumn (October 2013)	17/10/2013	31/10/2013

Table 6-4: Dates of the repeated co-heating tests carried out in the Holywell test house.

	November 2012	June 2013	October 2013
Mean Solar Irradiance (W/m^2)	18.3	199.3	29.0
Mean Internal-External Temperature Difference (^oC)	20.4	13.5	13.2
Mean External Temperature (^oC)	4.7	18.3	11.8
Internal Set-Point Temperature (^oC)	25	30	27
Mean Windspeed (m/s)	1.6	1.0	0.6
Mean Electrical Power (W)	3485	1905	2129

Table 6-5: Mean conditions during each of the repeated co-heating tests in the Holywell test house, in addition the mean heating power over the test has been included.

As can be seen in Table 6-5, for these tests the selection of the testing periods resulted in a range of test conditions, with the test carried out in July having significantly higher external temperatures and levels of solar irradiance. This should result in a good examination of the data analysis methods ability to cope with differing testing conditions. In order to ensure a significant internal-external temperature difference over each of the tests carried out in different seasons, different internal temperature set points were used for each test; of 25^{o}C, 27 ^{o}C and 30 ^{o}C for the winter, autumn and summer (November 2012, October 2013 and June 2013) tests, respectively. Different internal set point temperatures were not found to have any significant impact on the calculated HLC in the methodological comparison carried out using the data gathered in the NHBC co-heating project (section 5.3), and was therefore not thought likely to cause a change in the measurement of the HLC in these tests.

The results of the tests are shown graphically in Figure 6-8 and summarised numerically in Table 6-6. The results are shown for each test, and separated by the data analysis method that was applied to calculate the HLC. Due to the high level of agreement in the result, error bars of ±5% have been displayed in Figure 6-8. These error bars represent a variation of ±5% in the measurement to which they are attached (i.e. not in the mean of a set of results).

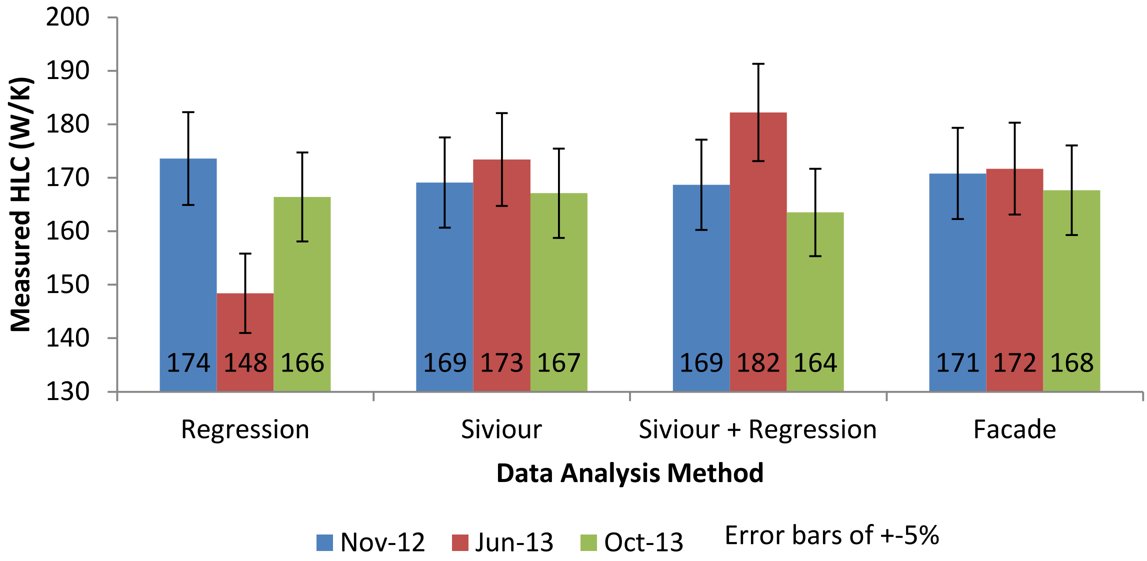


Figure 6-8: Results of the repeated co-heating tests in the Holywell test house. The error bars show a variation of ±5% in that result.

	HLC (W/K)				
Analysis Method	**Nov-12**	**Jun-13**	**Oct-13**	**Mean**	**Standard Deviation (W/K)**
Regression	173.6	148.4	166.4	162.8	13.0
Siviour	169.1	173.4	167.1	169.9	3.2
Siviour + Regression	168.7	182.2	163.5	171.5	9.6
Facade	170.8	171.7	167.7	170.1	2.1

Table 6-6: Numerical summary of results of the repeated co-heating tests carried out in the Holywell test house.

The results of the repeated tests carried out in the Holywell house further demonstrate that co-heating in the summer months can be successfully applied, especially if the facade method is used. The result from each of the tests is within a ±5% spread for all of the analysis methods apart from the regression method, and even the results as calculated by this method fall within a ±10% spread.

The HLC as calculated by the facade method again results in the lowest standard deviation; followed by the Siviour, Siviour plus regression and finally regression methods.

The result of the June 2013 test, according to the regression analysis method seems to be a clear outlier in Figure 6-8 and Table 6-6, resulting in a markedly lower HLC that all other tests and analysis methods. This is a similar finding to the lack of repeatability in the results of the regression analysis method observed in the long-term co-heating test carried out as a part of the NHBC co-heating project (the results of which are shown in Figure 6-1), in which the results of the regression method varied most widely from the best estimate of the HLC during period of particularly high solar irradiance. The co-heating plot for the June test in the Holywell house (Figure 6-9) shows that the process of forcing the line of best fit through the origin, as recommended by Bauwens et al (2012), may partially cause this discrepancy. Though it should be noted that this process has been followed for each of the regression analyses carried out, and is not unique to this particular test.

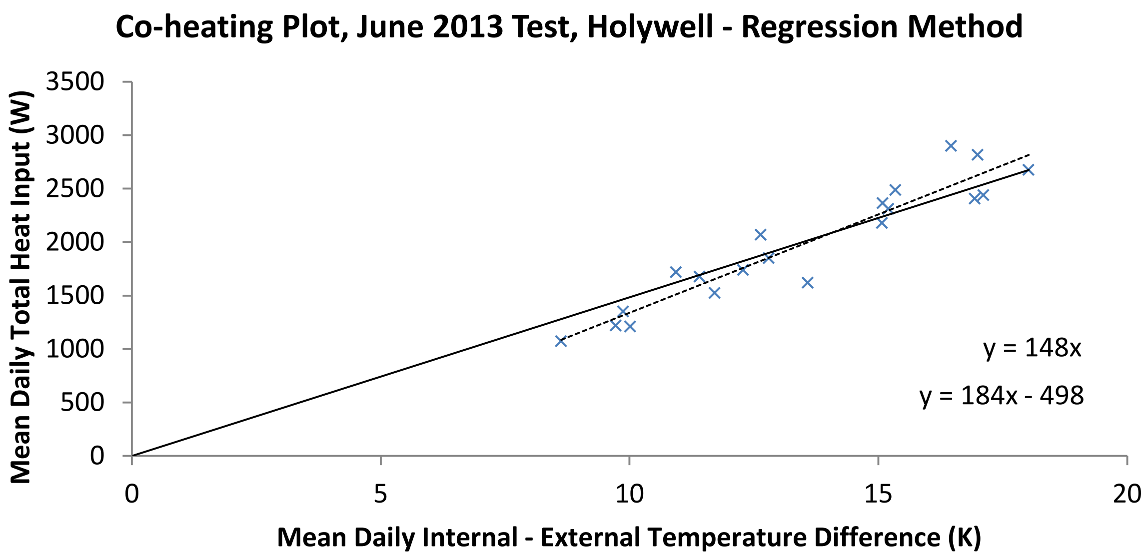


Figure 6-9: Co-heating plot for the June 2013 co-heating test carried out in the Holywell test house, the results have been analysed according to the regression method.

Visually, there appears to be no significant difference in the result of the test according to the season that it was carried out in. This impression is confirmed statistically; as no significant relationships were found between the calculated HLC according to any method and external condition variables (tests were applied for mean external temperature, global solar irradiance and wind speed).

6.2.2. Inter-Seasonal Tests in 209 Ashby Road

The dates over which the co-heating tests in the test house at 209 Ashby Road were carried out, and the mean conditions which occurred over these periods, are shown in Table 6-7 and Table 6-8, respectively. Due to constraints on the availability of the test houses and co-heating equipment, the 'summer' test in 209 Ashby Road had to be carried out earlier in the year than would have been ideal – in late May. Despite this limitation, a comparison was still successfully carried out between a co-heating test carried out in the usual winter heating season, and two carried out outside of the usual co-heating period.

Test	Start Date	End Date
Winter (March 2013)	14/3/2013	31/3/2013
Spring (April 2013)	19/4/2013	6/5/13
Summer (May 2013)	13/5/2013	30/5/13

Table 6-7: Dates of the repeated co-heating tests carried out in the test house at 209 Ashby Road.

	March 2013	April 2013	May 2013
Mean Solar Irradiance (W/m^2)	74.2	174.5	148.5
Mean Internal-External Temperature Difference (^oC)	21.8	15.8	17.9
Mean External Temperature (^oC)	2.9	11.1	11.1
Internal Set-Point Temperature (^oC)	25	27	30
Mean Windspeed (m/s)	1.9	1.5	1.6
Mean Electrical Power (W)	9981	6478	8049

Table 6-8: Mean conditions during each of the repeated co-heating tests in the test house at 209 Ashby Road, in addition the mean heating power over the test has been included.

As in the tests carried out in the Holywell test house, internal temperature set-points of 25, 27 and 30^oC were chosen to ensure a significant internal-external temperature difference. The results of the co-heating tests carried out at Ashby Road are shown in Figure 6-10, with a numerical summary in Table 6-9.

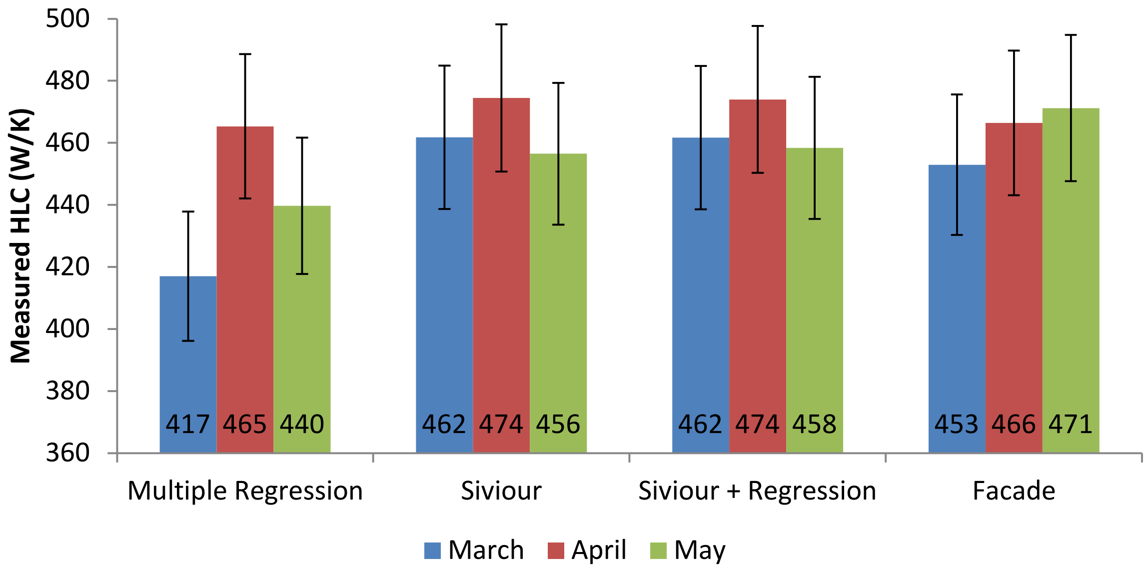


Figure 6-10: Results of the repeated co-heating tests in the test house at 209 Ashby Road. The error bars show a variation of ±5% in that result.

	HLC (W/K)				
Analysis Method	**Mar-13**	**Apr-13**	**May-13**	**Mean**	**Standard Deviation (W/K)**
Regression	417.0	465.3	439.7	440.7	19.7
Siviour	461.8	474.5	456.5	464.2	7.5
Siviour + Regression	461.7	474.0	458.4	464.7	6.7
Facade	452.9	466.4	471.2	463.5	7.7

Table 6-9: Numerical summary of HLC results of the repeated co-heating tests carried out in the test house at 209 Ashby Road.

The finding of the tests at the Holywell house is repeated in these tests in 209 Ashby Road, with all the HLC as calculated by all data analysis methods falling within a ±10% range, despite two of the tests being carried out outside of what is usually considered the most suitable time for co-heating. The result according to the Siviour, Siviour + regression and Facade methods all fall with a ±5% range, as was observed in the tests carried out at the Holywell test house. These headline results provide further evidence that co-heating can be successfully carried out throughout the year if an elevated internal set-point temperature is used to ensure a significant internal-external temperature difference.

In this set of tests, the HLC as calculated by the Siviour + regression method over the three tests have the lowest standard deviation, followed very closely by the Siviour and Facade methods. Each of these methods also results in a very similar mean HLC across the three tests, with a variation well below the estimated accuracy of the co-heating test of ±11%. As was the case in the Holywell tests, the mean HLC result according to the regression method is lower than that calculated by the other three methods. As in the Holywell tests, there was no statistically significant or observable relationship between any weather conditions during the tests and the calculated HLC – for any data analysis method.

6.3. Measured vs. Translated Irradiance for Solar Gain Calculations

As was described in section 4.3.3, there are two variants of the facade solar gain method. In the full application of the method, the first variant, the solar irradiance incident to each facade containing glazed elements is measured using pyranometers which are attached as close to the centre the facade as possible. In this sub-section this variant of the method will be referred to as 'measured'.

However, this approach may not always be possible due to practical constraints, such as difficulty in mounting the pyranometers (if the dwelling was in a high-rise flat for example), attachment to a data logger and concerns over the security of the sensors. Therefore an alternative, second variant, has been proposed where global horizontal irradiance, commonly available from weather stations, is translated to calculate the irradiance incident to each facade. This method was described in detail in section 4.3.3, and will be referred to as 'translated' in this sub-section. In this section the impact on the calculated HLC made by the choice of the variant of the facade solar gain method is considered.

The perceived benefit of the 'measured' variant to determine the irradiance on each facade is that the measurement will, to some extent, account for the effect of overshading. This is a rather complex matter; of course one pyranometer per facade will never be enough to account for the variation of shading across that facade. The application of a statistical method, such as the regression, Siviour or Siviour + regression methods; avoids this hard to deal with issue.

However, as all statistical corrections are applied to the original dataset, they assume that there is a simple relationship between heating power, internal-external temperature difference and solar irradiance. This takes no account of other complicating factors, such as changes in wind speed, long-wave radiative heat loss, or charging and discharging of the house's thermal mass, which will impact upon the heat input rate to the house and are likely to be co-correlated with the solar irradiance in some way.

In the ‘translated’ variant of the facade solar gain method, the irradiance reaching each facade is calculated by a translation of the global irradiance measured at a weather station - and hence unlikely to be effected by overshading. As such it falls in between the position of the statistical methods and the ‘measured’ variant of the facade method: the measurement does not account for overshading, but the analysis does not require any assumptions to be made about the co-dependence of weather condition variables. The issue of overshading when using the translated variant of the facade method is recognised as a clear source of uncertainty; methods to address the issue are analysed and discussed later in this chapter.

For each of the co-heating tests carried out as a part of this study, solar irradiance was measured on each facade with glazed elements. This allows a direct comparison between measured irradiance falling on each of these facades and that calculated through a translation of the global horizontal irradiance. The comparison for the tests carried out in the Holywell Test House is shown in Figure 6-11.

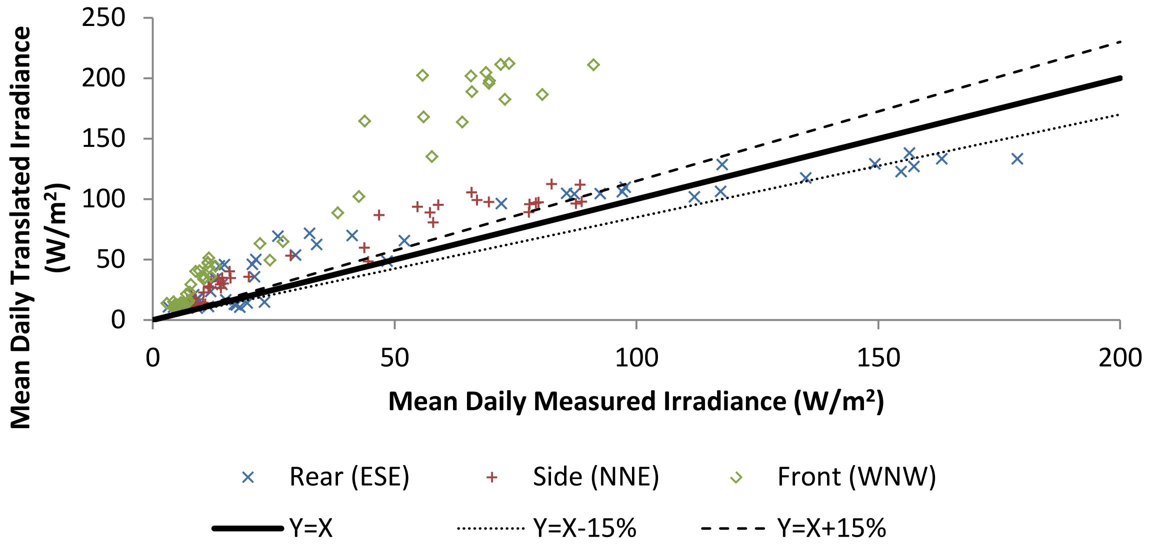


Figure 6-11: Mean daily measured and translated (from global horizontal irradiance measurements) irradiance reaching the three facades with glazing during the co-heating tests carried out in the Holywell test house. Lines for Y=X±15% have been added to show the measurement uncertainty of the pyranometers used on each facade.

It can be seen that there is a close agreement between the measured and translated irradiance for the rear (ESE) and side (NNE) facades, but a significant discrepancy for the front (WNW) facade – with the translated irradiance significantly higher than the measured value. It can also be seen that the discrepancy between the measured and translated irradiance on the front facade increases as the irradiance increases.

There are several possible reasons for this discrepancy; it could be connected to the accuracy of the measurement taken at each facade, or the measurement of global horizontal irradiance at the weather station, or in the translation of horizontal irradiance to that falling on each facade, or in the effect of overshading for that location.

It can be seen in Figure 6-11 that where there is a discrepancy between the measured and translated values, the translated value is larger in the vast majority of cases. Given that no account is taken of overshading in the translation, this result is as expected and suggests that overshading may be a major cause of discrepancy between the two values.

Further evidence that overshading may be the most significant cause of the discrepancy between measured and translated irradiance can be seen in Figure 6-12. As explained in section 4.3.3, the calculation of the total translated irradiance is constituted of three parts – direct (or beam), diffuse and reflected irradiance. In Figure 6-12, the direct element is plotted on the x-axis, clearly this element will be the most heavily affected by overshading. The difference between the measured and translated irradiance, on an hourly mean basis, is shown on the y-axis. This plot can be used to judge whether there is any relationship between the quantity of direct irradiance and the difference between translated and measured irradiance.

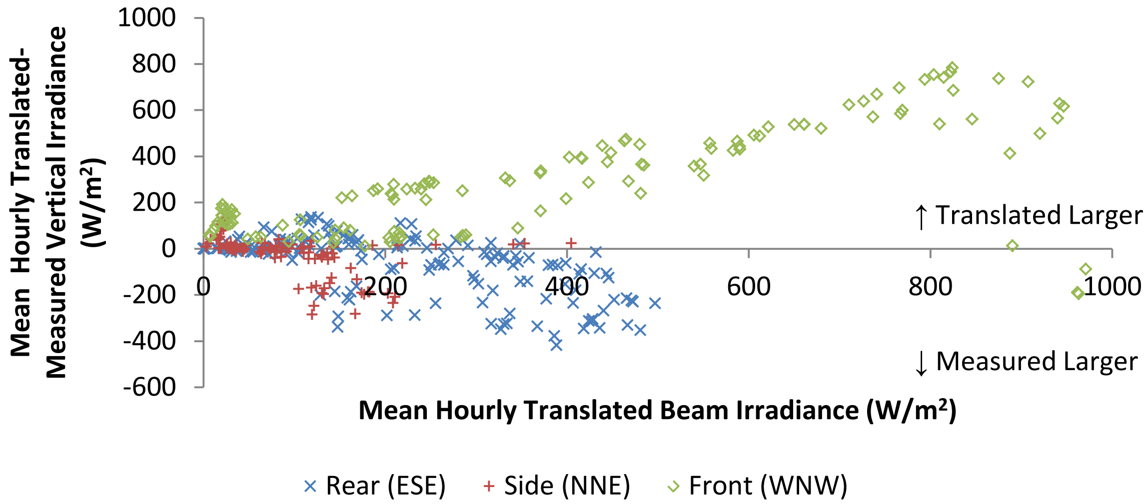


Figure 6-12: Mean hourly translated irradiance minus mean hourly measured irradiance versus mean hourly beam irradiance falling on each facade of the Holywell Test House during the summer co-heating test carried out at this site.

It can clearly be seen in Figure 6-12 that for the front facade, which was observed in Figure 6-11 to have the largest discrepancy between measured and translated irradiance, there is a strong positive relationship between the translated beam irradiance and the difference between measured and translated total irradiance. In other words, where the translation predicts more direct irradiance there is a larger difference between the translated and measured values, suggesting that the discrepancy between the two is likely to be caused by a miscalculation of the direct element of the total irradiance – which would be consistent with overshading.

There is no clear relationship between beam irradiance and translated-measured irradiance for the side facade, suggesting that overshading is not an issue for this facade. However, there does seem to be an opposite relationship for the rear facade – there is a larger translated-measured difference for a higher beam irradiance, but in this case the measured value is larger. This suggests that the error is not associated with overshading, and may suggest that the translation underestimates the direct element of the total irradiance falling on the facade. It can be seen in Figure 6-11 that at a daily level the translated-measured difference is reasonably small, which suggests that the possible underestimation of the direct element is offset to some extent by an overestimation in the diffuse or reflected parts.

Figure 6-13 shows the comparison between measured and translated irradiance for the co-heating tests carried out at 209 Ashby Road. Similar results to those observed in the tests at the Holywell test house (Figure 6-11) can be seen in Figure 6-13. There is close relationship between translated and measured vertical irradiance for two of the three facades, again for one of the facades (the rear, or NNW facade) there is a discrepancy between the two values. Where there is a difference between the two values the translated irradiance is higher in the majority of cases. Interestingly, the facade which has the largest difference between translated and measured irradiance, the rear facade in this case, has a similar orientation, north-north-west, to that which showed the largest difference in the Holywell test – the west-north-west orientated front facade.

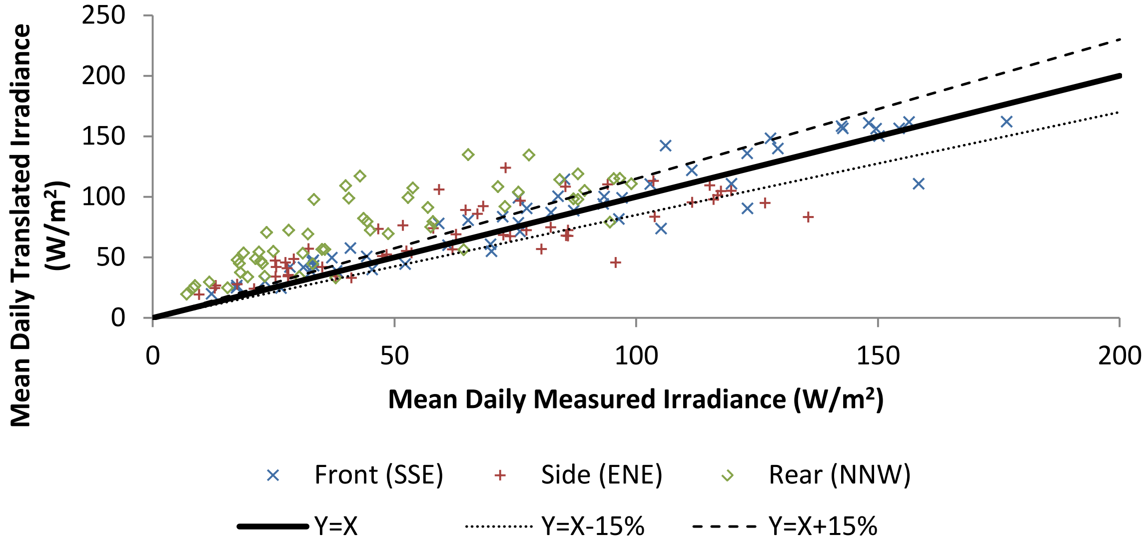


Figure 6-13: Mean daily measured and translated (from global horizontal irradiance measurements) irradiance reaching the three facades with glazing during the co-heating tests carried out in the test house at 209 Ashby Road. Lines for Y=X±15% have been added to show the measurement uncertainty of the pyranometers used on each facade.

Figure 6-14 shows the same analysis for the summer co-heating test at 209 Ashby Road as was shown for the summer co-heating test at the Holywell test house in Figure 6-12, with the translated-measured irradiance difference compared to beam irradiance. The summer co-heating tests were chosen in both cases, as the issues of overshading are most pronounced when the level of direct solar irradiance is higher.

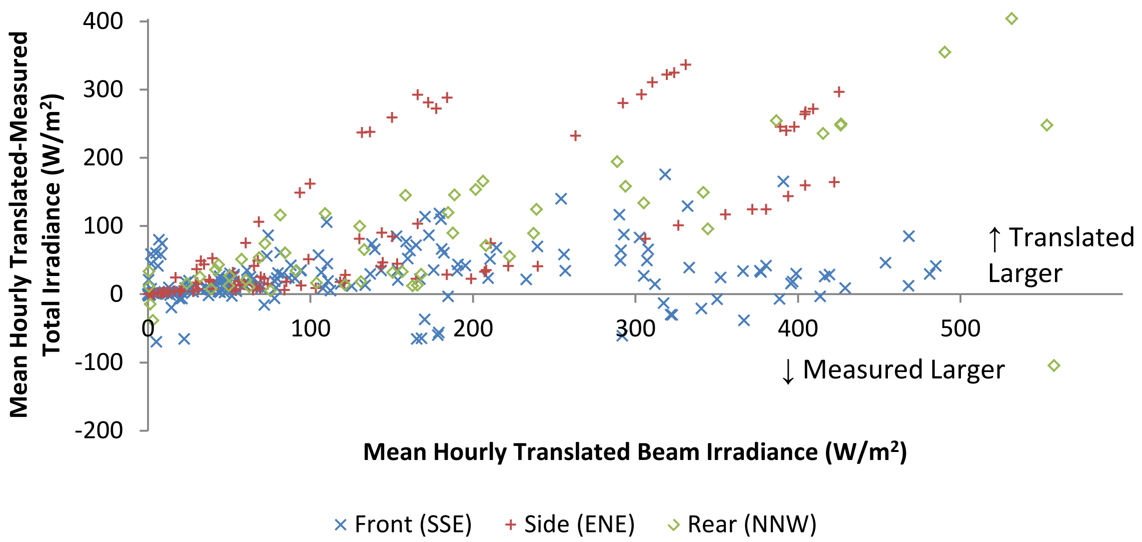


Figure 6-14: Mean hourly translated irradiance minus mean hourly measured irradiance versus mean hourly beam irradiance falling on each facade of the test house at 209 Ashby Road during the summer co-heating test carried out at this site.

As was evident in Figure 6-13, it can be seen in Figure 6-14 that there is a closer relationship between translated and measured irradiance, with a smaller difference between the two in general. It can also be seen in Figure 6-14 that there seems to be some positive relationship between translated beam irradiance and the difference in translated-measured total irradiance, for the side and rear facades of 209 Ashby Road. This suggests that there may be some overshading of these facades, in the same way as there was of the front facade of the Holywell test house.

Various methods could be used to correct for overshading. In SAP, a simple weighting factor is applied, this weighting factor is adjusted according to the percentage of the surrounding sky that is blocked by obstacles (BRE, 2011). The weighting factor is also adjusted according to the season, with a lower weighting factor in the summer as the Sun is higher in the sky and hence less prone to overshading. The winter factors range from 0.3-1.0 for heavy and very little overshading respectively, and the summer factors from 0.5-1.0. A factor of 0.77 is recommended for average or unknown overshading (BRE, 2011).

It is clear from Figure 6-11 - Figure 6-14 that there was not a constant level of overshading for each facade, however as a first step the average overshading weighting factor, of 0.77, was applied to all datasets to see if this led to an improvement in the agreement between translated and measured irradiance. The comparison between measured and translated irradiance at each facade with glazing, shown in Figure 6-11 and Figure 6-13, is reproduced below in Figure 6-15 and Figure 6-16 with an overshading factor of 0.77 applied to each daily mean average value.

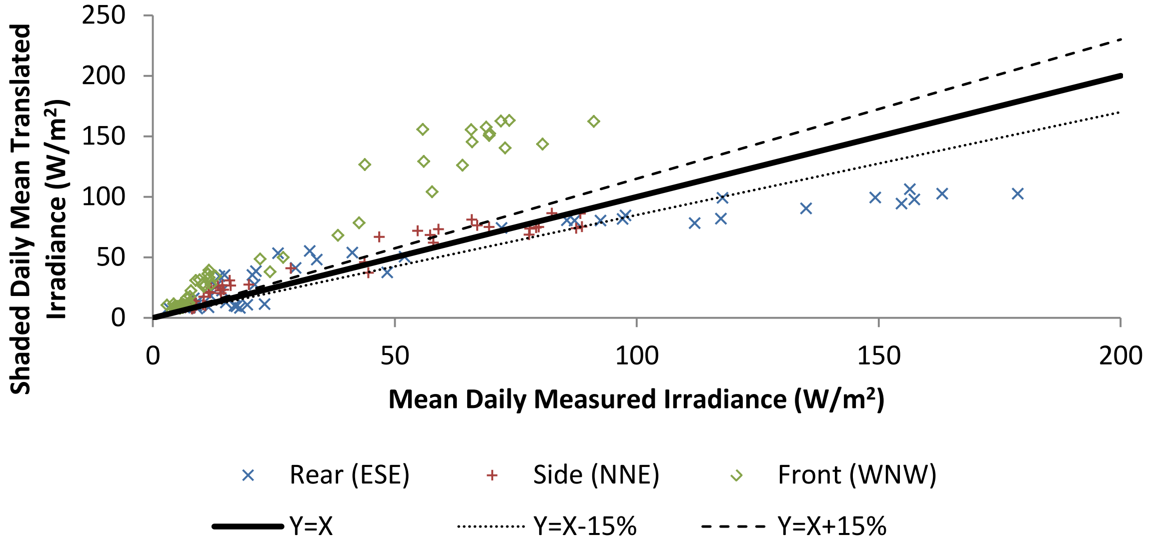


Figure 6-15: Measured vs translated irradiance on each glazed facade of the Holywell test house during the co-heating tests carried out there, an overshading factor of 0.77 has been applied to the translated irradiance.

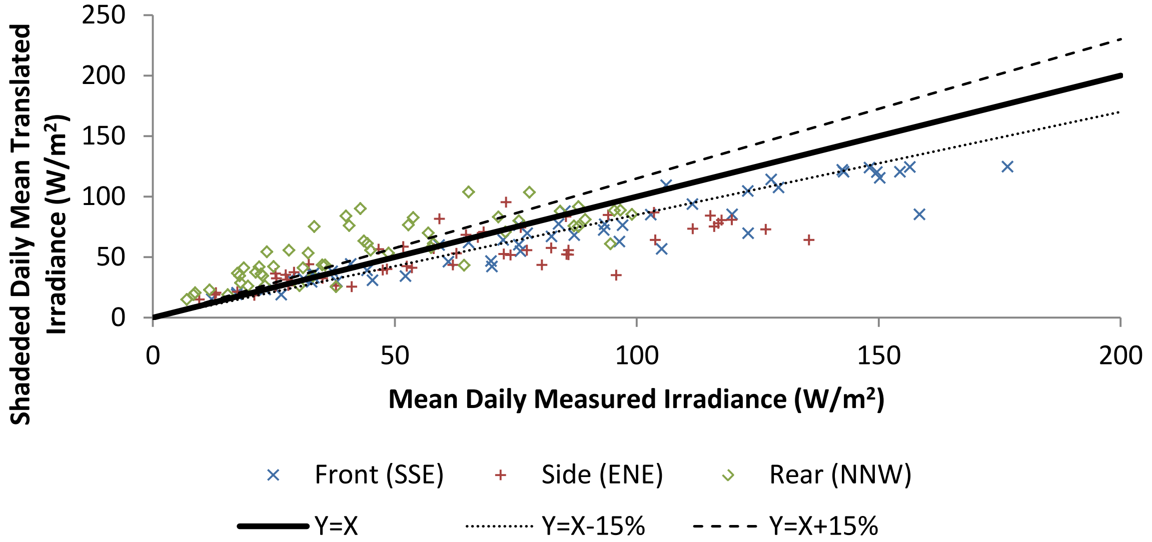


Figure 6-16: Measured vs translated irradiance on each glazed facade of 209 Ashby Road during the co-heating tests carried out there, an overshading factor of 0.77 has been applied to the translated irradiance.

It is clear in Figure 6-15 and Figure 6-16 that the application of the overshading factor does not completely correct the differences between the measured and translated values for solar irradiance falling on the facades of the two test houses. However, a comparison of the mean difference between daily translated and measured irradiance before and after the application of the shading factor, shown in Table 6-10, indicates a significant overall improvement in the level of fit.

		Mean Translated-Measured Solar Irradiance (W/m^2)			
		Rear	**Side**	**Front**	***Mean***
Holywell	No-Shading	5.6	15.1	51.5	*24.1*
	With Overshading Factor	-7.7	4.3	33.2	*9.9*
209 Ashby	No-Shading	27.2	2.9	4.5	*11.5*
	With Overshading Factor	10.4	-12.6	-15.6	*-5.9*

Table 6-10: Comparison between the mean translated and measured solar irradiance (where a positive difference indicates that the translated irradiance is higher) before and after the application of a solar shading factor of 0.77 to each daily mean translated solar irradiance value.

As would be expected, given the differences in overshading level that were observed earlier in this chapter, the level of fit between measured and translated irradiance is not improved for all facades by the application of a 'one size fits all' overshading factor. This could be improved by choosing an overshading factor for each facade based upon the surrounding environment, as is recommended in SAP (BRE, 2011). The comparison between measured and un-shaded translated data was used to interpolate an overshading factor for each facade, based upon the data collected in the co-heating tests, these factors are shown in Table 6-11.

	Overshading Factor			
	Rear	**Side**	**Front**	***Mean***
Holywell	1.1*	0.7	0.4	*0.7*
209 Ashby	0.7	1.0	1.0	*0.9*

Table 6-11: Calculated overshading factors for each facade of the Holywell test house and 209 Ashby Road.

The application of these 'ideal' overshading factors would allow the closest possible fit between measured and translated values of solar irradiance on each facade. Clearly, however, it would not be possible to calculate these in a situation where it was not possible to install pyranometers on each facade! It is not possible to say that the values calculated here represent the 'correct' overshading factors. As has been discussed, there are several possible reasons for a discrepancy between measured and translated values – while the calculation of these overshading factors has assumed that overshading was the only source of discrepancy. Indeed, the calculated factor for the rear facade of the Holywell test house (which is highlighted by a *) illustrates this point. A positive overshading factor does not make any physical sense, therefore the error must occur somewhere else in the measurement or calculation. However, the rest of the calculated overshading factors fall within the range of values listed in SAP (BRE, 2011), which provides confidence in the translation method.

Having considered in depth the accuracy of the translation method in determining the vertical solar irradiance, the effect of the discrepancy between the measured and translated values on the calculation of HLC for each of the co-heating tests carried out will now be considered. Despite the importance that has been attached to its calculation in this chapter, it is important to remember that in most co-heating tests the solar gains do not constitute the largest part of the heat input to the house. Therefore, in considering the impact of inaccuracy in the calculation of solar irradiance on each facade on the eventual calculated HLC, the effect of the inaccuracy on the estimation of the total heat input to the house is the crucial factor. This is shown numerically in Table 6-12, for each of the co-heating tests carried out.

		Mean Daily Solar Gain (W)				
		Meas-ured	Trans-lated	Translated-Measured	Mean Daily Total Power (W)	Translated -Measured as % of Total Power
Holywell	Winter	48	49	1	3534	0.0%
	Transitional	82	155	73	2212	3.3%
	Summer	473	477	4	2378	0.2%
209 Ashby	Winter	497	398	-99	10478	0.9%
	Transitional	964	845	-119	7442	1.6%
	Summer	680	711	32	8728	0.4%

Table 6-12: Numerical summary of the effect of inaccuracies in the translation of global horizontal solar irradiance to irradiance on each facade on the estimation of total heating power. The mean daily total power in the table refers to the electrical heating power plus the solar gain calculated the measured solar irradiance on each facade.

In the analysis shown in Table 6-12, the total heating power calculated using the facade method with measured solar irradiance for each facade was used as a ‘best estimate’ baseline measurement, against which the results using the translated irradiance values was compared. The first observation to make is that as a percentage of the total heating power to the house, the error introduced by the use of the translation method is relatively low across all tests – ranging from 0%-3.3%. It is also clear that the influence of the measured-translated difference in solar gain is heavily dependent upon the total heat input to the house. The discrepancies between the measured and translated solar gains for the tests in 209 Ashby Road are higher than those for the tests in the Holywell test house. However, as the HLC of the 209 Ashby Road is much higher, there is a larger total heat input to the building therefore the impact of the larger discrepancies in solar gain figures on the total heat input to the house is diluted.

It also appears that the difference between measured and translated solar gain sums may be lower during the summer. This may be due to a reduced level of overshading in the summer, due to the sun being higher in the sky – and hence less likely to be blocked by obstacles (as is reflected in the SAP recommended overshading factors discussed earlier in this section).

To provide the final step in this analysis, Figure 6-17 shows a comparison of the HLC calculated when analysed using the 'measured' and 'translated' variants of the facade method, for the co-heating tests carried out at 209 Ashby Road and Holywell. It can be seen that there is a close agreement between the HLC calculated using the measured and translated variants, with all results falling within a ±5% interval when compared to each other.

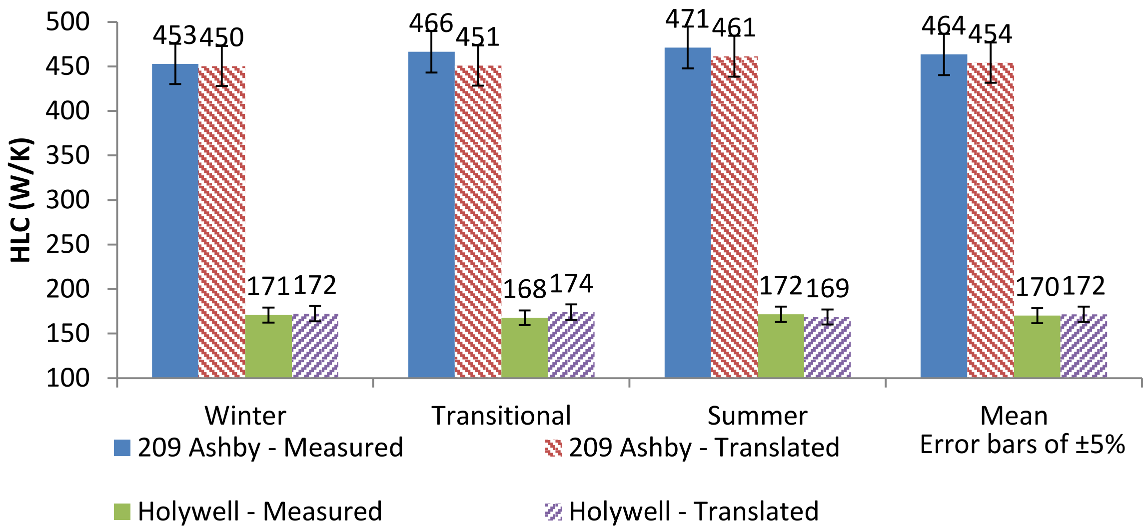


Figure 6-17: Comparison of the results of the co-heating tests in the Holywell and 209 Ashby Road test houses, using the two variants of the facade solar gain estimation method (with solar irradiance measured at the facade or calculated via a translation from a measurement of global horizontal solar irradiance).

This reproducibility of both the measured and translated variants of the facade method compare very favourable with the results as calculated by the 'statistical' methods (regression, Siviour and Siviour + regression methods), which are shown in Figure 6-8 and Figure 6-10. This is further demonstrated by a comparison of the HLC as calculated by all analysis methods and variants, which is presented in Table 6-13.

	Analysis Method	Mean HLC (W/K)	Standard Deviation (W/K)
Holywell	Regression	163	13.0
	Siviour	170	3.2
	Siviour + Regression	171	9.6
	Facade (Measured)	170	2.1
	Facade (Translated)	172	2.8
209 Ashby	Regression	441	19.7
	Siviour	464	7.5
	Siviour + Regression	465	6.7
	Facade (Measured)	464	7.7
	Facade (Translated)	454	5.0

Table 6-13: Summary of the results of the repeated co-heating tests carried out in 209 Ashby Road and at the Holywell test house (the translated results include the 0.77 overshading factor).

Despite the issues with overshading which have been discussed, the translated and measured variants of the facade method both provide a repeatable and accurate measurement of the HLC, and have been shown to perform better than existing statistical methods. This finding is supported by both the results of the repeated tests carried out in 209 Ashby Road and at the Holywell test house, and those of the long-term testing (presented in section 6.1), which also used the translated variant of the facade method.

It has been shown that the translated variant does introduce some added uncertainty in comparison to the measured version, and that this is likely to be related to an inaccurate assessment of overshading. This could be improved by better methods of estimating the overshading factor to apply, such as by a site survey. This would be likely to increase the accuracy of the estimation of solar irradiance reaching the glazed facades, and hence the HLC.

6.4. Summary

In combination, the results of the long-term co-heating test and the repeated co-heating tests, presented in sections 6.1 and 6.2 respectively, have shown that co-heating can be successfully carried out during the summer months using the facade solar gain estimation method and a rigorous testing procedure, such as that described in section 4.3.

The results of both the long-term and repeated tests showed that the multiple regression method of analysing co-heating data to correct for the effects of solar gain was the least repeatable of the methods considered. In particular, it produced extreme variations in the HLC for tests carried out in the summer months.

The Siviour and Siviour plus regression methods, showed a similarly low level of reproducibility in the long-term tests, but performed better in the repeated tests carried out in the test houses in Loughborough. This could be due to the significantly lower thermal performance of the test houses in Loughborough, in comparison to the test house at BRE (the Holywell test house and Ashby Road have HLCs of more than double that of building 50.3 at BRE Garston).

The facade method resulted in the most repeatable results in both the long term and repeated tests. This was true for both of the variants proposed, where the irradiance reaching each facade is either measured at each facade or calculated via a translation from a measured global horizontal solar irradiance.

Beyond the reproducibility of the results according to each method there are further considerations in deciding which method is most appropriate. A wider consideration of the advantages and disadvantages of each of the analysis methods compared in this chapter is given in Table 6-14, with recommendations of the most suitable applications for each method.

Analysis Approach	**Advantages**	**Disadvantages**	**Suitable Applications**
Facade solar gain estimation method – measured variant	- Most repeatable results in long-term and repeated co-heating tests - Includes the effect of shading to some extent - Simplifies data analysis	- Expensive - Difficult to measure representatively across the whole facade	Full co-heating test: - Capital cost small if sensors are re-used - Highest reproducibility
Facade solar gain estimation method – translated variant	- Weather station solar data sufficient: reduces measurement cost and complexity - More repeatable results than statistical analysis methods	- Difficult to accurately account for overshading - Increased complication in data analysis	LIUHB test: - Greater accuracy than statistical approaches - Less invasive - Lower cost
Siviour and Siviour plus regression methods	- Weather station data sufficient - Effect of overshading included and not effected by sensor placement - Currently most commonly used method - Simple and quick analysis	- Less repeatable results than facade method, particularly during summer - Requires range of weather conditions during testing period to inform regression - Correction for solar gain assumes that there is no co-correlation with other weather variables	Full co-heating test: - Often used in co-heating analysis, so allows comparison of results - Simple, quick analysis
Multiple regression analysis	- Weather station data sufficient - Effect of overshading included - Simple and quick analysis - Commonly used method	- Lowest reproducibility in long-term and repeated tests - Requires range of weather for regression - Solar gain correction assumptions	To allow comparison against other co-heating results

Table 6-14: Advantages, disadvantages and recommended uses for each analysis method to estimate solar gains in co-heating tests.

In general, the statistical methods offer an elegant method of simply dealing with the problems associated with overshading. In addition, they can be applied to solar data which is commonly collected at weather stations, which has the significant advantage of removing the necessity for onsite measurements. This reduces cost, and also deals with practical issues such as connecting external sensors with internal data loggers and security issues associated with external placement of expensive measurement equipment.

The measured variant of the facade method provides a similarly simple analysis. However, it must be accepted that a single measurement of the irradiance taken on a facade will not accurately reflect the dynamic effects of overshading across the whole surface. The translated version of the facade method also suffers from overshading issues, though it does remove the requirement for onsite measurements. Despite the overshading issue the facade method, in both of its variations, offered the highest reproducibility across the long-term and repeated tests and provided consistent measurement of the HLC in all three buildings both within and outside of the traditional co-heating season, offering a method to extend the acceptable season for co-heating tests.

Chapter 7 The Loughborough In-Use Heat Balance Test

The previous two chapters have sought to improve the experimental and data analysis methods associated with the co-heating test, in particular understanding the uncertainty associated with the test and how this is affected by the weather conditions that occur during the test. Developing an understanding of these relationships has helped to show that co-heating testing is possible in many houses throughout the year. This work has addressed some of the most pressing issues that bar the co-heating test from general use as a quality assurance and regulatory tool.

However, the work has not addressed perhaps the most fundamental issue – the access requirements of the co-heating test. While it is possible that a two week testing period may be acceptable in a new-build scenario, it is particularly problematic if one is seeking a tool to measure the effectiveness of retrofits. Where a house has occupants it is very unlikely that it will be possible to carry out a test that requires the building to be empty for that length of time. Therefore there is a clear need for another test that could be carried out in a much shorter time span, or while the house is in-use.

As its name suggests, the Loughborough In-Use Heat Balance has been designed such that it can be carried out while the house is in-use. This chapter describes the experimental results that have informed the development of the method. The development of the method has taken place in three stages, described in full in section 3.2. The three stages involved testing in an unoccupied test house, including the application of several synthetic occupancy variables, measuring the effect of a retrofit applied to the Holywell test house, and a case study application in an occupied house. The Holywell test house was used for the unoccupied and synthetic occupancy tests, and a 1950s semi-detached masonry building was used in the occupied house case study. In each stage of the development the results of the in-use test were compared to a benchmark co-heating measurement, with solar gains quantified using the translated variant of the facade method.

7.1. Comparison with the Results of a Co-Heating in an Unoccupied House

The first step in testing the LIUHB method was to compare the results of the in-use method against those of a standard co-heating test in an unoccupied house. This provides a comparison of the result according to the two methods independent of the added uncertainties associated with occupation of the house.

As described in section 3.2, the initial tests of the LIUHB were carried out in the Holywell test house. The Holywell test house has been described in detail already (section 4.1.1), but it is useful at this stage to briefly repeat that it is a rather small, timber framed, detached house with a condensing boiler that provides hot water and heating via a traditional radiator system. The heating is controlled by a programmable timer and a single bi-metallic strip thermostat, located in the hall. The repeated co-heating tests carried out in the Holywell test house, the results of which were given in section 6.2, were used to define the baseline measurement of the HLC of 170W/K.

Three different tests were carried out in the house in this first stage of trialling the in-use method. The first sought to replicate a standard co-heating test as closely as possible, using the installed heating system. To that end, for the first in-use test the heating was turned on continuously with a set point temperature of 25^{o}C.

For the next two tests more realistic heating practises were applied. During the second in-use test a lower set-point temperature of 20^{o}C was chosen, in line with the internal temperature assumed in SAP of 21^{o}C for living spaces and 18^{o}C for bedrooms (BRE, 2011), but still with the heating system on continuously. For the third in-use test a 20^{o}C set point temperature was used with a typical two heating period schedule (Kane et al., 2014), with heating periods from 06:00-09:00 and 16:00-21:00. These timings were used for all two period heating schedules applied in the in-use tests in the Holywell test house.

The mean weather conditions during each of the in-use heat balance tests carried out in the Holywell test house are shown in Table 7-1. The total heat input displayed is the sum of the average electrical power and boiler output power, and does not include solar gains. The boiler output is calculated by multiplying the volume of gas consumed by an average value for the calorific value of gas and the winter seasonal efficiency of the boiler (BRE, 2014b) (described in detail in section 4.4.2).

	In-Use Test 1	In-Use Test 2	In-Use Test 3
Mean Value During Test	**25°C Constant**	**20°C Constant**	**20°C 2 Periods**
External Temperature (°C)	7.5	4.6	8.0
Internal Temperature (°C)	26.2	23.0	18.7
Internal-External Temperature Difference (°C)	18.7	18.4	10.7
Global Solar Irradiance (W/m^2)	17.3	26.4	60.6
Wind Speed (m/s)	2.1	1.1	1.4
Total Heat Input - Electrical + Gas (W)	3063	2772	1370

Table 7-1: Mean value for weather conditions and heat input during each of the in-use heat balance tests carried out in the Holywell test house.

The results of each of the in-use heat balance tests are shown in Figure 7-1. The daily mean power values for each have been corrected to include solar gains using the translated facade method.

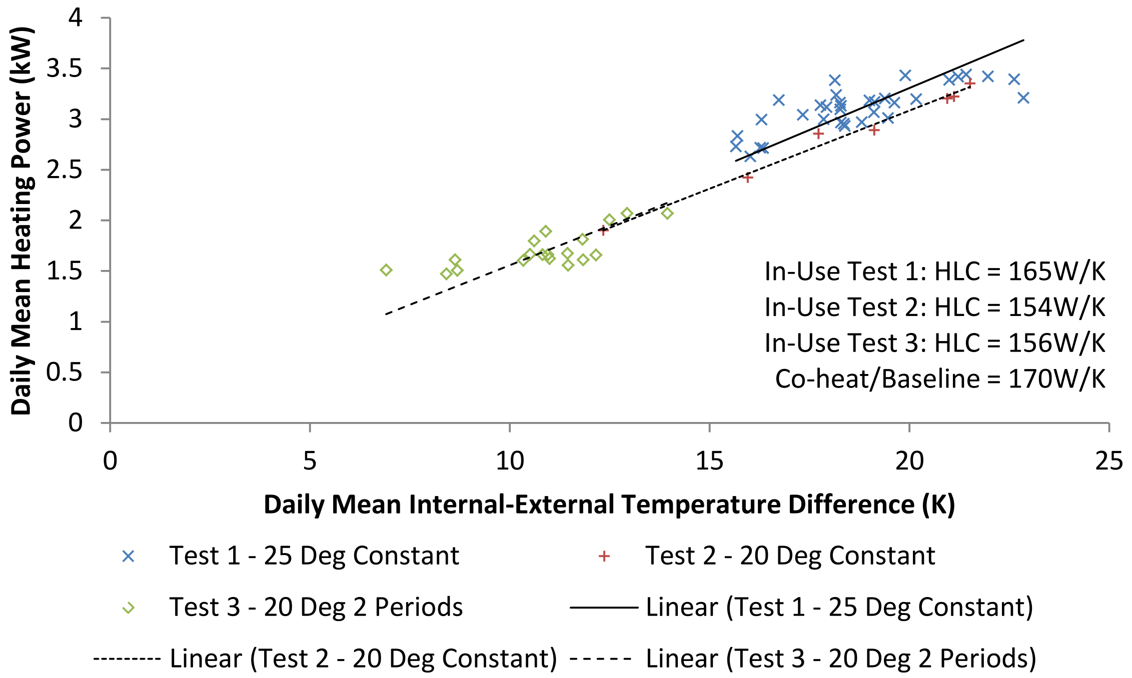


Figure 7-1: Co-heating plot of the three in-use heat balance tests carried out in the Holywell test house with no synthetic occupancy conditions applied.

It can be seen in Figure 7-1 that there is a reasonably close agreement between the three tests and the co-heating baseline measurement. Given the estimated uncertainty of the co-heating method calculated in section 5.2, of -11%, +12%, a minimum expected uncertainty of the LIUHB method of ±15% has been estimated. This is to take into account the extra uncertainty associated with variables associated with occupation and in estimating in the output of the boiler, this estimate will be discussed further later, but is introduced here as a guide to an acceptable level of agreement between results as calculated by the LIUHB and co-heat methods. The result of the three tests is compared to the co-heating baseline in this context in Figure 7-2.

Each of the three in-use tests resulted in a slightly lower HLC than the co-heating test, though all of the results lie within the proposed ±15% boundary. It is therefore not possible to judge from this small sample whether the observation of a slight underestimation of the HLC would be repeated in further in-use tests.

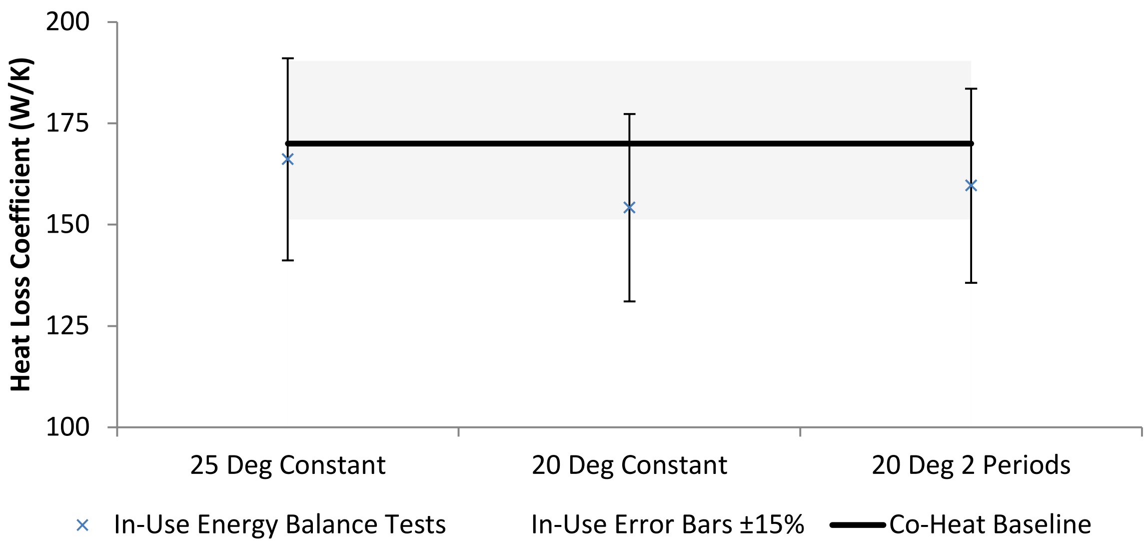


Figure 7-2: Results of the three LIUHB tests carried out in the Holywell test house compared to the co-heating baseline measurement, the shading shows an area of uncertainty of -11%, +12% around the baseline co-heating measurement.

It should be noted that the co-heating test has an estimated uncertainty of -11%, +12%, which is represented by the shaded area in Figure 7-2. The combination of uncertainties of the co-heating and in-use measurements therefore results in a maximum possible difference of -26%, +27%, between a co-heating and in-use result which remains within the combined uncertainty boundaries.

With this in mind, the results shown in Figure 7-2 demonstrated a successful first trial of the in-use heat balance method, with the results agreeing closely with those of a full co-heating test. Of course, this does not provide much supporting evidence for the success of the 'in-use' part of the method; however it is a significant result, providing justification to continue with the study of the LIUHB method.

These tests were carried out in an empty house in order to minimise the added uncertainty in comparison to a standard co-heating test. However, two clear differences between the two methods which are likely to influence uncertainty remain, both associated with the way that heat is supplied and distributed. For the in-use test the heat is supplied by the gas boiler, and distributed via radiators, in comparison to the fan heaters used in co-heating. This difference affects the uncertainty in the measurement of heat delivered, but also constrains the way in which the heat supply can be spread throughout the house, which is likely to lead to a more uneven temperature distribution throughout the internal space. In a co-heating test this issue is further addressed by the use of air mixing fans, clearly these would be inappropriate for use in an occupied house and cannot be used when applying the in-use energy balance test.

Gas consumption can be measured to a high degree of accuracy; it is the estimation of the boiler efficiency that adds uncertainty. For the tests carried out in the Holywell house the efficiency of the boiler was assumed to be equivalent to the winter seasonal efficiency given in the SAP boiler efficiency database (BRE, 2014b). However, it is likely that the actual efficiency will vary slightly from this value, and could vary over time depending upon temporally varying conditions. This was investigated using a heat meter installed in the central heating circuit, which allowed a live measurement of boiler efficiency; the results of this investigation are given in section 7.3.

The statistics in Table 7-2 show that, as expected, there was significantly greater temperature variation throughout the house during in-use tests than during co-heating tests. This is inevitable due to the differences in heat supply and distribution, and could be problematic as it means that the same boundary conditions are not applied across all elements of the building fabric. The observed uneven temperature distribution was consistent across all three of the in-use tests described in this sub-section, but more pronounced where there was a higher internal set-point temperature (i.e. for in-use tests 1 & 2). The median coldest and warmest rooms varied between tests. Unsurprisingly, given the stratification observed during the in-use tests, the coldest rooms were all downstairs and the warmest upstairs.

Test	Median Coldest Room	Median Warmest Room	Mean Max Room Temperature Difference (°C)
In-Use 1 – 25°C constant	Kitchen	Bathroom	6.3
In-Use 2 – 25°C 2 periods	Living Room	Front Bedroom	5.2
In-Use 3 – 20°C 2 periods	Living Room	Bathroom	4.4
Co-heat 1	*Kitchen*	*Living Room*	*0.7*
Co-heat 2	*Bathroom*	*Front Bedroom*	*0.7*

Table 7-2: Descriptive statistics for temperature variation occurring during the in-use tests. The last column shows the mean of the largest difference in temperature between any rooms, sampled on a 5 minutely basis. The statistics from two winter co-heating tests carried out in the Holywell test house are included for comparison.

A temperature variation between rooms was observed, with a particularly marked difference between the volumetrically weighted average temperature upstairs and downstairs. This is shown for an example day during each in-use test in Figure 7-3, Figure 7-4 and Figure 7-5.

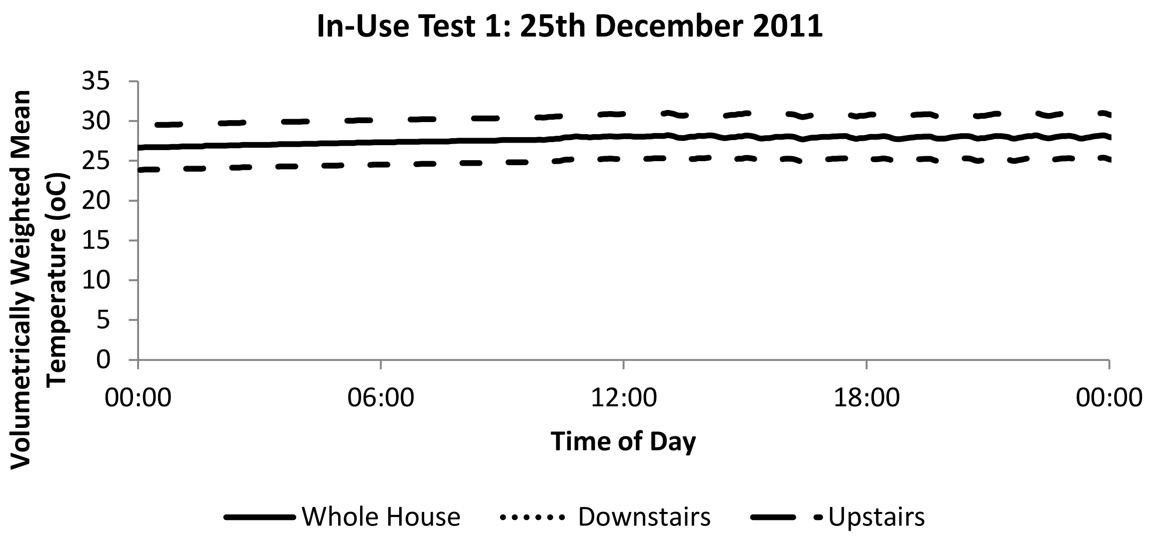


Figure 7-3: Temperature profile during example day of in-use test 1 – 25°C set point temperature and constant heating.

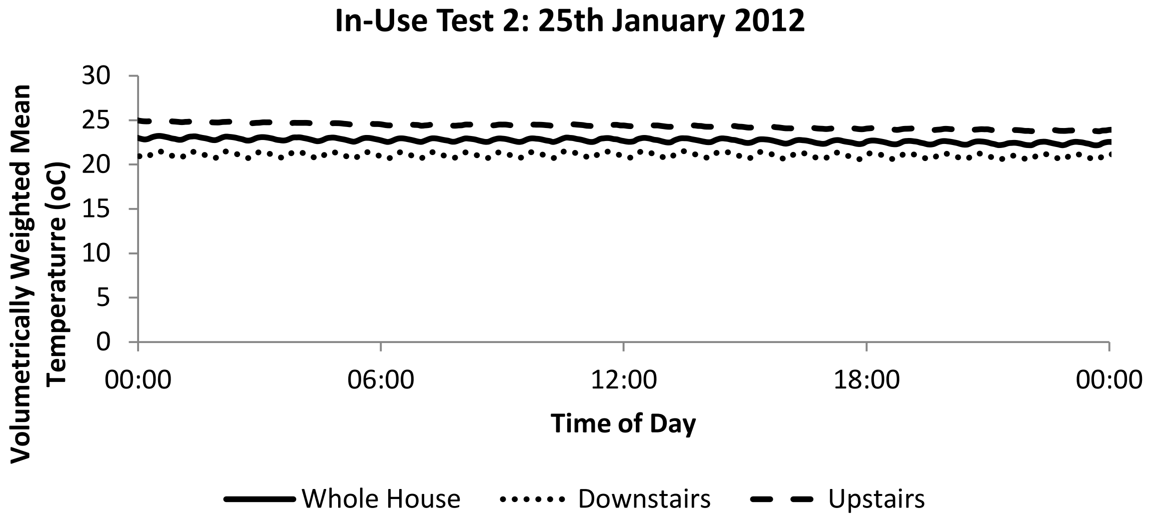


Figure 7-4: Temperature profile during example day of in-use test 2 - 20°C set point temperature and constant heating.

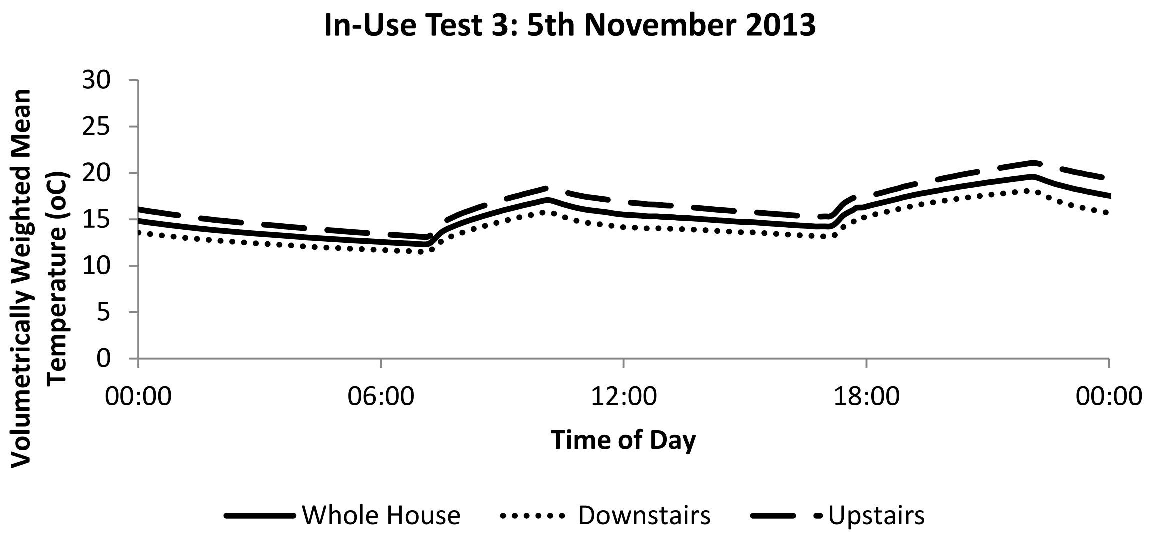


Figure 7-5: Temperature profile during example day of in-use test 3 - 20°C set point temperature and two heating periods.

The observed temperature variation between rooms makes clear the importance of measuring the temperature in every room, in order to ensure a representative measurement of the temperature of the whole space. A representative measurement of the average internal temperature is absolutely crucial to accurate measurement of the HLC, as a measurement skewed towards a warmer or colder area of the house will affect the result. The possible extent of this skew is shown for in-use test 1 in Figure 7-6.

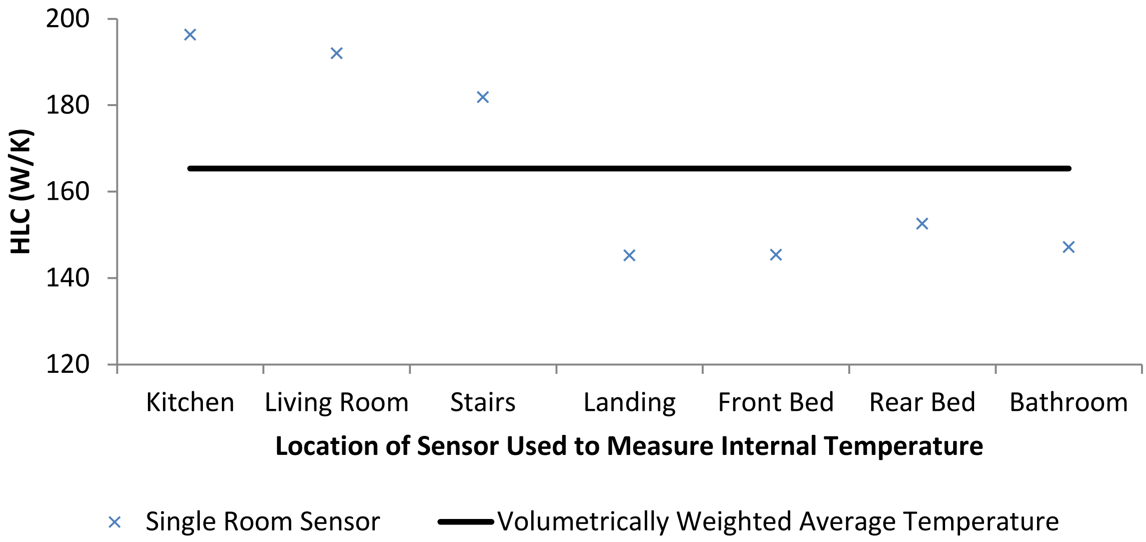


Figure 7-6: Showing the variation in calculated HLC if the temperature from a single room is used to define internal temperature, compared to a volumetrically weighted average internal temperature. The data in this figure is from in-use test 1: 25^{o}C internal set-point, constant heating.

It can be seen in Figure 7-6 that if the temperature of one of the downstairs rooms is used as the internal temperature, a significantly higher HLC results. This is because those rooms are cooler, resulting in a smaller internal-external temperature difference for the same heat input, which skews the heat balance to give a higher HLC (the opposite is true for the upstairs rooms). It can also be seen that even for a temperature sensor located at the centre of the house (in the Holywell house this location is halfway up the staircase; therefore the sensor is labelled 'stairs' in Figure 7-6), there is a skew in the calculated HLC as the mean temperature at this location is lower than that volumetrically weighted average temperature. This further demonstrates the importance of measuring the temperature in each room to allow the volumetrically weighted average value to be calculated.

In Figure 7-7 the relationship between the internal temperature used and the resulting HLC is shown, again for in-use test 1 with a 25^{o}C set-point and a constant heating profile. In this chart each data point shows the average temperature for a single room, and the resulting HLC if the temperature in this room alone was used to define the internal temperature of the house.

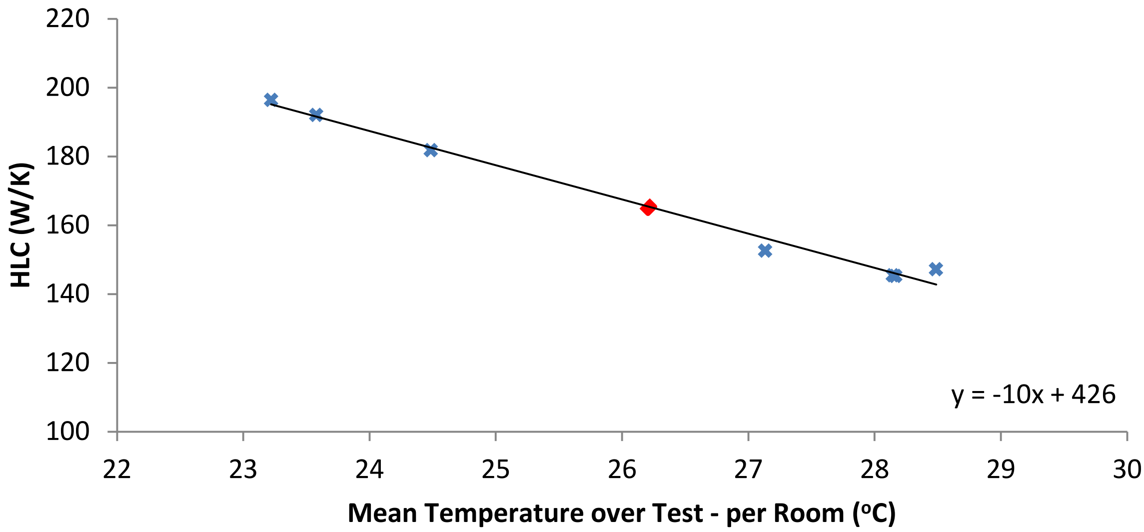


Figure 7-7: Variation in calculated HLC if the temperature from a single room is used to define internal temperature for in-use test 1. Each data point represents the temporally averaged mean temperature, and resulting HLC, for a single room; with the results for a volumetrically weighted average temperature shown by a red diamond.

Figure 7-7 shows that for every degree in difference in internal temperature there is a 10W/K change in the calculated HLC, which equated to a 6% difference compared to the HLC calculated using the volumetrically weighted average temperature. The distribution of downstairs rooms to the left of the red diamond (which is the volumetrically weighted average temperature) and the upstairs rooms to the right is clear to see in the figure. Comparisons for in-use tests 2 and 3, each using a 20°C set-point with constant heating and two heating periods respectively, are shown in Figure 7-8 and Figure 7-9.

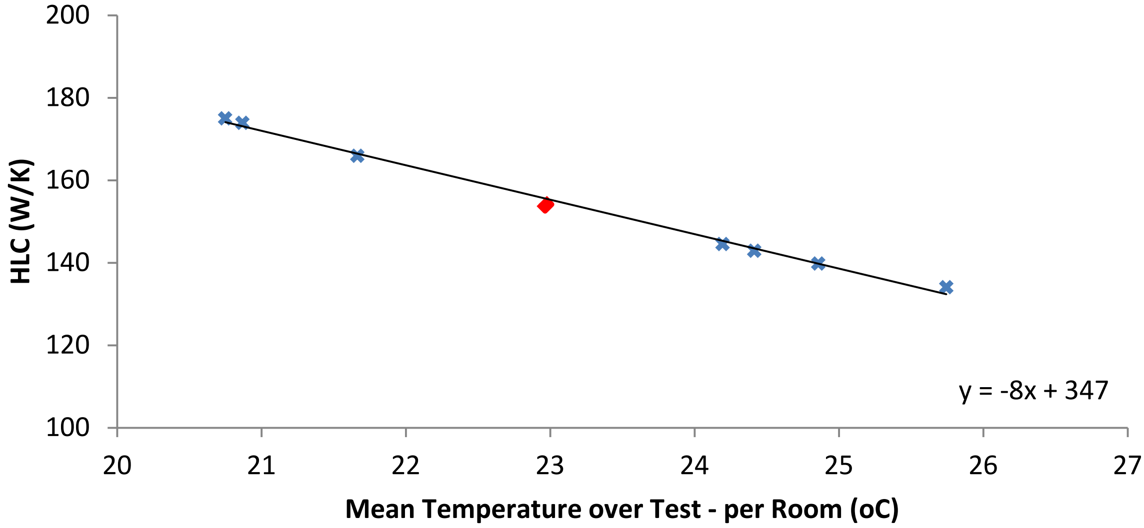


Figure 7-8: Variation in calculated HLC if a single room temperature is used to define internal temperature for in-use test 2, with a 20°C set-point and a constant heating profile. Each data point represents the mean temperature and associated HLC for a single room, with the results for a volumetrically averaged internal temperature shown by a red diamond.

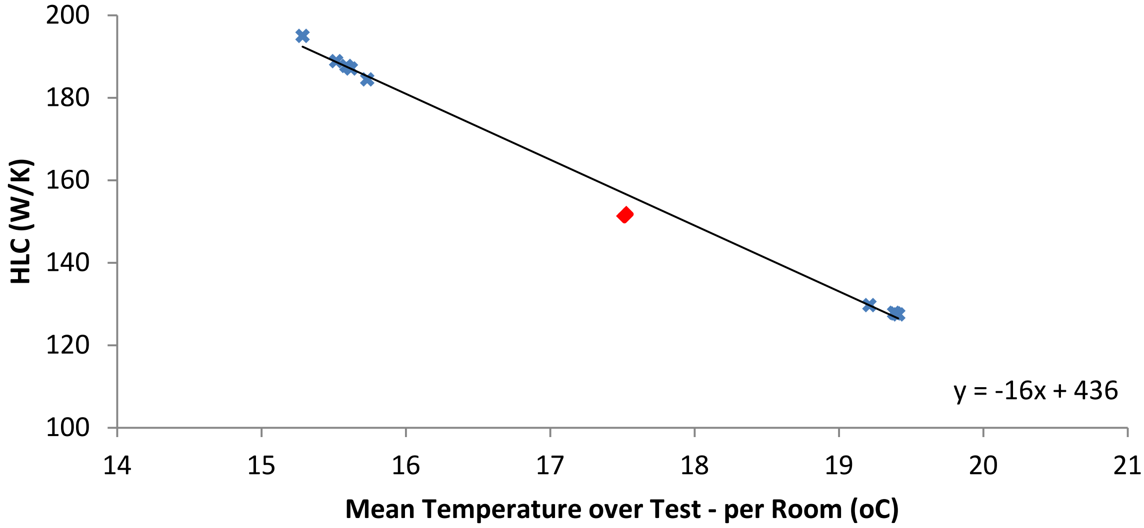


Figure 7-9: Variation in calculated HLC if a single room temperature is used to define internal temperature for in-use test 3, with a 20°C set-point and two heating periods. Each data point represents the mean temperature and associated HLC for a single room, with the results for a volumetrically averaged internal temperature shown by a red diamond.

Figure 7-8 and Figure 7-9 show that a similar relationship between internal temperature and the resulting HLC exists for all three tests. Though there is a stronger relationship for in-use test 3, where there was a greater temperature variation between rooms. Given that this represents perhaps the most likely heating pattern to occur in occupied houses, the importance of effective temperature measurement and averaging to ensure a representative measurement of the whole internal space in the house is further demonstrated.

Despite the issues identified with internal temperature variation and the added uncertainty in measuring the heat input provided by a central heating system; the results of these in-use tests, shown in Figure 7-2, demonstrate a successful initial trial of the LIUHB test. Showing that, in this particular house, the HLC can be measured using the installed central heating system as the heat source. Clearly this represents a significantly cheaper and easier experimental method than that usually applied in co-heating tests.

The results also suggest that the greater variation in temperature throughout the house did not have a large impact on the measurement of the HLC, as long as a volumetrically weighted mean temperature is used.

7.2. The Impact of Sensor Placement

In a house during normal occupation the internal temperature will vary spatially dependent upon a number of factors, therefore the placement of sensors to measure internal temperature is a vital part of taking a representative measurement of the whole space. Evidence of the additional temperature variation throughout a house during in-use tests, in comparison to co-heating tests, has been presented on a room by room and floor by floor basis (Table 7-2 and Figure 7-3 - Figure 7-5). This showed a significant variation in internal temperature, even in an empty house with all internal doors open, and particularly the influence of thermal stratification – causing a significant difference between downstairs and upstairs mean temperature.

To investigate the issue of temperature distribution on a smaller scale, an experiment was designed to measure the spatial temperature variation in a single room (the front bedroom, which can be seen on the floorplan in Figure 4-2). A grid of temperature sensors was arranged in three layers vertically, with nine sensors in each layer. The layers were arranged such that the temperature was measured close to the floor, at mid-height and close to the ceiling, with nine measurement positions spread evenly around the room. The experiment was carried out with three different sets of conditions: during a standard co-heating test and during two in-use energy balance tests, one with constant heating and a 25°C set point temperature, and another with a 20°C set point and two heating periods. The results for an example day during a co-heating test are shown in Figure 7-10.

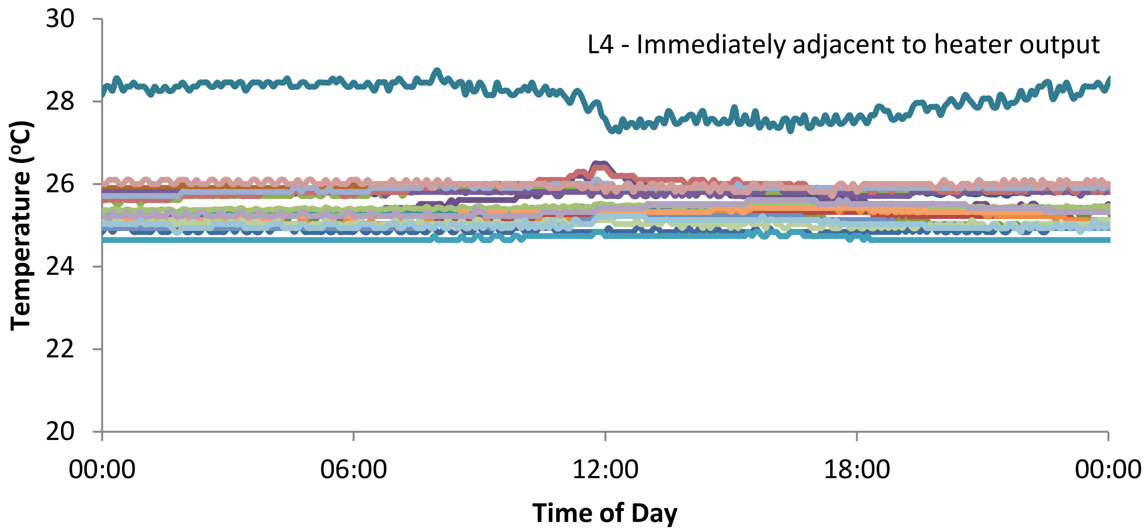


Figure 7-10: Spatial temperature variation test results for an example day during a co-heating test, the temperature traces of each of the 27 temperature sensors are shown.

It can be seen in Figure 7-10 that there is very little variation in the temperature distribution throughout the room during the co-heating test. Only sensor L4 shows an increased temperature, this is due to its proximity to the output of the fan heater in this room. This shows the effect of the mixing fans used in co-heating, this effect is particularly easy to notice when the results for the co-heating test are compared to those of an in-use test with the same set-point temperature – shown in Figure 7-11.

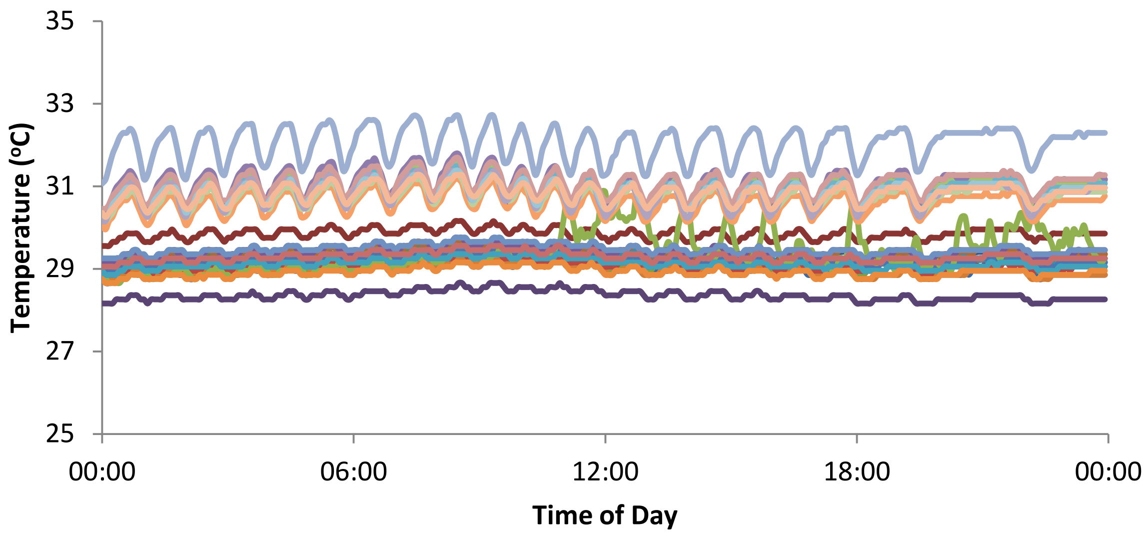


Figure 7-11: Spatial temperature variation results for an example day of an in-use test with constant heating and a 25^{o}C set point temperature.

As Figure 7-11 shows, there is considerably more variation in the temperature during the in-use test. In fact there is so much variation that it is difficult to see a clear pattern, however, when the mean temperature of each layer (lower, middle and top, located close to the floor, at mid-height and close to the ceiling, respectively) is taken a much clearer picture emerges, as shown in Figure 7-12.

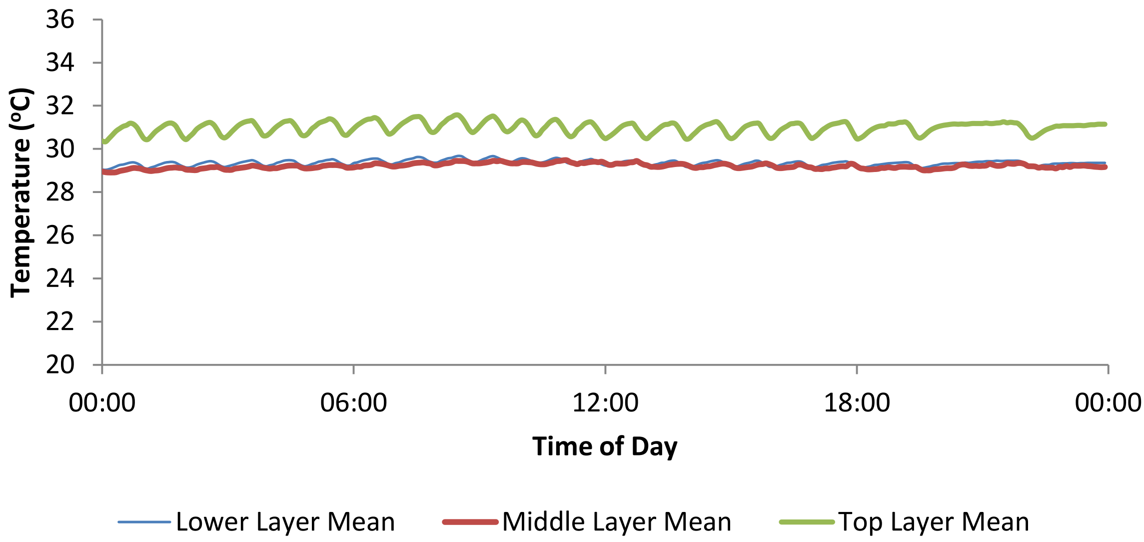


Figure 7-12: Spatial temperature variation results for an in-use test with constant heating and a 25°C set-point, the mean temperature of each layer, calculated on a 5-minutely basis, is shown for ease of comparison.

It is clear from Figure 7-12 that the lower and middle layers are at a very similar temperature, but the top layer is significantly warmer. This relationship is repeated in an in-use heat balance test with a lower temperature set point, of 20°C, and two heating periods, as shown in Figure 7-13.

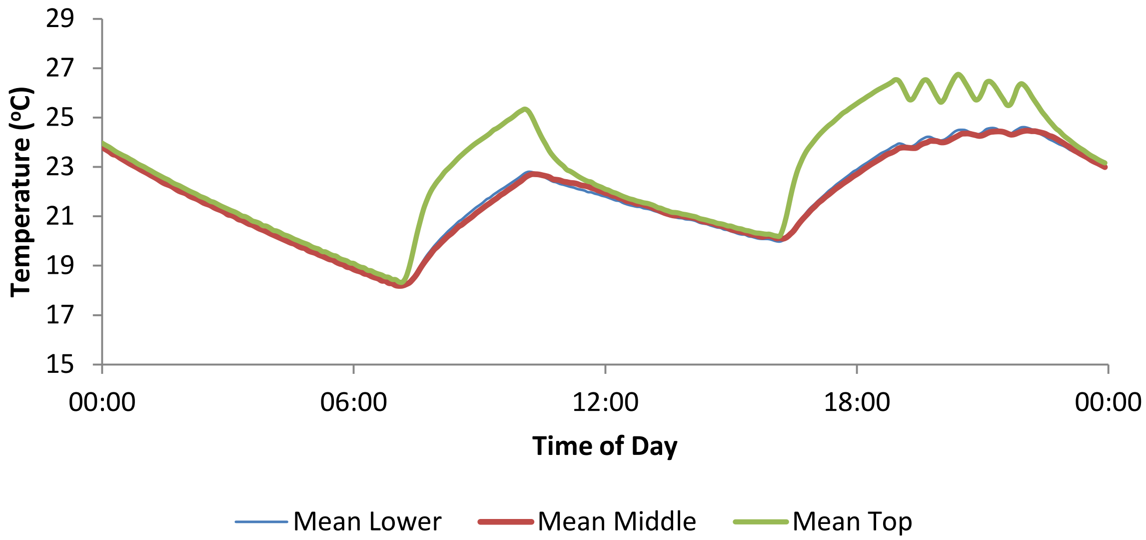


Figure 7-13: Mean temperature of each layer during an in-use heat balance test with a set-point temperature of 20°C and two heating periods.

It can be seen in Figure 7-13 that the temperature of all layers reaches a similar level while no heating is supplied to the room, with the difference between the top and lower layers being re-established while heat is supplied. These charts all show the effect of stratification on a room scale while the house is heated during in-use tests. The effect on a whole house scale is demonstrated by the temperature reached in this room while the heating is on, which is significantly above the set-point temperature that is controlled by the thermostat positioned downstairs, in the hall. The extent of the stratification within the room is shown in Table 7-3.

	Mean Temperature of Layer (°C ±0.5°C)		
Test	**Lower**	**Middle**	**Top**
Co-heat – 25°C set-point	25.8	25.4	25.4
In-use - 25°C constant	29.4	29.2	31.0
In-use - 20°C 2 periods	21.7	21.7	22.8

Table 7-3: Spatial temperature variation results summary for stratification investigation.

As Table 7-3 shows, the effects of stratification were limited to the top layer in this test, with an average temperature approximately 2°C higher than that of the lower or middle layers while heat is being supplied. The temperature of the lower and middle layers were within ±0.5°C of each other, which is the uncertainty range of the sensors used, so the results suggest that in this room any sensor locations used in this region will result in the same measurement. Although these results are consistent it should be noted that they were all collected in one room. Therefore the experiment was repeated on a smaller scale in the living room, with just one sensor at each height, rather than the grid that was used in the upstairs bedroom. This set-up allows an insight into stratification, but not into variation in temperature around the room.

The results for an example day during a co-heating test and an in-use test, using a 20°C set-point temperature and two heating periods are shown in Figure 7-14.

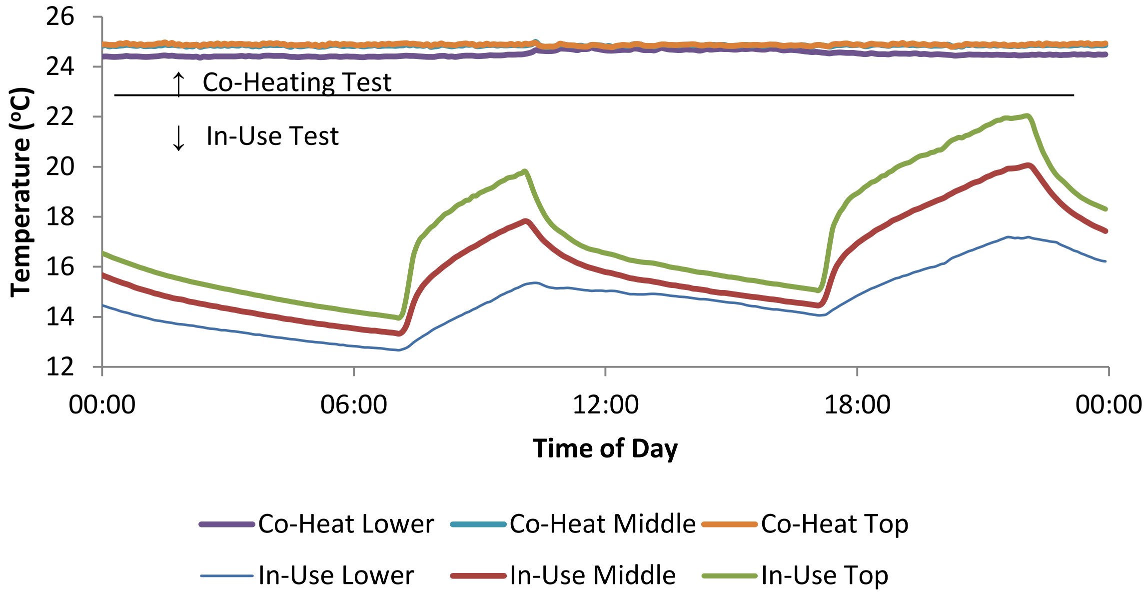


Figure 7-14: Results for the small-scale spatial temperature variation experiment in the living room during a co-heating test (temperature set-point 25°C) and an in-use test with a 20°C set-point temperature and two heating periods.

As was the case in the bedroom, there is no evidence of stratification during the co-heating test, with the mixing fans clearly effective. It is clear though, that in the living room there is a different shape to the stratification during the in-use test than there was in the bedroom. In this case there is an increasing temperature between each layer, from the lower to the top; instead of the lower and middle layers having the same temperature as was the case in the upstairs bedroom. The results shown for an example day in Figure 7-14 are consistent for the whole period of the test, as shown in Table 7-4.

	Mean Temperature of Layer (°C ±0.5°C)		
Test	**Lower**	**Middle**	**Top**
Co-heat – 25°C set-point	24.5	24.9	24.9
In-use - 20°C 2 periods	14.1	15.7	17.0

Table 7-4: Spatial temperature variation results observed in the living room, the mean values for the complete period of each test (2 weeks for co-heating, 3 weeks for the in-use test) are shown.

So the results show that for the in-use tests there will be a temperature difference vertically across the room, which is of course as would be expected, but that the profile will be different in different rooms. As data has only been gathered in two rooms it is not possible to say what the distribution will be. A comparison between the mean temperature of each layer, during each spatial temperature variation experiment, and the mean temperature of all sensors in all layers is shown in Table 7-5.

	Mean Temperature of Layer (^oC ±0.5^oC)			
Test	**Lower**	**Middle**	**Top**	**Mean All Sensors**
Bedroom: Co-heat - 25^oC	25.8	25.4	25.4	25.5
Bedroom: In-use - 25^oC constant	29.4	29.2	31.0	29.8
Bedroom: In-use - 20^oC 2 periods	21.7	21.7	22.8	22.1
Living Room: Co-heat - 25^oC	24.5	24.9	24.9	24.8
Living Room: In-use - 20^oC 2 Periods	14.1	15.7	17.0	16.0

Table 7-5: Results of all spatial temperature variation experiments undertaken.

The comparison shows that the mean temperature of the middle layer has a close agreement with the mean temperature of all sensors in all tests. This suggests that a temperature reading taken at mid-height would give a representative measurement of the mean temperature in the room as it varies vertically.

The extent of vertical temperature variation has been considered in detail; next the variation in temperature laterally will be examined. The mean temperature at each sensor in the spatial temperature variation experiment is shown during in-use tests with a 25^oC set-point and constant heating, and 20^oC set-point with two heating periods, in Figure 7-15 and Figure 7-16 respectively.

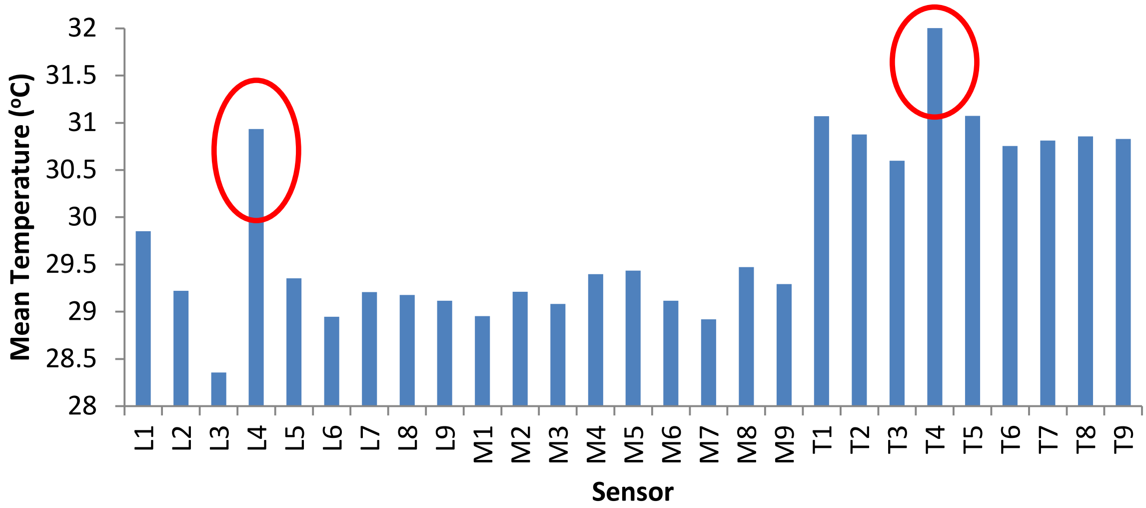


Figure 7-15: Mean temperature of each sensor in the spatial temperature variation experiment during an in-use heat balance test with a 25°C set-point and constant heating. Sensors labelled L are in the lower layer, M in the middle layer and T in the top layer.

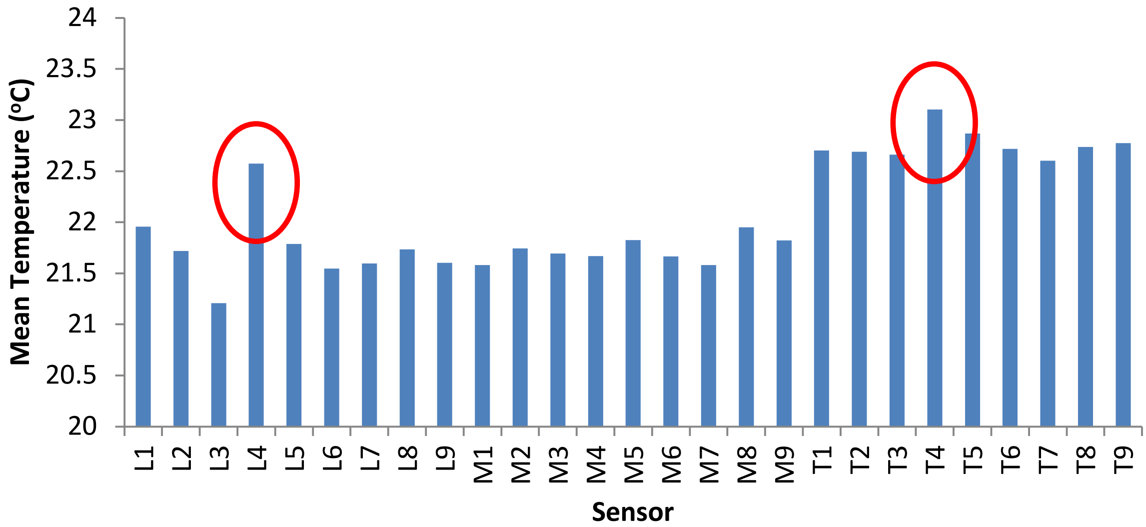


Figure 7-16: Mean temperature of each sensor in the spatial temperature variation experiment during an in-use heat balance test with a 20°C set-point and two heating periods.

In both Figure 7-15 and Figure 7-16 sensors L4 and T4 show a higher average temperature over the test. This is not surprising at this the 4^{th} column of sensors were positioned immediately adjacent to the radiator in the room. The temperature traces for an example day of the experiment are shown in Figure 7-17.

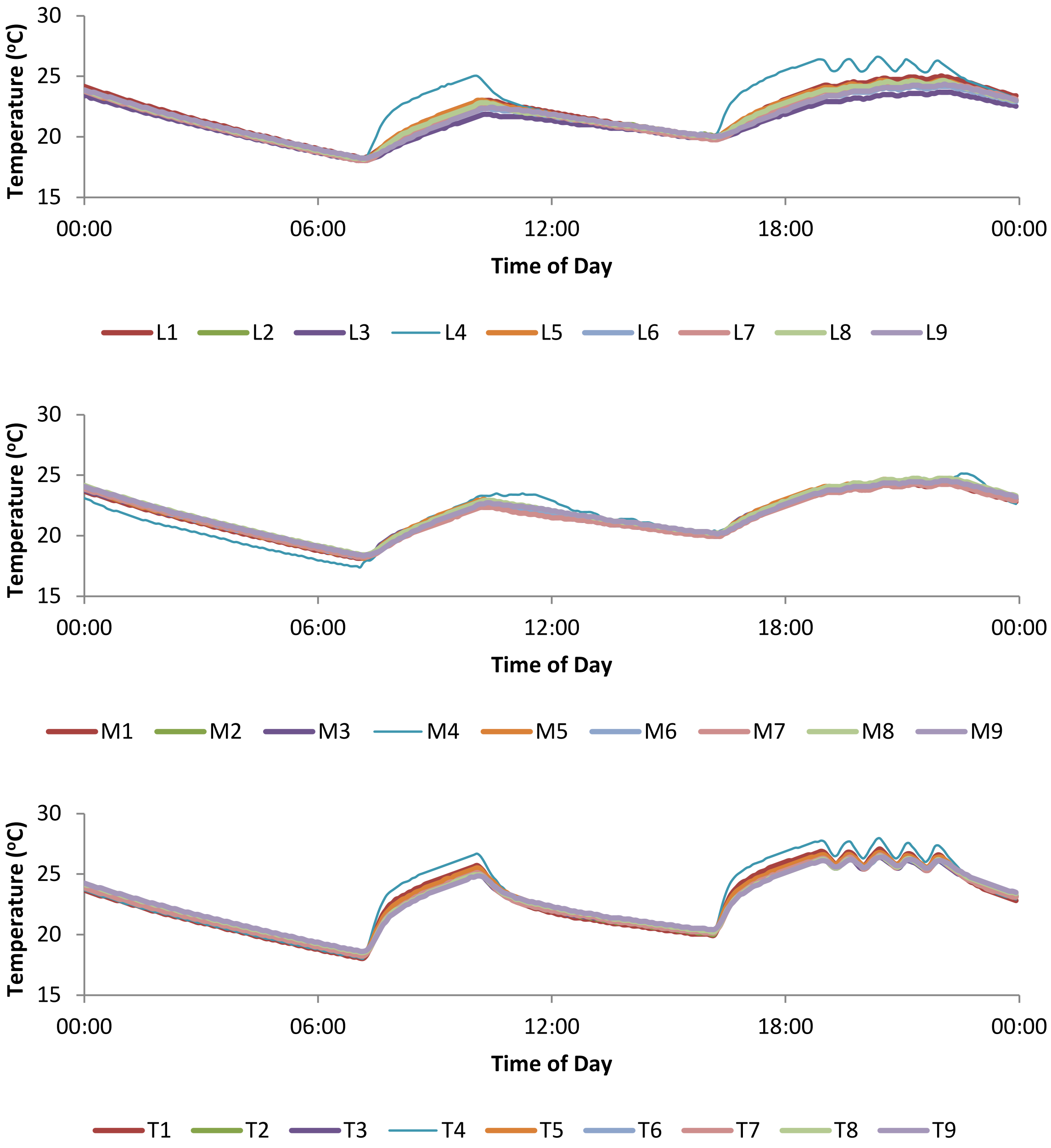


Figure 7-17: Temperature traces for each layer of sensors (L-lower, M-middle and T-top) in the spatial temperature variation experiment for an in-use test with a set-point of 20°C and two heating periods.

It is clear from Figure 7-17 that apart from the 4th column of sensors (labelled L4, M4 and T4), there is a uniform temperature distribution across the space laterally, with all variation within the uncertainty of the measurement. The results show that only the measurements taken very close to the radiator were directly by it, as none of the sensors positioned just 1 metre away from the 4th column showed any variation from the farther sensors.

Of course it should again be noted that these results are only for one room in one house, furthermore this is a rather simple scenario with only one heat source (the radiator) in the room.

The situation would be more complex in other situations where there could be several heat sources, such as electrical appliances, cookers or secondary heating.

The combination of the analysis in the vertical and lateral directions shows the suitability of the directions typically given to position sensors at mid-height in a room, and away from the direct influence of heat emitters. The analysis has shown the importance of following this advice, with misplacement leading to a misrepresentation in the mean temperature of the room of around 1-2^{o}C in both the cases studied. The evidence from the analysis has also shown that as long as this guidance is followed, the exact location within a room does not appear to make a large difference to the temperature measurement.

7.3. Boiler Efficiency Measurement

In the vast majority of houses the heat supplied by a gas or oil boiler will contribute the largest part of the input to the heat balance in an in-use heat balance test. This makes quantifying the uncertainty in the measurement of this heat input a vital part of establishing the total uncertainty of the LIUHB. While the notional efficiency of any particular boiler can be easily found in the SAP boiler database (BRE, 2014b), in-situ studies have shown that there can be considerable variability between the performance of similar machines. The performance of a particular boiler is dependent upon a number of factors associated with the installation of the boiler, the way it is operated and the conditions in which it operates.

The year-long, in-situ monitoring study of 60 condensing boilers carried out on behalf of the Energy Savings Trust (EST) in 2009, provides excellent information regarding the variation in performance of installed boilers across a reasonably large sample (Orr et al., 2009). In addition to this evidence, a series of experiments was carried out in the Holywell test house to investigate the effect on boiler efficiency of a series of different control strategies. The boiler tests included changes to the internal temperature set-point, the length and timing of heating periods, and the setting of thermostatic radiator valves (TRVs) throughout the house.

The EST study found a mean efficiency for regular boilers of 85.3%, with a standard deviation of 2.5%, which compared to a seasonal efficiency of 90.4% (standard deviation 1.1%) according to the SAP database for the sample (ibid). This sample has a slightly higher mean efficiency than the boiler installed in the Holywell house, but this result can be used to give an estimate of the maximum possible uncertainty in the heat output of a boiler for a stated efficiency. At a 95% confidence level, the maximum uncertainty would be -6.64%, there is not an upper band as the observed efficiency was always lower than expected. The schedule and results of the boiler efficiency trials carried out in the Holywell test house is shown in Table 7-6.

Test	Heating Periods	Temperature Set Point (°C)	TRV Setting	Monitoring Period	Measured Efficiency (%)
1	2: 0600-0900, 1600-2100	20	5/5	2 days	86.7
2	2: 0600-0900, 1600-2100	20	3/5	2 days	88.5
3	1: 0600-2100	20	3/5	3 days	85.4
4	1: 0600-2100	16	3/5	2 days	83.4
5	1: 0600-2100	16	5/5	11 days	84.8
6	24 hours	20	5/5	7 days	84.0
7	24 hours	16	5/5	2 days	84.3

Table 7-6: Description and results of the boiler tests.

The final column in Table 7-6 shows the measured boiler efficiency during each of the tests; the mean efficiency was 85.3%, with a range from 83.4%-88.5% and a standard deviation of 1.8%. The results of the experiments agrees closely with those found in the EST study, suggesting that a significant amount of the variation observed in those results may be related to the way in which the boiler is operated, rather than a variation in performance of the boilers themselves. It should be noted that this evidence is based upon the performance of a single boiler, while the EST study is based upon measurements carried out on many boilers. It should be noted, however, that with combination of the EST study and the testing reported in this thesis only represents a total sample of 61 boilers, which is very small in comparison to the total number of boilers in use. The resulting estimate of the uncertainty in the output of the boiler from this information cannot, therefore, be considered statistically significant and is only the best possible estimate from the available information.

The measured efficiency of the boiler only reached the stated SAP winter seasonal efficiency of 87.3% (which is typically used for the efficiency of supplying space heating (BRE, 2011)) in one of the boiler tests, test 2. The mean measured efficiency across all tests was 2% lower than the winter seasonal efficiency, with the lowest efficiency 3.9% lower.

During the boiler tests several supporting measurements were taken in order to investigate possible causes for changes in efficiency, these included:

- Mean internal air temperature in every room
- Mean external air temperature
- Mean water temperature at the outlet of the boiler
- Mean return water temperature to the boiler
- Mean flow rate in the central heating pipework.

From these measurements the following properties were derived:

- Percentage of heating period during which there was a flow in the central heating pipework – this is used as a proxy measurement of when the central heating pump is operating
- Mean flow – return water temperature
- Mean internal – external air temperature
- Total hours of flow in the central heating pipework
- Mean flow rate in the central heating pipework during periods when there was a measured positive flow (i.e. when the central heating pump was operating).

Finally, the following observed properties were also included in the analysis:

- Sum of heating hours per day in all heating periods (e.g. two periods of 0600-0900 and 1600-2100 give 8 total hours)
- Internal temperature set-point
- TRV settings.

The Pearson's product-moment correlation coefficient was calculated between each property and the measured boiler efficiency across the seven boiler tests. The statistical significance of each correlation was then calculated using a two-tailed t-test, significance was tested at the 95% level. At this point it should be noted that the seven tests represent a rather small sample size, with each test carried out over a short period. There is also a strong possibility of co-correlations between some of the variables. Therefore the results should be interpreted with caution, in the knowledge that statistically significant correlation, or lack of it, does not prove or disprove causality.

Statistically significant negative correlations were observed between boiler efficiency and two variables: external temperature and total heating hours; while a significant positive correlation was found with the percentage of the heating period that the central heating pump operated. It seems likely that these three pieces of information could be combined to state that the boiler operates more efficiently for a higher load:

- when the heating demand is higher due to a lower external temperature,
- and when the heating is on for a shorter length of time, and therefore is less likely to reach the set-point temperature in the heating period – as demonstrated by the high percentage of time with the central heating pump in operation.

This conceptual link between the variables with statistically significant correlations with boiler efficiency helps to build confidence in the findings.

The results of these tests and those of the EST monitoring study now give two indications as to the maximum possible uncertainty in the measurement of heat input from the boiler (-3.9% and -6.64%, respectively, for the results of the measurements carried out in this thesis and reported in the EST study). The measurements carried out in the EST monitoring study will include the effects of both variations in operating conditions and variation in performance between boilers. Therefore, the maximum uncertainty reported in the EST study, of -7% (rounded to 1 significant figure) compared to the reported SAP seasonal efficiency of the boiler, has been chosen for use in this study as the estimate of uncertainty in the heat input from a boiler.

This uncertainty could be reduced by additional measurements, which could vary in their detail depending upon the level of accuracy that is sought. The level of measurement could range from the installation of a heat meter in the central heating system, as was used in these tests; to a one-off measurement of flow rate using a non-invasive ultra-sonic flow meter combined with ongoing measurement of the flow and return temperatures using contact temperature sensors external to the pipework. However, any such measurements are thought likely to be too high in cost and invasiveness for application in this style of test. This is especially so given the high level of agreement between the results of in-use heat balance and co-heating tests, presented in section 7.1, which were analysed using the SAP winter seasonal efficiency of the boiler to calculate it's heat output.

7.4. Synthetic Occupancy Tests

The presence of occupants causes an extra, unpredictable, set of variables in an in-use test compared to a test carried out in an empty house. In this section the results of an investigation into the added uncertainty caused by these variables in the LIUHB test are reported, the investigation was carried out using the application of synthetic occupancy in the Holywell test house. Four occupancy variables were chosen for the synthetic occupancy tests: window opening, hot water use, internal gains (electrical & metabolic) and window covering by blinds. For each variable associated an occupant behaviour pattern was sourced from previous research, in each case the most extreme reasonable behaviour was selected in order to detect the maximum possible uncertainty contributed by each.

The variables were applied individually in a series of in-use heat balance tests so that the effect of each could be investigated. Each test lasted for a period of at least one week. For each variable a calculated estimate of its effect on the measured HLC was produced. The estimate was then compared to the measured effect. Using this method an estimate of the total uncertainty in the LIUHB method was calculated, which was then compared to the results of a full synthetic occupancy test, during which each of the variables was applied simultaneously. The testing was carried out during the 2012/13 and 2013/14 winters.

7.4.1. Synthetic Occupancy Variable 1 - Window Opening

The effect of window opening is perhaps the most obvious source of uncertainty in any in-use method. While other actions, such as electrical appliance use or cooking, could change the way the heat is supplied and measured, window opening causes an immediate and seemingly unpredictable change in the thermal performance of the house. In order to account for this potential source of uncertainty in the LIUHB three questions must be addressed:

1. How large is the likely change in thermal performance?
2. What is the scale of this change relative to the performance of the whole house and therefore what additional uncertainty could be added to the measurement of the HLC?
3. Could this effect be measured or removed (i.e. ask people not to open windows)?

These questions were addressed using tests carried out in the Holywell test house. In order to address the first question it is necessary to understand what the effect of opening windows or external doors could be – and specifically what the resulting change in the air infiltration rate to the building would be. To investigate that infiltration rate measurements were taken using the blower door method (BSI, 2001b), while each manually operable window in the house was opened to different extents. The range of tests that could be carried out was limited as after the total extra leakage area passed a certain level, approximately $0.6m^2$, there was too much variation in the building pressure measurement to record accurate results. The air change rate at 50 Pascals pressure difference across the building, which is measurement taken by the blower door test, has been converted into an infiltration rate at normal pressure difference for ease of understanding using the K-P model (Sherman, 1987). The results of the test are shown in Figure 7-18, with the infiltration rate measured by the blower door test, and converted by the K-P model, compared to the area of the window opening in each test. The results shown were collected by opening six different windows spread across the house, including windows on the ground and first floor and on each facade with glazing.

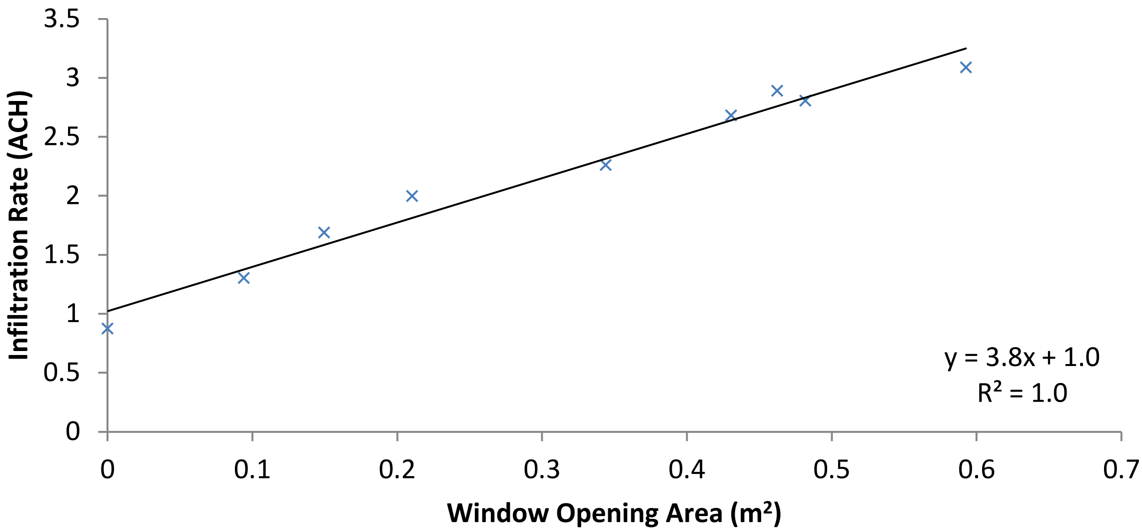


Figure 7-18: Change in infiltration rate due to window opening; each data point shows the result of a blower door test with different windows throughout the house opened to varying degrees.

Figure 7-18 shows that there was a close linear relationship between the area of the window opening and the resulting change in the infiltration rate to the building, at a rate of 4 air changes per hour for every m^2 of extra opening area. This relationship was independent of the height of the window, and the room and facade that it was located in.

The oft repeated refrain in this thesis, that this result is for one house only, must again be used here. Furthermore, it is likely that the relationship between infiltration rate and opening area would be temporally affected by weather conditions such as a higher wind speed, direction, or internal-external temperature difference which would all cause a different pressure gradient across the house. This calls into the question the suitability of the blower door test to carry out this measurement; as in this test the pressure difference over the building is closely controlled compared to the natural variation that will occur in real life. However, this effect could be offset by research that shows that window opening is less likely for lower external temperatures and higher wind speeds (Fabi et al., 2012; Johnson and Long, 2005).

This linear relationship between infiltration rate and window opening was also found in the only other similar study found in the literature (Howard-Reed et al., 2002). This study was carried out in two occupied houses in America using a tracer gas decay method, which allowed measurements in different weather conditions over a period of several months and with different combinations of open windows. This is a significant finding as it is likely that different combinations of window openings, particularly in different facades, would cause different airflow paths through the house. The effect of these different airflow paths, such as cross or stack ventilation for example, is not accounted for in the blower door-based method used in this study, but is accounted for in the tracer gas method employed by Howard-Reed (2002).

The combined results of the Howard-Reed et al study in occupied houses and those measured in the empty Holywell test house for this project, though they represent a sample of only three houses, adds confidence in the finding of this study of a linear relationship between window opening and added ventilation.

This linear relationship between window opening area and additional air infiltration means that the expected additional heat loss associated with a given window opening area, and length of opening, can be easily calculated for a set of internal and external conditions in the Holywell house. This method is used to allow a comparison between the expected effect on the measurement of the HLC using the LIUHB, and the observed effect.

The window opening schedule used in the synthetic occupancy tests was (a description of the process of selecting this schedule can be found in section 3.2.4):

- Kitchen window, open 18:30-18:45
- Bathroom window, open 07:30-08:00
- Bedroom windows (front and rear facade), open 08:00-08:15.

The opening area and associated estimated additional ventilation for each of the windows actuated in the synthetic occupancy experiments are shown in Table 7-7.

Window	Opening Area (m^2)	Additional Ventilation (ACH)
Kitchen	0.43	1.8
Bathroom	0.33	1.4
Front Bedroom	0.59	2.4
Rear Bedroom	0.46	1.9

Table 7-7: Window properties for each of the windows actuated in the synthetic occupancy experiments.

The observed relationship between window opening area and increase in the ventilation rate allows the additional energy consumption associated with this window opening behaviour to be estimated. This can be used to predict the effect on the measured HLC during the in-use test with the window opening synthetic occupancy variable.

The estimated additional heat loss due to window opening (Q_w) is calculated using (EQ 7-1):

$$Q_w = \rho \, C_P \, \Delta T \, \Delta v \, V \qquad \text{(EQ 7-1)}$$

Where ρ is the density of air (kg/m^3) at the mean indoor temperature during the window opening, C_p is the specific heat capacity (J/kgK) of air at the mean indoor temperature, ΔT is the internal-external temperature difference (K), Δv is the additional ventilation due to window opening (ACH) and V is the internal volume of the house (m^3).

The air temperature close to the open window is likely to be different to the volumetrically weighted mean indoor temperature, which could affect the amount of heat loss. However, the heat loss due to the window opening does not occur only in that space, there will be a complex network of heat transfer throughout the building. Therefore, as the method considers the whole internal volume as a single space, it has been decided to use the mean internal temperature to calculate the ΔT which is inputted to (EQ 7-1).

The empirically defined relationship between window opening area and additional ventilation in the Holywell house, where each square metre of additional opening results in 3.8 additional air changes per hour, has been used to create Figure 7-19. The figure shows the relationship between the area of a window opening and the additional heat loss that this opening is likely to cause. In order to give a visual reference of the scale of the heat losses, the total HLC of the Holywell house, with all windows closed, has been displayed.

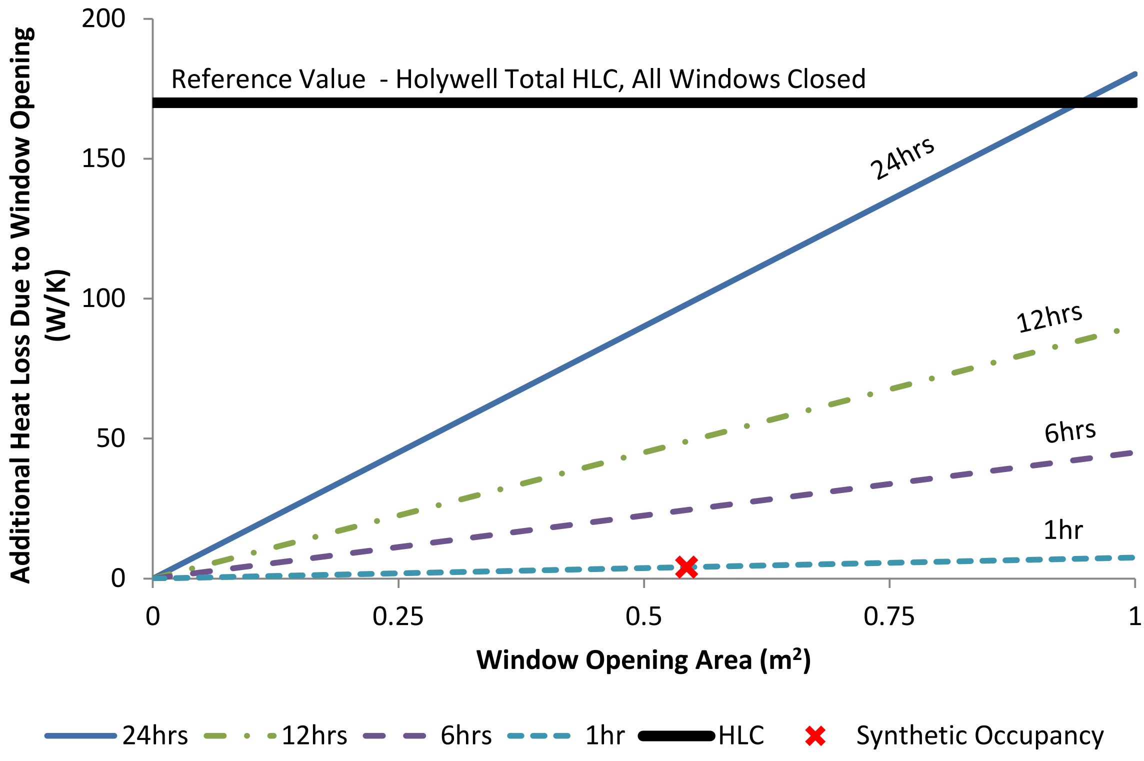


Figure 7-19: Relationship between window opening and additional heat loss in the Holywell test house. The labelled trendlines show the effect of a window opening area of different sizes for different lengths of time per day. The total HLC of the house, with all windows closed, has been shown to give context to the size of the heat losses. The estimated combined effect of the window opening profile used in the synthetic occupancy experiment is shown by the red X.

It can be seen in Figure 7-19 that window opening has the potential to cause a significant uncertainty during an in-use test in the Holywell house. This graph is specific to the Holywell test house and will show a different relationship for other houses, this relationship will depend primarily upon the airtightness and level of fabric performance of the house with all windows closed.

Figure 7-19 shows that in the Holywell house, a window opening of 0.94m^2, open 24 hours per day would double the heat loss rate from the house. This opening area could occur at one window or some combination of many windows. However, it can be observed that this is a very large window opening for the middle of winter and represents very extreme behaviour. The effect of the window opening schedule applied during the synthetic occupancy experiments is shown in Figure 7-19 by a red X. This provides a more realistic context for the levels of uncertainty that could be introduced by window opening in occupied dwellings. The estimated additional heat loss caused by the synthetic occupancy window opening is 4.1W/K, which is 2.4% of the total HLC of the building (as measured by co-heating tests). Therefore the estimated total heat loss rate for the in-use heat balance test, including the effect of the window opening, is 174W/K.

The reason that window opening has a small impact on the total heat loss coefficient in the Holywell test house is associated with the performance of the house itself. The total heat loss is comprised of two components, the fabric and infiltration heat loss:

$$\text{Total Heat loss} = \text{Fabric heat loss} + \text{Infiltration heat loss} = \sum UA\,\Delta T + 1/3\,N\,V\,\Delta T \qquad \text{(EQ 7-2)}$$

Where $\sum UA$ is the sum of the U-value of each building element (W/m^2) multiplied by its surface area (m^2), N is the air permeability of the house (ACH), V is the internal volume of the house (m^3) and ΔT is the internal-external temperature difference. For ease of comparison both sides of the equation can be divided by ΔT, so that it is stated in terms of heat loss rates rather than total heat loss. The total HLC of the Holywell test house, as measured by co-heating tests, is broken down into a fabric component of 130W/K and an infiltration component of only 40W/K:

$$\text{Total HLC} = \text{Fabric heat loss rate} + \text{Infiltration heat loss rate} = 130\text{W/K} + 40\text{W/K} = 170\text{W/K} \qquad \text{(EQ 7-3)}$$

Window opening only affects the infiltration heat loss from the building, specifically by changing the air permeability of the house. A comparison of (EQ 7-2) and (EQ 7-3) makes it clear that a very large change in the air infiltration rate would be required in order to cause a significant change in the total heat loss rate from the Holywell test house. Clearly this is a relationship specific to a particular house; the heat loss due to window opening is related to the opening area and therefore is not affected by the fabric performance of the house or its air tightness. This means that in houses with lower heat loss rates the effect of window opening will be relatively larger, causing a larger uncertainty in the result of the LIUHB method. Comparison of the equations also suggests that the effect of window opening will be more pronounced for smaller houses (with a lower internal volume).

The relationship between the additional uncertainty in a HLC measurement by an energy balance test and the total HLC of a house of the same internal volume as the Holywell test house is shown in Figure 7-20. The additional heat loss caused by the window opening profile used in the synthetic occupancy tests, of 4.1W/K, has been used to generate Figure 7-20.

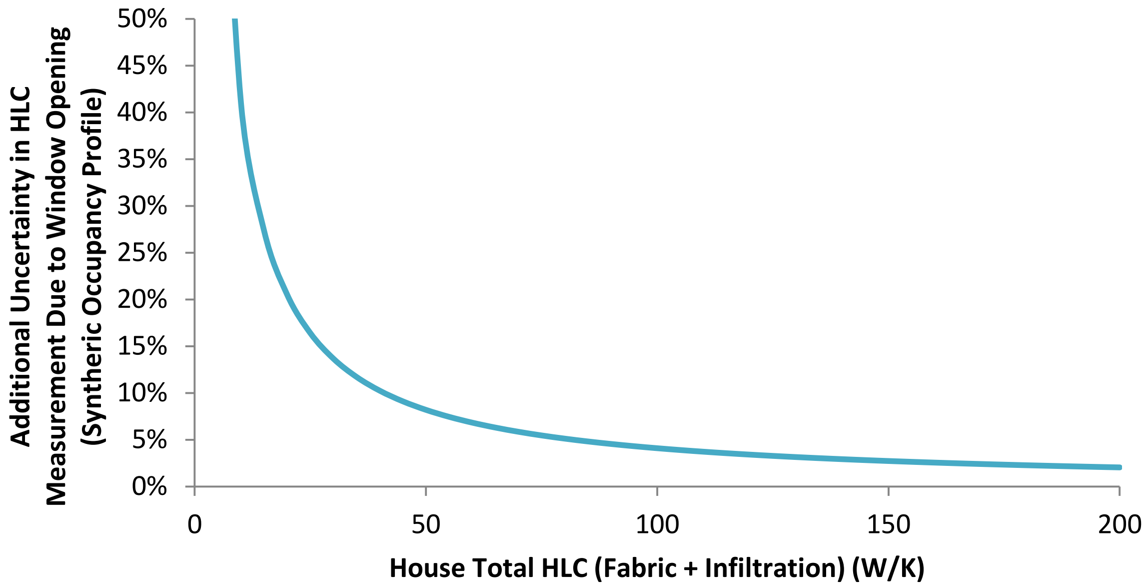


Figure 7-20: The relationship between the total HLC of a house and the additional uncertainty in the HLC measurement by an in-use energy balance test due to the window opening profile used in the synthetic occupancy tests.

The relationship shown in Figure 7-20 highlights that the in-use energy balance test may not be appropriate for use in highly performing houses, as the relative impact that could be caused by window opening increases as the total HLC of the house decreases. There is an added uncertainty of greater than 5% for houses with an HLC lower than 75W/K, and greater than 10% for houses with an HLC lower than 40W/K. It is important to note that the relationship shown in Figure 7-20 is specific to a house of the same internal volume as the Holywell test house and to the window opening behaviour applied in the synthetic occupancy tests.

This subsection has described significant efforts to estimate the effect of window opening on an LIUHB test, resulting in an estimated HLC including the effect of window opening of 174W/K. This estimated HLC is compared with that measured in the window opening synthetic occupancy test, and the baseline measurements gathered by a co-heating test and an in-use test carried out in an empty house in Figure 7-21.

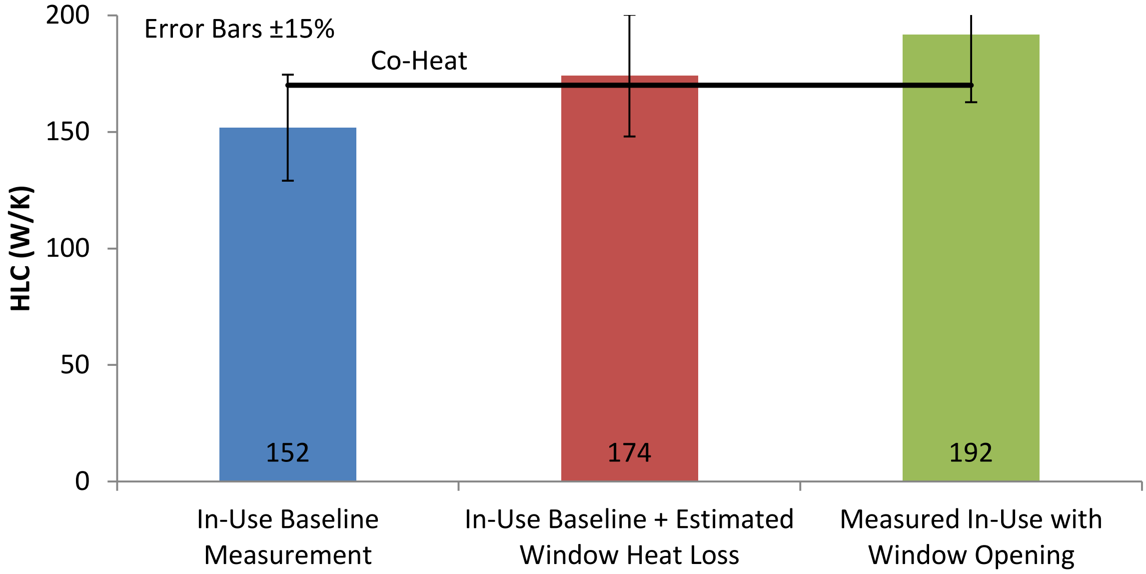


Figure 7-21: Comparison between the results of the baseline in-use heat balance (taken with no synthetic occupancy applied), the estimated HLC including the additional heat loss due to window opening, and the measured HLC from the in-use test with window opening.

As expected, a higher HLC was measured for the in-use heat balance where the window opening synthetic occupancy conditions were applied. The difference in HLC was larger than was expected, with the in-use test with window opening resulting in a HLC 18W/K higher than the co-heating test compared to an expected increase of 4W/K.

However, the estimated uncertainty of the test, ±15%, results in a significantly larger plausible variation in the HLC than difference between the estimated and measured effects of window opening. Therefore it is not possible to say whether the discrepancy between the two is real or simply a result of random error.

What can be stated is that all results lie within this area of uncertainty around the co-heating measurement, despite the reduced testing period of 1 week compared to the recommended 3 weeks. The results of the in-use test with window opening synthetic occupancy, combined with the estimation of additional heat loss due to window opening, suggest that window opening would add uncertainty to the result of a LIUHB test. This added uncertainty is unlikely to be large enough to significantly bias the result of the test, however, for most window opening behaviours. Though, as Figure 7-19 shows, an extreme level of window opening could introduce far more uncertainty that the estimated level for the whole test, of ±15%. This issue will be larger for houses with a lower HLC (i.e. more highly performing houses), as the same change in heat loss rate due to window opening will represent a higher percentage of the total HLC of the house. In such cases, the HLC as measured by an LIUHB test would give an inaccurate, under-estimate of the fabric performance of the house. Rather, it would give an accurate measurement of a composite house-plus-occupant combination; this is not the aim of the method, but could be a useful metric. Further to this, the method may also offer a method of real-time feedback to occupants, informing them of the energy costs of their window opening behaviour.

7.4.2. Synthetic Occupancy Variable 2 - Hot Water Use

Hot water use could introduce an additional source of uncertainty to the LIUHB test as boilers may operate at a different efficiency for this application in comparison to space heating. This is not accounted for in the LIUHB analysis method, which assumes that the boiler operates at the listed efficiency for all fuel consumption. Hot water use could also add to uncertainty due to transmission and storage losses, and heat lost in warm water going to the drain. In this section the results of an investigation into the additional uncertainty that these factors could introduce through the application of synthetic occupancy are presented.

In the LIUHB method all heat inputs to the internal volume are summed regardless of how they are delivered, therefore the transmission and storage losses are assumed to cause useful heat gains to the house and are therefore ignored. This assumption is not considered to add any uncertainty in the HLC measurement as long as all distribution pipework and storage is contained within the building envelope.

An Energy Savings Trust investigation into in-situ performance of boilers found that regular gas boilers heated hot water at approximately the same efficiency as space heating, but that combination boilers delivered hot water with a reduction in mean efficiency of approximately 9% (Orr et al., 2009). This uncertainty will have a variable effect on the uncertainty of the measurement of the HLC via an LIUHB test dependent upon the proportion of gas that is used for space and water heating. Over a five year period between 2005-2011, domestic hot water production constituted a 16% share of total domestic energy consumption (DECC, 2012). A 9% uncertainty in the measurement of 16% of the total heat input would result in an added uncertainty of 1.4% in that measurement. The percentage of heat that is energy used by the boiler for space and water heating could be measured using heat flow meters. However, given the relatively small size of this additional uncertainty and the potential added measurement complexity required this source of uncertainty was ignored and it is assumed that the boiler works at the listed efficiency for all gas consumption.

This leaves the heat loss due to waste hot water going to the drain. The size of this heat loss will depend on the amount of hot water used and on how the water delivered at the tap is used. The way that the hot water is used is important because it will define the percentage of the heat delivered to the water that is released as a heat gain to the house, and that which will be released to the drain (for instance water used in a bath will have a longer period to cool than water used in a shower). In BREDEM it is estimated that 25% of the energy in the hot water delivered to the tap will be converted into a space heat gain, additionally an estimated 17.6% of the energy delivered at the tap is converted to space heat gains due to distribution heat loss (Anderson et al., 1996). This gives a context for the size of the unmeasured heat loss that could result from water heating. In the case of the in-use test with synthetic occupancy in the Holywell test house however, this loss can be estimated more accurately as the temperature and volume of hot water flowing into the drain was measured using a temperature sensor installed in the drain.

During the synthetic occupancy tests a total of 84 litres of hot water was released per day, according to a schedule derived from an Energy Savings Trust study, shown in Table 7-8 and described fully in section 3.2.4. Water was heated during two periods each day, 07:00-09:00 and 17:00-19:00.

Time of Release	**Volume of Water (litres)**	**Mean Water Temperature at Drain (^oC)**
3:00	6	40.1
9:00	30	42.9
14:00	12	42.6
18:30	24	43.0
22:30	12	42.2
TOTAL	*84*	*42.2 (mean of all periods)*

Table 7-8: Water release schedule for the in-use test with the hot water use synthetic occupancy variable.

Table 7-8 shows that there was a very consistent but rather low delivery temperature at the tap. This could be indicative of low storage losses and high distribution losses, but these were not measured. The heat loss due to warm water being released to the drain (Q_{WD}) was calculated using (EQ 7-4), where ρ is the density of water at the outlet temperature (kg/m^3), C_P is the specific heat capacity of water at the outlet temperature (kJ/kgK), V is the volume of water (m^3), and ΔT is the temperature difference between the water at the outlet and mean internal temperature (K).

$$Q_{WD} = \rho\, C_p\, V\, \Delta T \qquad \text{(EQ 7-4)}$$

The calculation resulted in an average heat loss rate per day due to warm water being released to the drain of 81W. The Holywell test house has a HLC of 170W/K, and the average internal-external temperature difference over the in-use test with the hot water use synthetic occupancy variable was 13.9K; therefore there was an average heat loss rate over the test of 2363W. So over the test, the heat loss due to wasted warm water was approximately 3% of the total heat loss on average. This fraction is clearly dependent upon both the performance of the house and the conditions during the test. A figure of 3% of the baseline HLC of the Holywell test house, without any heat loss to waste warm water, is 5W/K; therefore the predicted HLC taking into account this additional heat loss is 175W/K. The predicted HLC of the LIUHB with additional heat loss due to waste warm water is compared to the measured result in Figure 7-22.

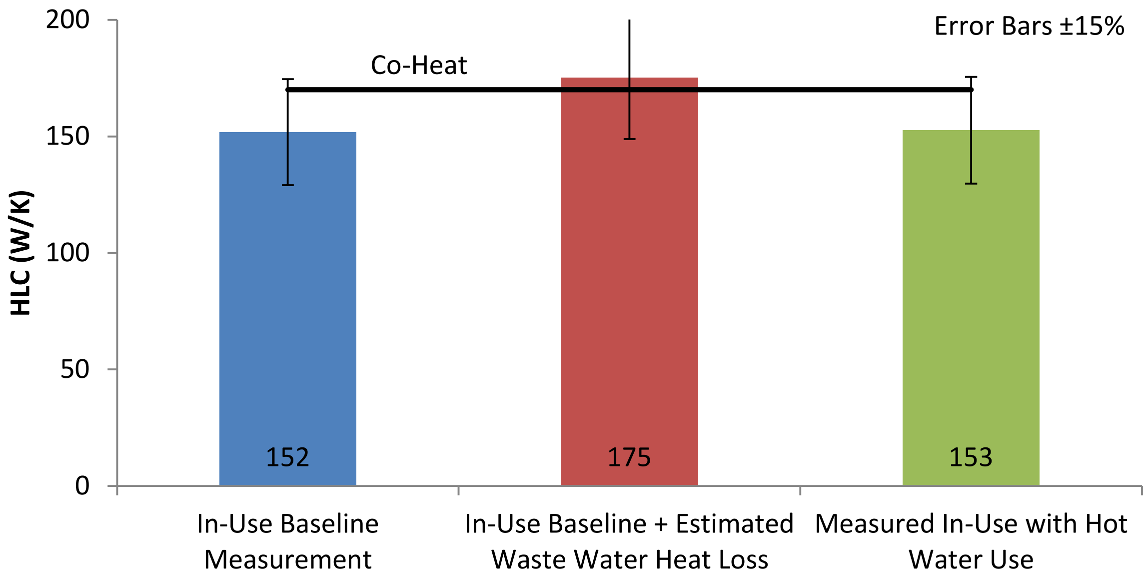


Figure 7-22: Comparison between in-use heat balance baseline measurement, the estimated result of the in-use heat balance with waste water heat loss and the result of the in-use heat balance with synthetic hot water use applied.

As was the case for the window opening synthetic occupancy test, the uncertainty of the method is simply too high to observe differences of a couple of per cent in the HLC. However, the HLC from the in-use test with hot water use is very slightly higher than the baseline measurement – though only by 1W/K. The tests does provide evidence to support the calculation that additional heat loss due to waste warm water does not introduce a large enough uncertainty to move the measurement outside of the stated uncertainty range of the method.

7.4.3. Synthetic Occupancy Variable 3 - Internal Gains due to Electrical Appliances and Metabolic Heat Generation

Heat gains due to metabolic heat generation of the occupants and use of electrical services and appliances are a direct result of carrying out an in-use test. Though both cause heat gains to a house there is a crucial difference in that electrical inputs can be relatively simply measured at the service meter and hence accounted for in the heat balance, metabolic heat generation however is much harder to measure in practise. In this sub-section the results of an investigation into the effects of both of these causes of internal gains, using synthetic occupancy tests, are presented. As described in section 3.2.4, two profiles describing the time and size of the internal gains were applied in two separate one week long synthetic occupancy tests. The profiles synthesise the presence of a family of four, and an elderly couple living with two children, Figure 7-23 and Figure 7-24 show a half-hourly breakdown of each profile.

The assumption that underpins the LIUHB is that all electrical energy consumption within the house will result in a heat gain, which can be added to the heat balance. The second assumption is that the internal volume of the house can be treated as one space for the application of the heat balance, and that variations in temperature throughout will not significantly affect the measurement of the HLC. These assumptions simplify the data analysis, and are the key to allowing the test to be carried out in a non-invasive manner.

If the first assumption is valid, then electricity consumption in a house should actually decrease the uncertainty of the HLC measurement. This is because electricity consumption, and hence the associated heat gain, can be measured with a higher degree of accuracy that heat input from other fuels which is dependent upon the efficiency of the heat generation (typically the boiler). The key relationship in regards to estimating this change in uncertainty is the proportion of the total heat gain that is due to electrical and other sources.

The second assumption, that variation in temperature throughout the internal space does not bias the measurement of the HLC, is more difficult to test. It was shown in section 7.1 that the HLC could be measured with sufficient accuracy despite a large temperature variation between rooms in the Holywell test house. For this test, the temperature variation between rooms will again be calculated to see if the disparity is increased due to the synthesised heat gains around the house.

As described in section 3.2.4, the internal gains were synthesised using a combination of fan heaters, tube heaters and light bulbs. Unfortunately, the tube heaters, which were intended to provide the majority of the gains, were found to have an internal thermostat after the completion of the testing. This meant that they automatically switched off having reached a certain surface temperature, which is a safety feature of the heaters. The result of this was that the delivered heat gain was slightly lower than was intended and was slightly variable for different days.

The delivered heat input was 8% and 13% lower than that set out in the occupancy profile for the family and elderly + children profiles (which were described in section 4.2.3), respectively. The switching of the heaters varied between days and between tests, due to different sets of conditions specific to each room on each day. However, the variation was not found to be large; with a mean standard deviation between samples of delivered heat input for the same 30 minute period of 9W (or 2.2% of the heat delivered in that 30 minute sample). Therefore, it is thought that the experiments gave a temporally representative synthesis of the profiles, but with a slightly reduced heat input. The profiles as they were designed and delivered are shown in Figure 7-23 and Figure 7-24, for the family and elderly + children profiles.

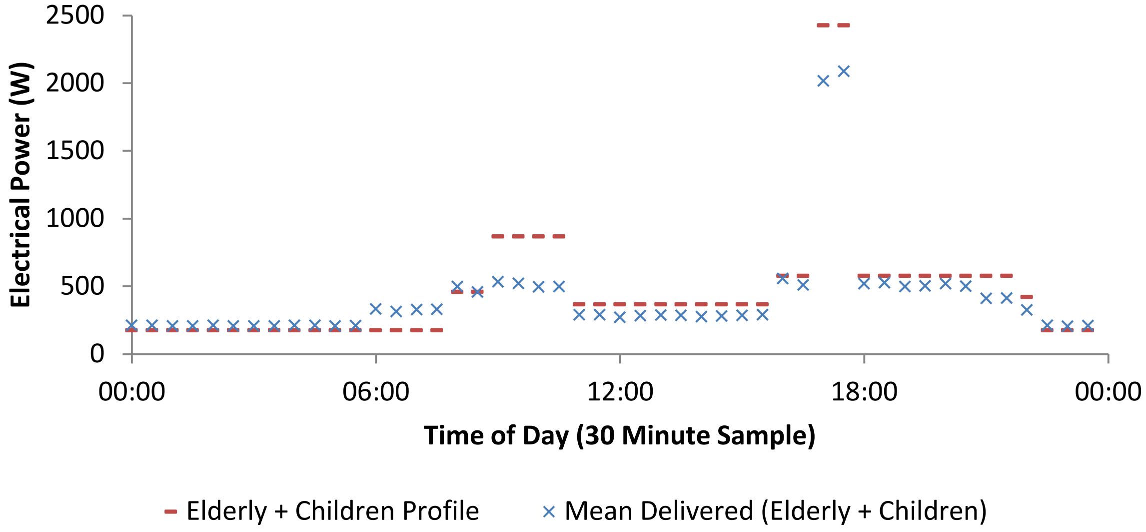


Figure 7-23: Designed and delivered internal gains profiles for the synthetic occupancy experiment with the 'elderly + children' profile.

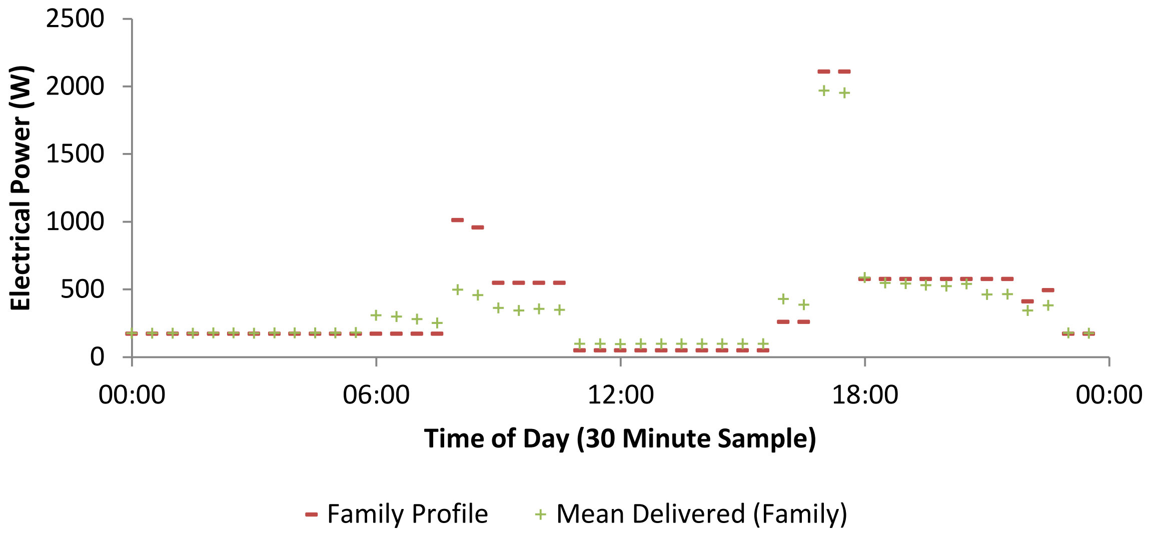


Figure 7-24: Designed and delivered internal gains profiles for the synthetic occupancy experiment with the 'family' profile.

As would be expected the percentage of the total heat gain to the house that comes from electrical sources increases for the internal gains synthetic occupancy tests in comparison with tests without synthetic occupancy applied, as shown in Table 7-9.

Test	Mean % Total Energy Input Electrical	Mean Internal-External Temperature Difference (^oC)	Mean External Temperature (^oC)
No synthetic occupancy	5%	9.8	7.7
Internal gains (family)	19%	11.8	8.2
Internal gains (elderly + children)	23%	11.3	7.9

Table 7-9: Proportion of total heat input from electrical sources for the internal gain synthetic occupancy tests.

It can be seen in Table 7-9 that the increase in the proportion of total heat input that is electrical is not reliant upon the external temperature. It can also be seen that the mean internal temperature is increased by the internal gains, as the internal-external temperature is larger for a similar external temperature. This provides evidence that the electricity consumption does indeed provide useful heat gains to the house.

This change in the distribution of the source of total heat input will have an impact on the uncertainty of the measurement of total heat input. As was demonstrated in section 7.3, the maximum uncertainty associated with measuring the heat input from a standard gas or oil fuelled boiler is likely to be around -7%. Added to this gas meters themselves have statutory limits for accuracy of ±2% (H.M. Government, 1983), giving a maximum possible uncertainty of -9%. In comparison electricity service meters have statutory limits for accuracy of +2.5%, -3.5% (H.M. Government, 1998). Therefore, the measurement of electricity consumption as a heat input to the house has a maximum associated uncertainty 5.5% lower than that associated with gas. The conclusion of this is that where electrical heat gains constitute a higher percentage of the total, the uncertainty in the measurement is reduced. The amount to which it is reduced depends upon the percentage of the total heat input that is contributed by each source; this relationship is shown in Figure 7-25. It can be seen in the figure that the uncertainty boundary varies from -9% +2%, if the heat input is from an oil or gas fired boiler alone, to -3.5% +2.5% if the total heat in is provided by electrical sources alone. Of course, in practice both of these situations are extremely unlikely to occur, as there will almost certainly be a mix of both sources and a third contribution due to solar gains that falls outside the scope of this chart. Figure 7-25 does however give an illustration of the range of possible uncertainties associated with the major constituents of the heat input.

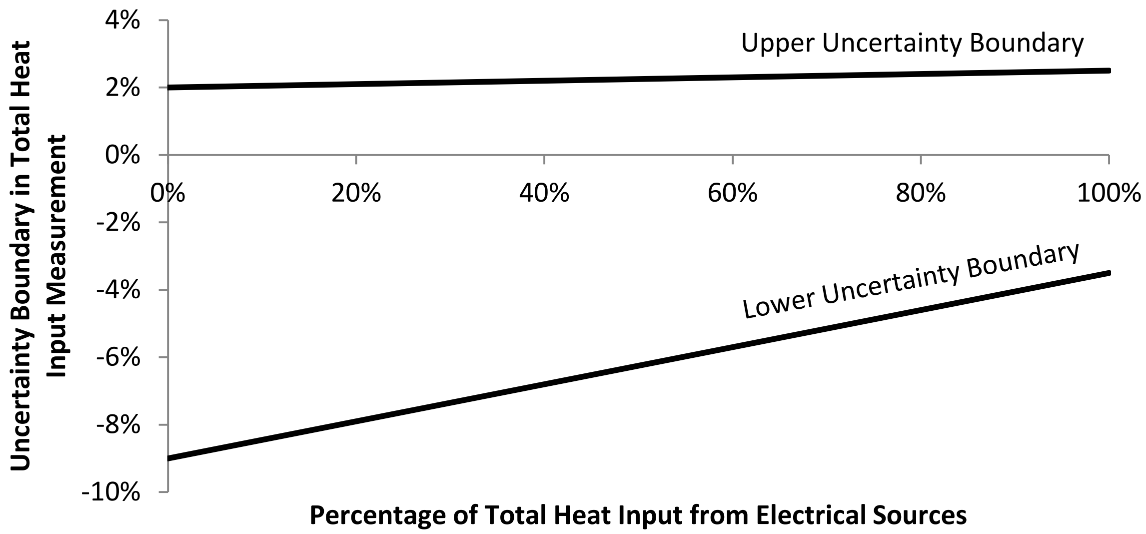


Figure 7-25: Relationship between uncertainty total heat input measurement and the proportion from electrical sources.

There was no additional temperature variation within the house during each of the internal gains synthetic occupancy tests compared to a test with no synthetic occupancy applied, as shown in Table 7-10.

Test	Mean Max Room Temperature Difference (^oC)
No synthetic occupancy	4.4
Internal gains – family profile	4.6
Internal gains – Elderly + children profile	4.4

Table 7-10: Temperature variation comparison between tests with and without internal gains synthetic occupancy.

This suggests that the combination of stratification and the heating system installed in the Holywell house have a much stronger influence on the temperature variation than gains from electrical items or metabolic heat generation.

The internal gain applied here are due to both electricity use and metabolic heat gains. While the electricity consumption can be easily measured, this is not the case for metabolic heat gains which are likely to be unaccounted for unless some method of occupancy detection is used. Therefore, the mean internal gain due to metabolic heat gains alone (in Watts) was compared to the total heat input (electrical + gas + solar) for both the elderly and elderly + child occupancy profiles. The result was that the metabolic heat gains accounted for 4.9% and 7.2% of the total heating power for the tests using the elderly and elderly + child profiles, respectively. This represents an additional uncertainty that is not accounted for in the current testing method.

The results of the in-use tests with internal gains synthetic occupancy conditions applied are shown in Figure 7-26 for both the family and elderly + children occupancy profiles. The results are compared to a baseline in-use measurement (which was measured with a full 3-week sampling period and no synthetic occupancy conditions applied) and the mean result of three co-heating tests carried out in the Holywell test house.

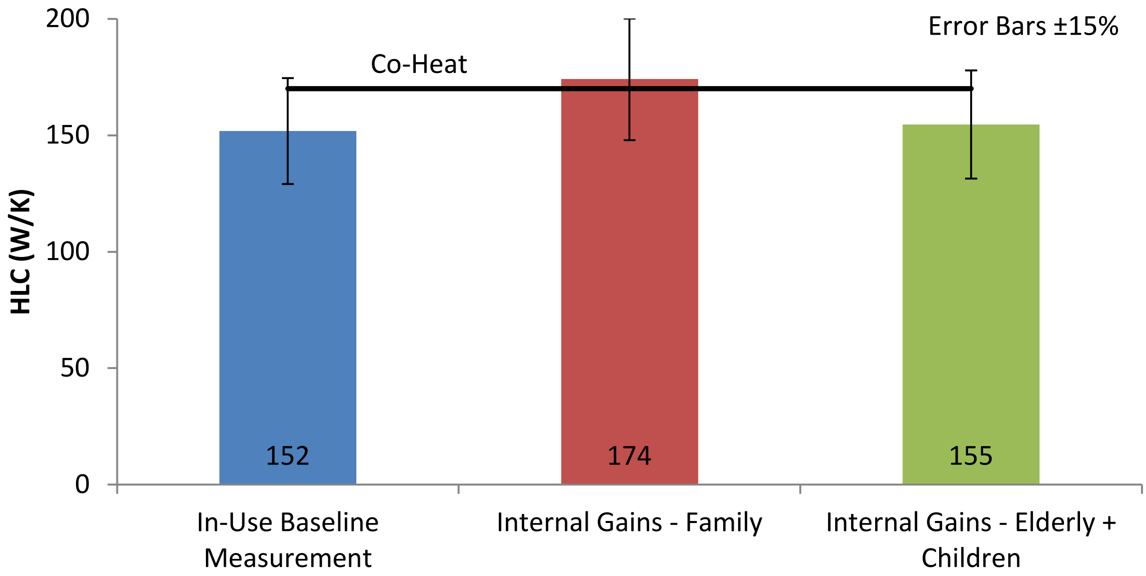


Figure 7-26: Results of the in-use test with internal gains synthetic occupancy conditions applied, compared with the results of an in-use test with not synthetic occupancy applied (in-use baseline measurement) and the results of co-heating tests.

Figure 7-26 shows that applying synthetic occupancy to represent the effects of internal gains due to electrical appliances, cooking (using electrical heat sources) and metabolic heat generation does not have a significant impact on the measurement of the HLC using the LIUHB method. All of the results fall within the estimated ±15% confidence interval of the co-heating measurement. In fact, it has been shown earlier that greater electricity consumption is likely to decrease the uncertainty in the measurement of the HLC as this energy consumption is not prone to the variations in boiler efficiency described in section 7.3.

One possible additional source of uncertainty that has not been considered is that some of the electricity consumption could occur outside of the heated envelope of the house, for outdoor lights or in garages for example. This would be particularly problematic if the electricity supply was used for charging an electric vehicle. It may be necessary to use sub-metering to avoid this source of uncertainty in cases where high electricity usage outside of the heated envelope is expected.

7.4.4. Synthetic Occupancy Variable 4 – Window Covering

Window covering of some kind; commonly with curtains, blinds or shutters; is very common in houses. When considered in the narrow context of the impact of this practise on an LIUHB test, the effect can be broken down into two broad categories; a change in the effective thermal resistance of what might be considered the window assembly, and a change in the way that heat gains occur due to solar irradiation.

Whilst in most cases the window would be covered during the night, and the covering removed during the daytime, clearly this will not universally be the case, and there is likely to be some cross-over period in the morning for much of the heating season. Therefore, to synthesise the maximum possible effect of window covering experiments were carried out with the windows uncovered at all times, and then covered at all times. This approach was adopted not to reflect the most likely usage pattern, but to establish the maximum uncertainty introduced by the occupancy variable. The windows were covered using standard roller blinds, installed at the edge of the window reveal.

An RDSAP model (BRE, 2011) of the Holywell test house was used to predict the change in the fabric heat loss rate due to window covering; this resulted in a predicted reduction in the fabric heat loss rate of 2.6W/K, or -2.2% of the value with no window covering. It is pertinent to note that this change in performance is significantly smaller than the estimated accuracy of the LIUHB test, ±15%. Therefore the synthetic occupancy is unlikely to show this small change in performance, but can provide evidence that the change in measured performance is not larger than this predicted amount.

The effect of window covering on solar gains to the house is a rather complex question. Undoubtedly the window covering will block some of the solar radiation from reaching the interior of the house and causing a heat gain, but what is happening to achieve this? Some of the radiation will be reflected by the window covering, and some of the reflected radiation will be reflected by the window back to the covering and so on. In addition to the reflected radiation, some will be absorbed by the covering, of this heat gain to the covering some will heat the air in the house, and some will heat the air in the gap between the covering and the window. This will in turn change the heat transfer coefficient at the window. Clearly this is a rather complex interaction, which would require detailed modelling to estimate with any confidence. What is important in this situation is what impact this has on the measurement of the HLC of the house. This is dependent upon a further set of conditions – the performance of the house, the amount and orientation of glazing and the weather conditions during the test. In order to simplify this extremely complex analysis, and in keeping with the measurement focus of this study, the issue was be addressed by data collected during the synthetic occupancy experiment. The experiment was carried out with the intention of establishing whether the issue causes enough uncertainty to warrant further detailed analysis.

The Siviour method offers a regression based data analysis technique to investigate the effect of covering the windows, using roller blinds in this case, in the Holywell test house. When calculating the HLC using the Siviour method the daily mean global solar irradiance is plotted on the x-axis against the daily mean heat input (gas + electrical) on the y-axis, both normalised by daily mean internal-external temperature difference (labelled DT on the following plots); the method was described in detail in section 2.6.1. The inverse of the gradient of this plot (referred to as a Siviour plot) gives the 'solar aperture' of the house, which is a measure of the effective area of glazing through which solar gains can occur. The solar aperture is linked to the properties of the house, but is also likely to be linked to the conditions during the test due to changing amounts of overshading and the sun's path. However, as both the baseline in-use heat balance and the test with window covering synthetic occupancy applied were carried out during winter, it should allow a reasonable comparison of the solar aperture with and without the window coverings applied. The Siviour plot for the in-use heat balance baseline test is shown in Figure 7-27.

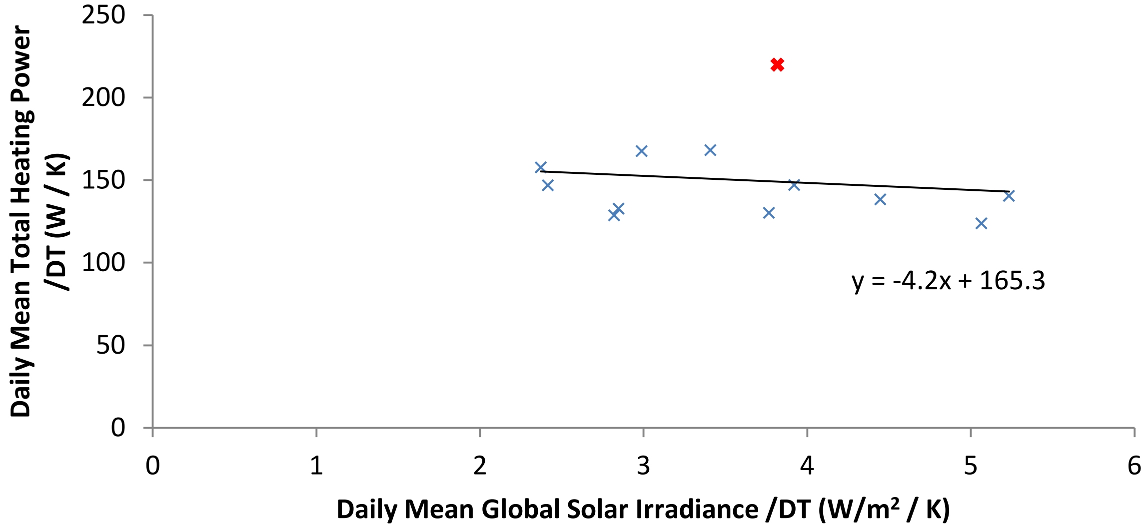


Figure 7-27: Siviour plot for the in-use heat balance baseline test (with no synthetic occupancy applied).

It can be seen in the Siviour plot that there is a reasonably clear relationship, with less heating power when there is a higher solar irradiance, resulting in a solar aperture of 4.2m^2. There is one seemingly anomalous point, which has been marked in bold and coloured red. It is thought that the anomalous result is caused by charging the thermal mass of the building, as the result occurred on a day with a significantly higher external temperature than the preceding period. This effect is likely to be more pronounced in in-use tests, where the internal temperature is not held constant, as it is in co-heating tests.

The solar aperture from the baseline test can be compared to that observed during the in-use heat balance test during which the window were covered with blinds, which was -16.2m^2, shown in Figure 7-28.

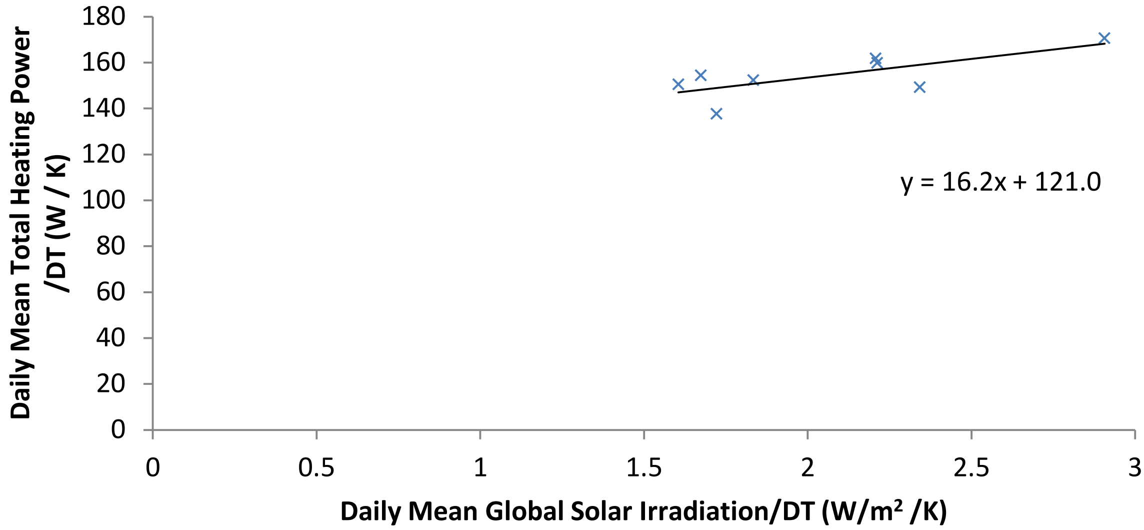


Figure 7-28: Siviour plot for the in-use heat balance test with the window covering synthetic occupancy variable applied.

Clearly there is a large difference between the two tests; in fact the test with window covering shows a positive relationship between heating power and solar irradiance – i.e. that a greater heat input is required for a given internal-external temperature difference on sunnier days. If this solar aperture were used in the Siviour + regression method it would result in *negative* solar gains. This does not make physical sense, and shows a problem inherent to applying the Siviour method using a small dataset, when outlier points can have a large influence on the regression (an issue highlighted by Butler and Dengel (2013), as described in section 2.6.1). This is demonstrated by the small range in the x-axis in Figure 7-28, which indicates that there were similar levels of daily mean global solar irradiance levels for each day during the test (for comparison, the standard deviation of the values during the window covering test was 2.9W/m^2, while it was 10.9W/m^2 for the baseline test).

There could, however, be a physical explanation for the difference in calculated solar apertures for the two tests. The Siviour method is used to determine the effect of short wave heat gains due to the level of solar radiation, but it does not account for long wave heat losses. This additional heat loss mechanism is not accounted for by any current analysis technique, and was highlighted by Stamp et al as a possible source of uncertainty in a study of simulated co-heating tests (Stamp et al., 2013).

Table 7-11 shows the mean monthly global and net radiation at the Loughborough University weather station during 2012. It can be seen in the table that the incoming short wave radiation from the Sun dominates during most of the year, but that long wave radiation is relatively larger during the winter months, as demonstrated by the lower (and negative) monthly mean net radiation figures.

Month	**Mean Global Solar Irradiance (W/m^2)**	**Mean Net Radiation (W/m^2)**
January	21.3	-22.7
February	48.1	2.0
March	99.2	29.9
April	114.7	42.8
May	173.6	86.0
June	146.9	72.7
July	166.7	85.9
August	137.2	66.6
September	106.6	37.6
October	56.7	9.0
November	24.4	-15.4
December	13.9	-25.2

Table 7-11: Mean monthly global and net solar irradiance during 2012, measured at Loughborough University.

The window covering in-use heat balance test was carried out during December 2013, during the test there was a mean net radiation of -27.6W/m^2; the baseline measurement was carried out in November with a mean net radiation of -15.6W/m^2. So, while both tests experienced a negative net radiation, the window covering test experienced a slightly lower mean net radiation.

To investigate the possible influence of long wave radiative heat loss from the house, a regression technique similar to the Siviour method was used, where net radiation was used instead of the global solar radiation. This gives a plot with daily mean values for electrical plus gas heating power divided by internal-external temperature difference on the y-axis, and daily mean net radiation divided by internal-external temperature difference on the x-axis. The result for the closed blinds test is shown in Figure 7-29.

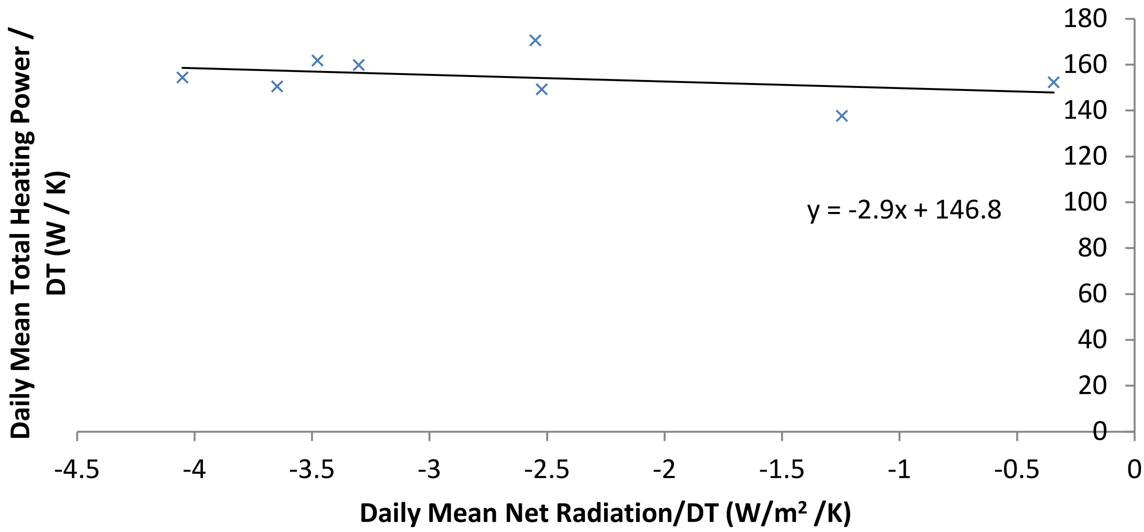


Figure 7-29: Alternative Siviour plot, using the daily mean net, rather than global solar, radiation for the window covering synthetic occupancy test.

The figure shows that using this analysis method there is a negative slope to the line of best fit, it can also be seen that each day during the testing period experienced a negative mean net radiation. The negative slope indicates that less energy is required to maintain the same internal-external temperature difference when there is greater net radiation – as would be expected. The HLC estimated by this method, defined by the y-intercept value of 147W/K, also falls within ±15% of the HLC of the house defined by co-heating. This suggests that the issue of long wave radiative heat losses could have been significant in this test, and that this analysis technique may be valuable during periods of low solar radiation.

It is also interesting to note that during this period of dull cool weather, which would typically be ideal for this type of testing, only two of the daily values for total heating power divided by internal-external temperature difference fell outside of a ±15% area around the HLC as measured by a co-heating test. This is despite a lack of any correction for solar gains. Therefore, it is likely that the requirement for a spread of different weather conditions to inform an accurate regression is primarily responsible for the poor estimate of solar aperture and HLC using the Siviour method in this case. It is likely that this would be remedied by a longer monitoring period than was available for the synthetic occupancy tests.

Indeed, using the facade method, which has been chosen to be used for comparison between the synthetic occupancy tests, the measured HLC is 153W/K, well within the estimated ±15% uncertainty area.

This test has demonstrated the difficulties that short monitoring periods, with similar weather conditions throughout, can cause problems for some regression techniques. This has made it difficult to isolate and estimate the effect of window coverings on the measurement. A comparison between the window covering synthetic occupancy test results and the baseline in-use and co-heating measurements is given in Figure 7-30.

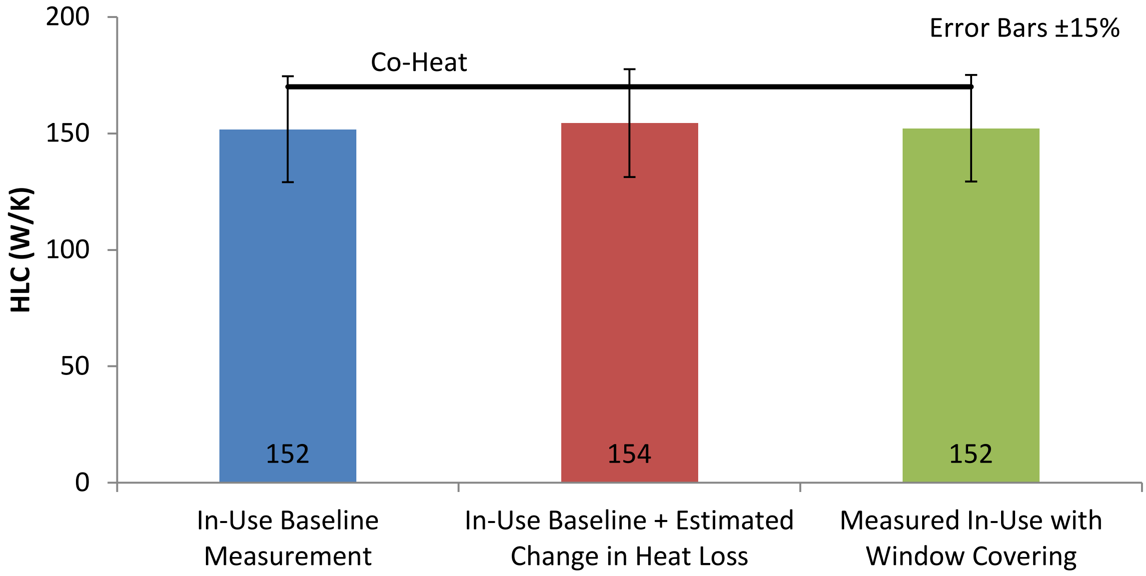


Figure 7-30: Results of the window covering in-use synthetic occupancy heat balance, compared to the estimated change in heat loss and a baseline in-use heat balance measurement with no synthetic occupancy applied.

The chart shows that the window covering did not cause a significant change in the measured HLC when the facade analysis method is used, with the result falling within ±15% of the co-heating measurement and the same to three significant figures as the baseline in-use measurement.

7.4.5. Full Synthetic Occupancy

In the full synthetic occupancy tests each of the variables described in the chapter were applied at the same time in order to examine their interaction. In total this included:

- Window opening to the schedule described in section 7.4.1.
- Hot water use according to the profile given by the Energy Savings Trust (Energy Savings Trust, 2008), as described in section 7.4.2.
- Electrical internal gains according to the 'family' profile defined by Porritt (Porritt, 2012), as described in section 7.4.3.
- Continuous window covering by blinds, as described in section 7.4.4.

The full synthetic occupancy test was carried out for a period of 55 days between 21st December 2013 and 13th February 2014. The test was carried out over an extended period to allow the possibility of investigating the effect of using different sampling periods, in particular what would be the effect of shorter monitoring periods or periods with different weather conditions.

The estimated effect of each synthetic occupancy variable was combined with measurement uncertainties to calculate the total expected uncertainty for the full synthetic occupancy test. The uncertainty in the temperature measurements and calculation of solar gain should not be any different to those taken during co-heating tests, as the same experimental and data analysis methods are used. Therefore the uncertainty in the measurement of the HLC caused by these two factors was taken as ±5% for the temperature measurements and ±9% for the calculation of solar gains, as calculated in the sensitivity analysis described in section 5.2.

Across the monitoring period the mean contribution of the total heating power from gas and electricity from electrical sources was 17.6%. The relationship between the percentage of total energy from electrical sources and measurement uncertainty in the total heat input, described in section 7.4.3 (Figure 7-25), can be used to calculated an uncertainty boundary of -8.0% +2.1% for this source.

Each of the synthetic occupancy variables affects only one of the upper or lower uncertainty boundaries. Opening windows can only increase the measured HLC, as the baseline measurement is taken with all windows and external doors closed; this is also true of additional heat loss caused by waste warm water. In contrast, window covering can only reduce the HLC compared to the baseline measurement, which is taken with no window covering. The effect of electrical internal gains is included in the calculation of the uncertainty associated with measurement of the total heat input. The additional uncertainty added by each of the four other occupancy variables was added to only the upper of lower uncertainty boundary as appropriate, as is shown in Table 7-12.

Uncertainty Source	Lower Boundary	Upper Boundary
Calculation of solar gains	-9%	+9%
Temperature Measurement	-5%	+5%
Heat input measurement	-8.0%	+2.1%
Window opening	0	+2.4%
Hot water use	0	+3.0%
Window covering	-1.6%	0
Metabolic heat gains	0	+7.2%
TOTAL UNCERTAINTY	**-13%**	**13.0%**

Table 7-12: Uncertainty associated with each occupancy variable and measurement, total uncertainty is calculated by quadrature sum of the influence of each.

The total effect of all occupancy variables and measurement uncertainties was summed using the quadrature sum method (Lomas and Eppel, 1992), this gave an estimated uncertainty boundary for the HLC of ±13%.

The results for the full synthetic occupancy test are shown in Figure 7-31; the results shown are for an analysis of the whole period of 55 days.

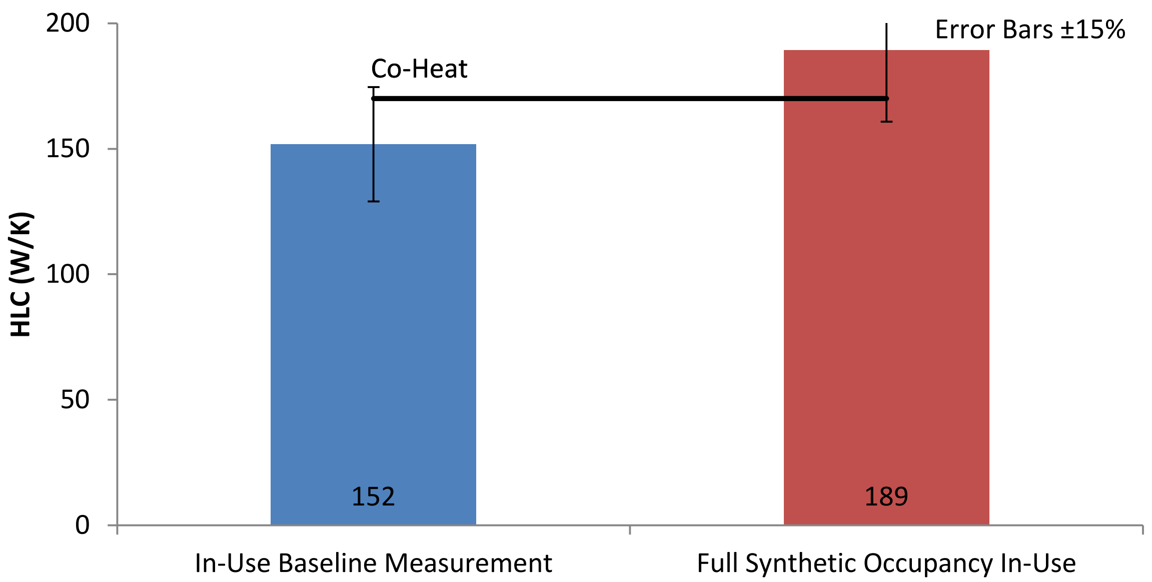


Figure 7-31: Results of the full synthetic occupancy test. Error bars showing the estimated uncertainty boundary of the in-use method, ±15%, are shown.

As shown in Figure 7-31, the result of the full synthetic occupancy test fell inside the estimated uncertainty boundary of ±15% of the result of the co-heating test. The result also fell within the ±13%

uncertainty boundary that was calculated above (though this boundary is not shown in Figure 7-31). The calculated HLC by each of the data analysis methods described is shown in Table 7-13.

Analysis Method	**HLC (W/K)**
Siviour	210
Siviour + Regression	207
Facade	189
Net Radiation Siviour	160

Table 7-13: Results of the full synthetic occupancy test by each possible data analysis method.

It is interesting to note that the adapted version of the Siviour method, using daily mean net radiation levels rather than solar radiation levels as described in section 7.4.4, results in a significantly lower HLC which is well within both defined uncertainty boundaries.

The variation in the calculated HLC given difference sampling periods of the whole test was also considered. Two different approaches were adopted for choosing the sample period, one dependent upon adjusting the final day of the sample period and the second based upon adjusting the first day of the sampling period. Where the final day was adjusted the same starting point was used for each sample, the final day was then moved back by one day at a time to gradually increase the sample period – finally reaching a sample of the whole period. The opposite approach was also used, with the first day of the sample being moved back by a day at a time so that the sample started as the whole period and was gradually shortened. For both approaches a minimum sampling period of twenty-one days was applied (as this is the recommended minimum monitoring period for the LIUHB). The progression of the calculated HLC for the varying sampling period can be seen, trending toward the value for the full period (189W/K for the facade analysis method) in the case of the final day adjustment and beginning from that point for the first day adjustment. The results of these analyses are shown in Figure 7-32 and Figure 7-33.

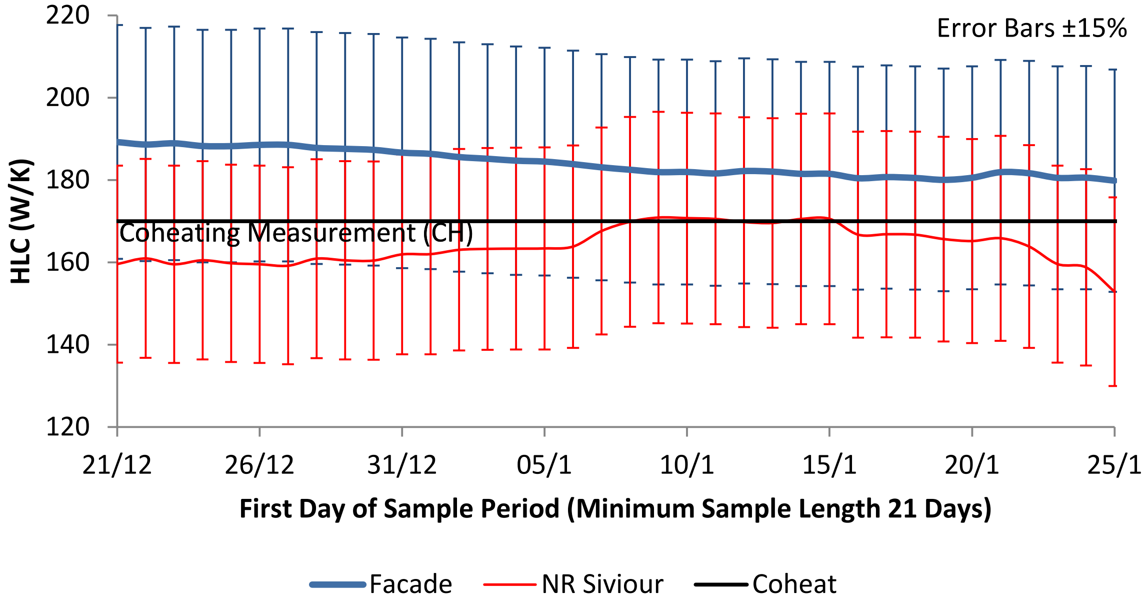


Figure 7-32: The effect of a different chosen sampling period on the calculated HLC, by the facade and net regression (NR) Siviour data analysis methods. The sampling period is adjusted one day at a time, reducing from the full monitoring period on the left to the last 21 days of the monitoring period on the right.

There is a clear trend in the calculated HLC by the facade method in Figure 7-32, with a lower calculated HLC for a sample later in the monitoring period, though the result is within the ±15% uncertainty boundary from the co-heating baseline for all samples. The results as calculated by the net regression Siviour method do not follow the same pattern however, with a constant phase at the start of the period followed by a drop in the calculated HLC towards the right hand side of the chart. As for the facade method, the calculated HLC is within the ±15% uncertainty boundary relative to the co-heating baseline for all samples. These results are consistent with the observation that long wave heat losses may have added an additional heat loss at the start of the monitoring period, which caused an artificially inflated HLC by the facade method – and indeed all current co-heating data analysis methods. It should be noted that the length of the monitoring period decreases travelling across the chart from left to right, which is likely to decrease the certainty of the measurement.

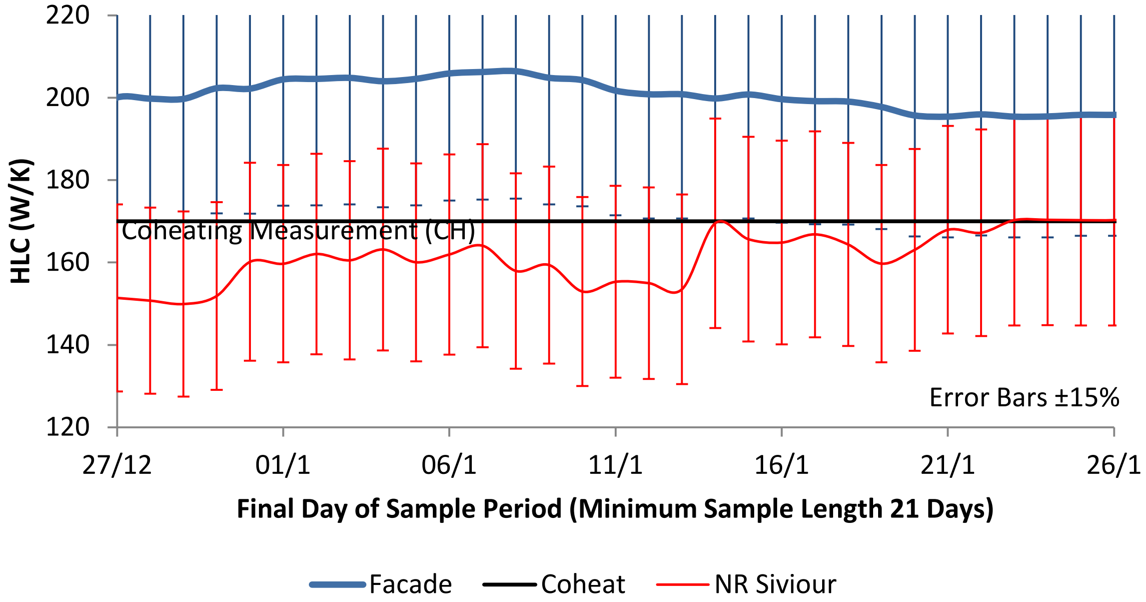


Figure 7-33: The effect of a different chosen sampling period on the calculated HLC, by the facade and net regression (NR) Siviour data analysis methods. The sampling period is adjusted one day at a time, increasing from the first 21 days on the left to the full monitoring period on the right.

The observation made from Figure 7-32 seems to be reinforced by the results shown in Figure 7-33. The HLC for the sampling periods towards the left hand side of the chart, which contains only data from the early stages of the monitoring period, result in a higher HLC by the facade method. The calculated HLC reduces as the sample length increases, but remains at a higher level due to the continued inclusion of the data collected at the start of the monitoring period. In comparison, the HLC as calculated by the net radiation Siviour method remains within the predicted uncertainty boundary for all samples, and does not show the same relationship between sample length and calculated HLC.

The results shown in Figure 7-32 and Figure 7-33 support the hypothesis that the calculation of the HLC by the facade method is influenced by long wave heat losses. Figure 7-34 shows the levels of daily mean global solar irradiance and net radiation for the monitoring period. It can be seen that there is a clear trend of increasing levels of net and global solar radiation throughout the monitoring period. This provides further evidence to support the suggested importance of long wave heat losses in increasing the calculated heat loss coefficient by the facade method. These weather conditions cause a similar problem for existing analysis methods; such as the multiple regression, Siviour and Siviour plus multiple regression methods; which also take no account of long wave losses.

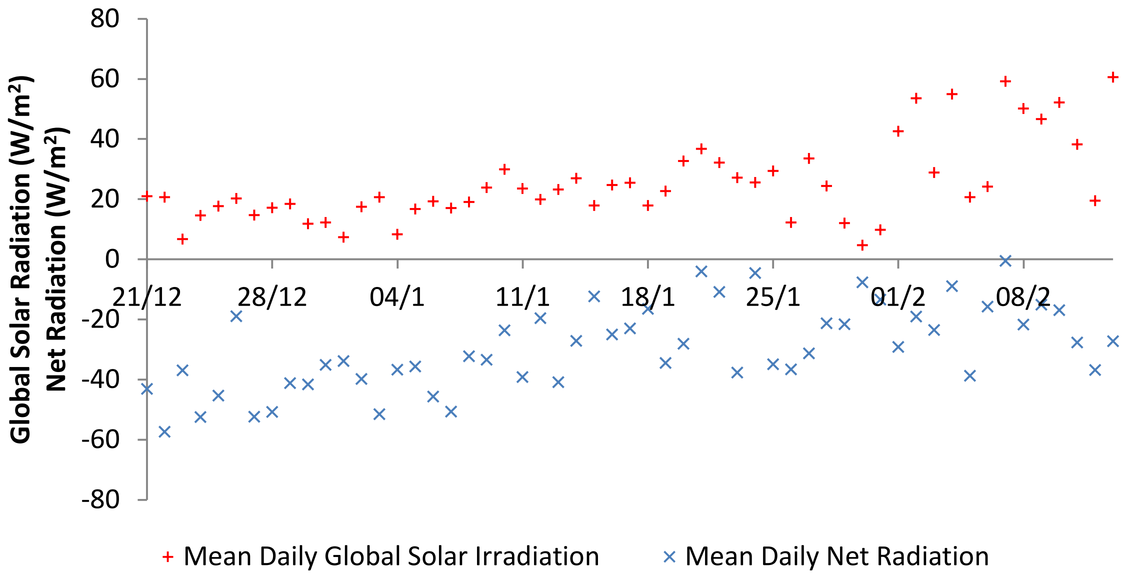


Figure 7-34: Daily mean global solar radiation and net radiation for each day of the simulated occupancy LIUHB test.

It seems that the net radiation regression is able to take the additional long wave heat losses into account, and calculate an accurate calculation of the HLC despite the weather conditions which adversely affect the facade method. This was further investigated by breaking down the monitoring period into a series of 21 day samples in the same manner as described in section 6.1. The results of this analysis are shown in Figure 7-35; each data-point shows the HLC for a 21 day sample of the dataset. The samples create a moving window into the whole period that moves one day at a time so that the first sample is 21/12/13-10/1/14, the second sample 22/12/13-11/1/14 and so on. In effect this analysis makes it possible to see what the result would have been in the testing period had begun at several different points during the whole monitoring period, with different weather conditions applying the each sample.

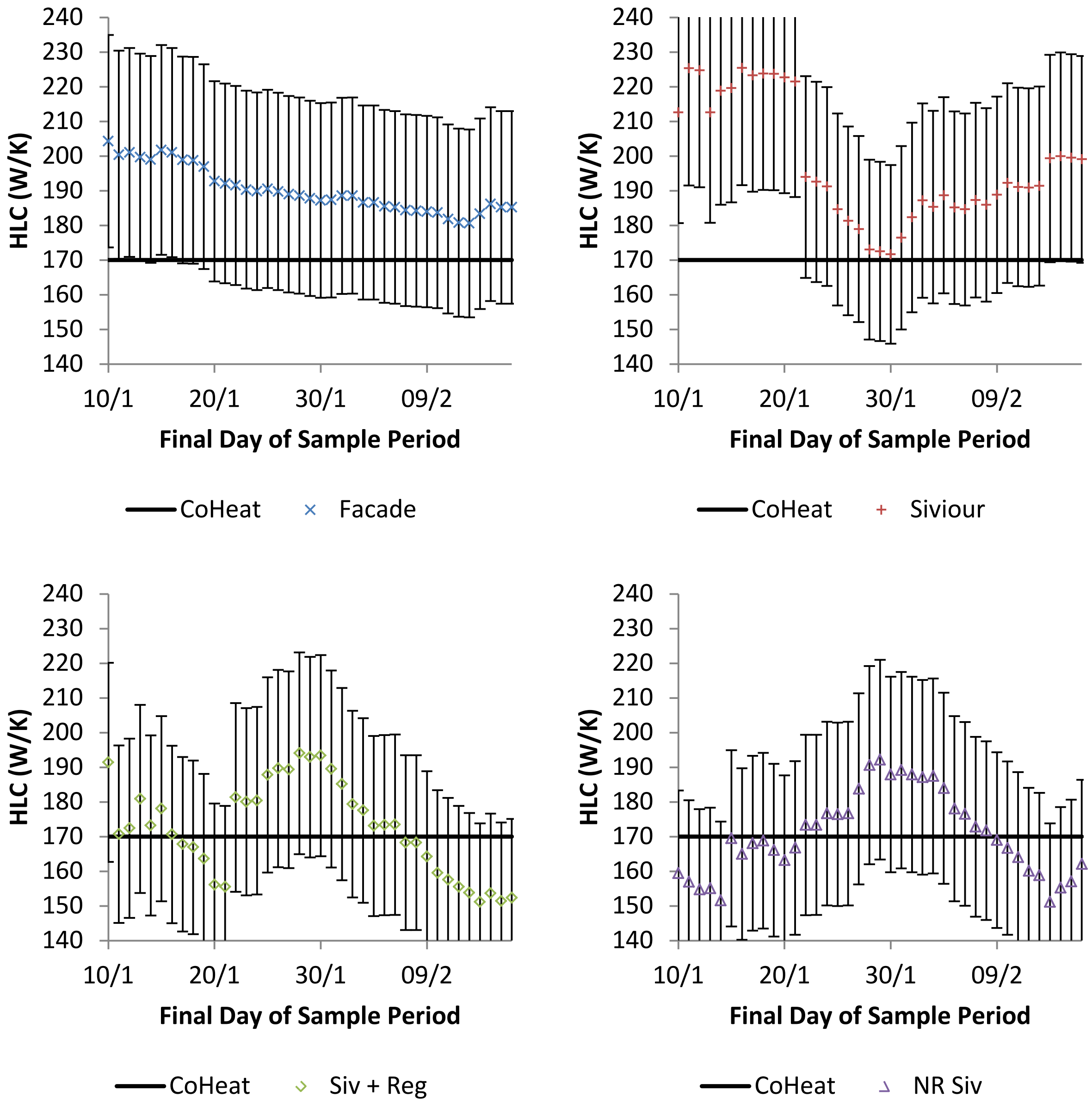


Figure 7-35: Variation in the HLC calculated by each data analysis method during the full synthetic occupancy LIUHB test, each data-point represents a sample period of 21 days of the total dataset with error bars of ±15% in the HLC shown.

It is clear in Figure 7-35 that the facade and Siviour analysis methods are affected by the weather conditions toward the beginning of the monitoring period – each resulting in an HLC higher than the upper ±15% boundary compared to the value measured by co-heating. Interestingly, this is not apparent for the Siviour + regression method, for which the calculated HLC is within the estimated uncertainty boundary of the co-heating measurement for all samples. This is also the case for the net regression Siviour method.

One major issue with this suggested method is the availability of net radiation data. In this particular application it is available from the Loughborough University weather station, but it is not as generally available as global solar radiation data. This may limit the application of such an analysis method, as its use would require a bespoke measurement of net radiation.

7.5. Pre and Post Retrofit Testing

One potential application for the LIUHB is to quantify the change in the thermal characteristics of a house following a retrofit. In order to test the effectiveness of the method in this application a retrofit was applied to the Holywell test house, with LIUHB and co-heating tests carried out before and after the retrofit (as described in detail in section 3.2.5). This ensured that a direct comparison between the results of the in-use test and a benchmark co-heating result could be compared before and after the application of the retrofit. The retrofit comprised the installation of loft insulation and the addition of clay impregnated boards to the walls inside the house. In this way the thermal mass, as well as the HLC of the house, was altered in order to assess the robustness of the in-use methods to changes in thermal mass as well as to the heat loss rate. No synthetic occupancy conditions were applied during the tests.

The results of the experiment include comparison of the pre and post retrofit results from the co-heating and in-use tests, and a comparison of the ratio of pre and post retrofit measurements. The results were also compared with RDSAP design predictions of the HLC both before and after retrofit as this is currently the most commonly used method to estimate the change in performance of a retrofit. When comparing the results of the co-heating and LIUHB tests it should be noted that there is an estimated uncertainty margin of ±10% and ±15% respectively for the two measurements. These combine to result in a worst-case total uncertainty interval between the results of ±25%.

The dates, duration and mean weather conditions for each of the in-use and co-heating tests carried out pre and post-retrofit are shown in Table 7-14. Delays in the commissioning of the project meant that the testing program was not started until April 2014 and continued into June, with the result that all testing was carried out outside of the usual co-heating season in warmer and sunnier conditions than would be ideal. To compensate for the warmer than usual testing conditions an elevated internal set point temperature, of 24^{o}C, was used for both in-use tests. A standard set point temperature of 25^{o}C was used for the pre-retrofit co-heating test and an elevated set-point of 30^{o}C was used for the post-retrofit co-heating test.

		Mean conditions during test			
Test	**Test Dates (and duration)**	External Temperature (°C)	Relative Humidity (%)	Global Solar Irradiance (W/m^2K)	Wind Speed (m/s)
Pre-retrofit in-use	11/4/14-2/5/14 (3 weeks)	10.6	77.6	140	1.42
Pre-retrofit co-heat	5/5/14-19/5/14 (2 weeks)	13.3	71.8	205	1.25
Post-retrofit in-use	26/5/14-16/6/14 (3 weeks)	14.9	78.1	162	1.00
Post-retrofit co-heat	16/6/14-1/7/14 (2 weeks)	16.0	75.6	198	1.05

Table 7-14: Mean weather conditions during each of the pre and post-retrofit in-use and co-heating tests.

The results of the pre-retrofit co-heating and LIUHB tests for the Holywell test house are shown in Table 7-15. It can be seen that there is an agreement to within the maximum acceptable uncertainty interval of ±25% between the results, for all analysis methods. For the recommended facade method the results agree to within 1%.

Analysis Method	**Co-Heat HLC (W/K)**	**LIUHB HLC (W/K)**	**Difference between LIUHB and Co-Heat Measurements**
Multiple regression	214	164	-23%
Siviour	217	184	-15%
Siviour & regression	187	176	-6%
Facade	185	185	-0% (to 1 S.F.)

Table 7-15: Results of the pre-retrofit co-heating and LIUHB tests

The results of the post-retrofit co-heating test and in-use tests are shown in Table 7-16. As for the pre-retrofit tests the results of the co-heating and LIUHB tests were within the total uncertainty boundary of ±25% for all analysis methods.

Analysis method	Co-Heat HLC W/K	LIUHB HLC W/K	LIUHB to Co-Heat Difference
Multiple regression	149	152	2%
Siviour	150	134	-11%
Siviour & regression	144	142	-1%
Facade	153	142	-7%

Table 7-16: Results of post-retrofit co-heating and LIUHB tests

Table 7-17 shows a close agreement in the ratio between pre and post-retrofit performance, as measured by the co-heating and LIUHB tests. The LIUHB test measured a change in performance of 23%, 6% larger than that measured by the co-heating test which is well within the uncertainty boundaries of the tests.

Test Method	Pre-Retrofit HLC	Post-Retrofit HLC	% Change due to Retrofit
Co-heating test	185 W/K	153 W/K	-17%
LIUHB	185 W/K	142 W/K	-23%
RDSAP Assessment	200 W/K	135 W/K	-33%

Table 7-17: Change in performance of the Holywell test house following a retrofit as measured by the co-heating and LIUHB tests and predicted by an RDSAP assessment.

The pre and post-retrofit HLC of the house as predicted by and RDSAP assessment are also included in Table 7-17. The results show that the RDSAP assessment predicted a higher than measured HLC before the retrofit and a lower than measured HLC following the retrofit for both the co-heating and in-use measurements. The combined result of these two discrepancies is that the RDSAP assessment predicts a significantly larger change in performance in the house than is measured, an inaccuracy that was correctly detected by the LIUHB test.

7.6. Occupied House Case Study

One of the great challenges of carrying out any post-occupancy analysis is the infinitely varied and unpredictable behaviour of inhabitants. It is recognised that this cannot be completely simulated in unoccupied test houses; clearly tests must be carried out in real, occupied homes to provide confidence in the results of the LIUHB method. There is a significant practical issue with this aim which is that the co-heating test is the only method currently available to define a baseline measurement of a house’s HLC. The invasive nature of the co-heating test makes this difficult to achieve in an occupied house.

This limited the original aim to carry out linked co-heating and LIUHB tests in several occupied houses of different types, with different occupiers, with only one such set of tests carried out in this study. The tests were carried out in a three bedroom, semi-detached house built in around 1950 with cavity wall construction. A full description of the house was given in section 4.1.4. The house is located in Loughborough, close to the Loughborough University campus; this meant that the weather data collected at the campus weather station could be used in the analysis.

The co-heating test was carried out between 23/12/12 and 5/1/13. The co-heating equipment and method used for the tests carried out in the test houses, described in section 4.1.4, was used with an internal set-point temperature of 25°C. The temperature was measured using HOBO U10 loggers, with the electricity consumption of the whole house measured at the service meter using a Plogg current transformer sensor and logger. The electricity consumption of each heater and mixing fan was also measured by a Plogg in-line logger. A heater and fan was located in each room, with an even temperature distribution achieved throughout the house. The test was carried out during a period of ideal co-heating conditions, with low temperatures and low solar irradiance, as shown in Figure 7-36.

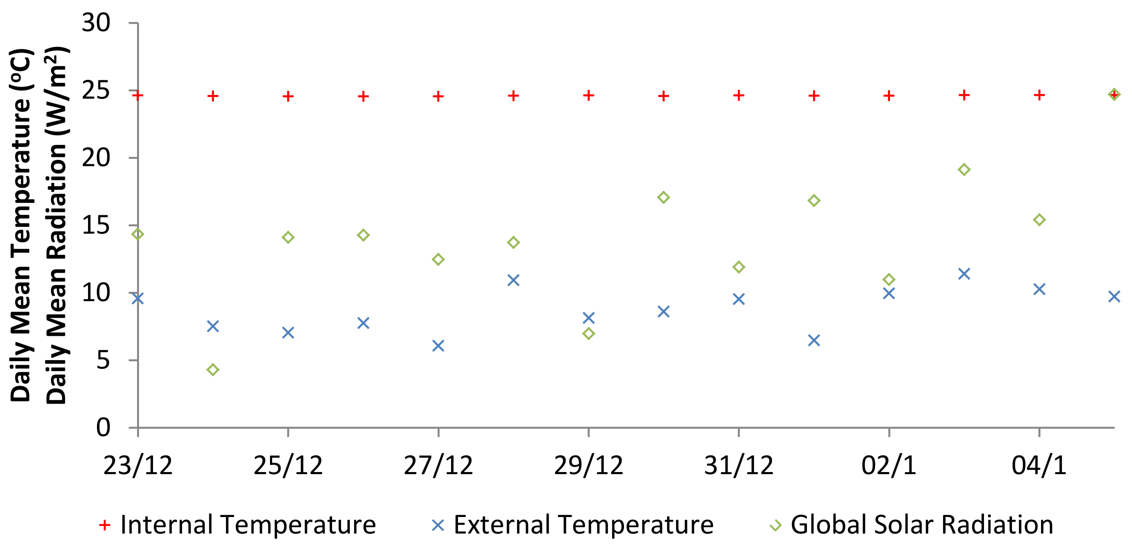


Figure 7-36: Internal temperature and weather conditions during the co-heating test carried out in an occupied house.

The conditions during the tests meant that there was very little difference in the HLC as calculated by any data analysis method as there was little need for a correction due to solar gains, this can be clearly seen in the co-heating plot (Figure 7-37).

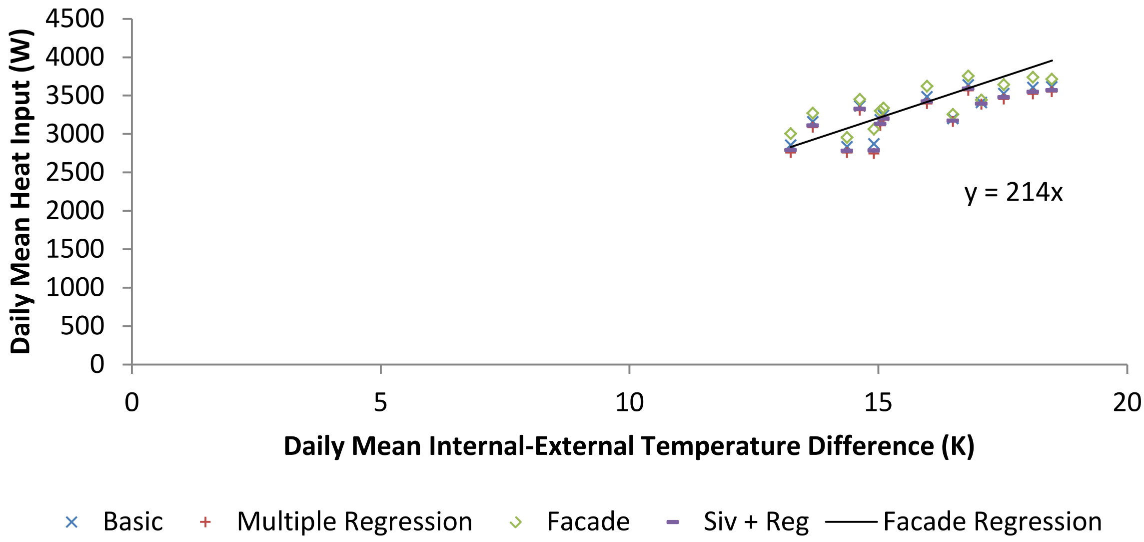


Figure 7-37: Co-heating plot for the test carried out in the occupied house.

The results by each data analysis method are given in Table 7-18.

Analysis Method	**HLC (W/K)**
Basic	207
Statistical	203
Facade	214
Siviour	205
Siviour + Regression	204
Net Radiation Siviour	206

Table 7-18: Results of the co-heating test carried out in the occupied house by each data analysis method.

The monitoring period for the LIUHB was 5/11/13-1/3/14. During this period the temperature was measured using HOBO U10 loggers, positioned at mid-height in each room. The loggers were placed in discrete locations out of direct sunlight and the direct influence of any heat sources. The electricity consumption was measured at the service meter using a Plogg current transformer logger. Gas consumption was measured using a pulse logger attached to the pulse output of the service meter, via an optical isolator to comply with gas meter regulations. As stated earlier, the weather conditions were taken from the Loughborough University campus weather station for both tests.

There were no secondary heating sources present in the house, though cooking was carried out using gas hobs which will introduce an extra uncertainty into the measurement as the consumption for this use was not measured specifically. During the monitoring period no requests were made of the occupants, they were simply informed that their energy consumption would be monitored and they should continue to use the house as normal. It was informally noted by the researcher that it was common for the windows in the bathroom and small bedroom to be opened for moisture control – the bedroom was often used for clothes drying. However, window opening was not measured during the monitoring period.

The daily mean temperature conditions over the monitoring period are shown in Figure 7-38. It can be seen that there was a relatively consistent low external temperature over the monitoring period. The most noticeable feature of the figure is the drop in internal temperature, and consequential fall in internal-external temperature difference, around the middle of the monitoring period. This coincides with Christmas and is likely to be due to the occupants leaving the house during this time.

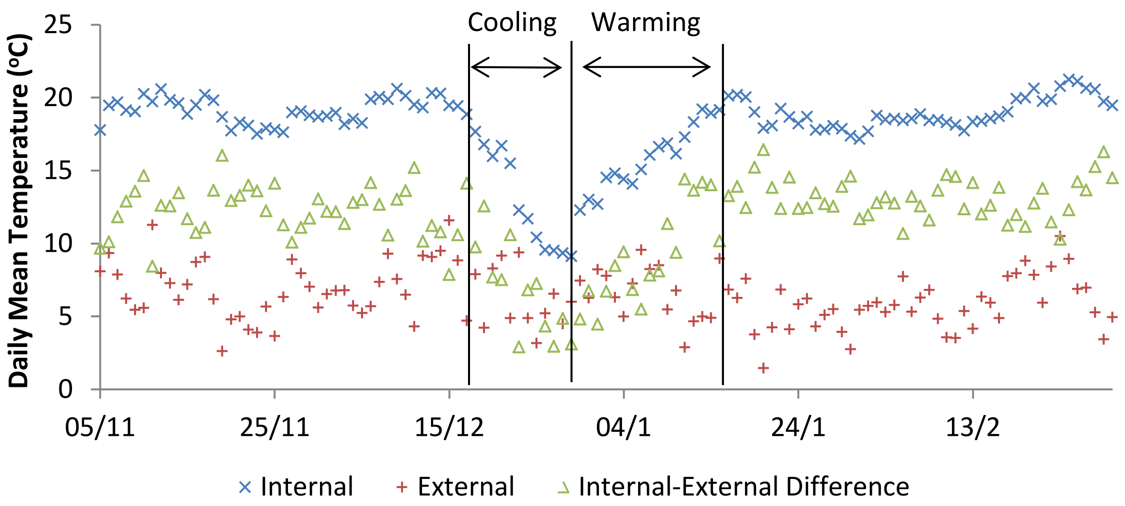


Figure 7-38: Daily mean temperature conditions over the monitoring period.

It is interesting to note the slow warming period in the internal temperature after the pre-Christmas reduction, with the internal temperature taking around two weeks to return to its previous level. It is likely that this cool down and warm up will be associated with a discharge and recharge of the thermal mass of the building, which occurs over a period of several days.

Figure 7-39, showing the total daily mean heat input to the house as well as the heat input broken into electrical and gas sources, confirms that the temperature drop over the Christmas period was associated with a lack of occupancy given the low use of both electricity and gas. This is shown by the period of very low energy usage, highlighted on the chart, consistent with no heating or appliance use (and hence no occupancy). There also seems to be a different usage pattern immediately prior to and following this period, with a lower level of heat input, which is highlight in blue on the chart. It is not possible to ascertain why there is a lower level of energy usage in this period; one possible explanation could be a lower number of occupants present at this time. This change in usage could explain the slow decline and increase in internal temperature around this period shown in Figure 7-38. A few days of particularly high energy usage are apparent immediately following an increase in internal temperature (the first points after the second and third shaded areas); these are likely to be associated with charging the thermal mass.

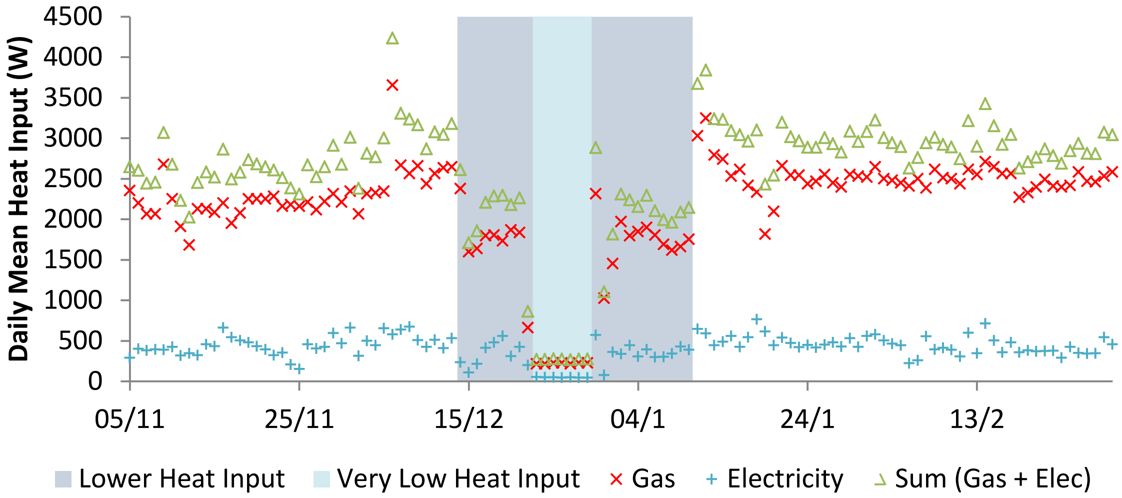


Figure 7-39: Daily mean heat input to the house broken into gas and electrical sources.

The daily mean amounts of global solar and net radiation during the monitoring period are shown in Figure 7-40. It can be seen that there was rather low global solar and net radiation levels for the majority of the monitoring period, with a particularly dull section in the middle where there was very little variation in the radiation conditions. Finally, there was a period with greater levels of global solar and net radiation at the end of the monitoring period.

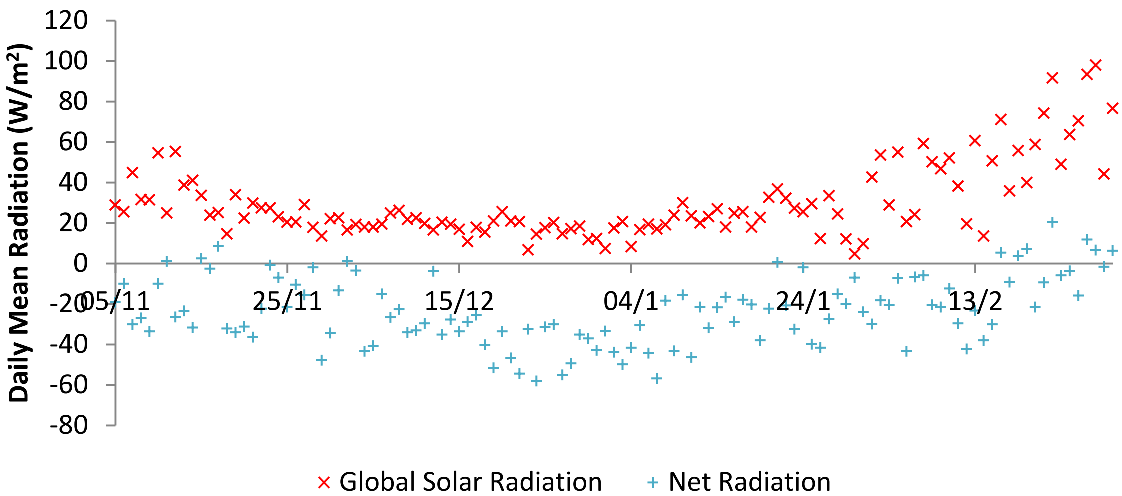


Figure 7-40: Daily mean global solar and net radiation during the monitoring period.

The results by each data analysis method are given and compared to the results of the co-heating test in Figure 7-41. The results of the in-use test were calculated using the full sample of 117 days which is likely to increase the confidence in the result compared to the recommended minimum test length of 3 weeks (21 days).

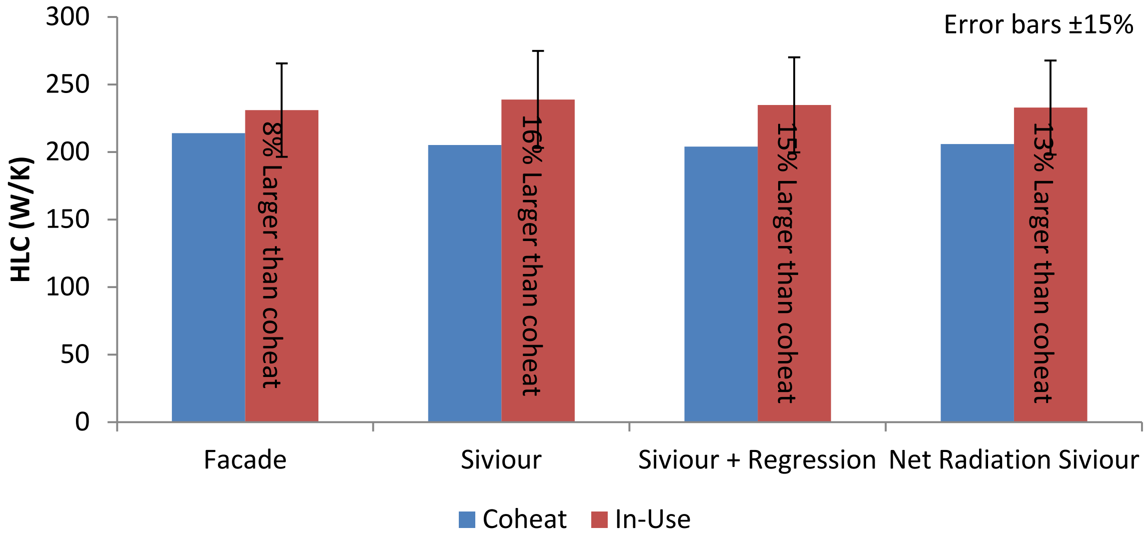


Figure 7-41: Comparison between the results of the LIUHB and co-heating tests in the occupied house case study.

There was a close agreement between the results of the in-use and full co-heating tests. The results of the in-use test fell within both estimated uncertainty boundaries around the co-heating result of ±15% and ±13%, when the preferred facade analysis method was applied, showing a successful demonstration of the method. However, the result of the in-use test fell outside of the ±15% zone for the Siviour and Siviour + regression methods.

As stated, the extended monitoring period is likely to increase the accuracy of the in-use test. Therefore the monitoring period was divided into a series of three week segments in order to investigate the range of possible results if different sub-sets of weather and occupancy conditions occurred. The same method of dividing the monitoring period as has been applied earlier in the thesis was applied, with samples taken to create a 21-day moving window into the data which moves by one day at a time. In this way the first sample was from 5/11/13-25/11/13 (inclusive), the second from 6/11/13-26/11/13 and so on, with the final sample from 9/2/14-1/3/14; in total there are 97 samples. The calculated HLC by each of the four main analysis methods are shown for each sample in Figure 7-42. As a guide to the accuracy of the result for each sample the calculated HLC using the facade method has been included in the figure. The facade method was chosen as the baseline for comparison as this is felt to give the most accurate measurement, as described in Chapter 6 and in keeping with the approach used in the rest of this chapter.

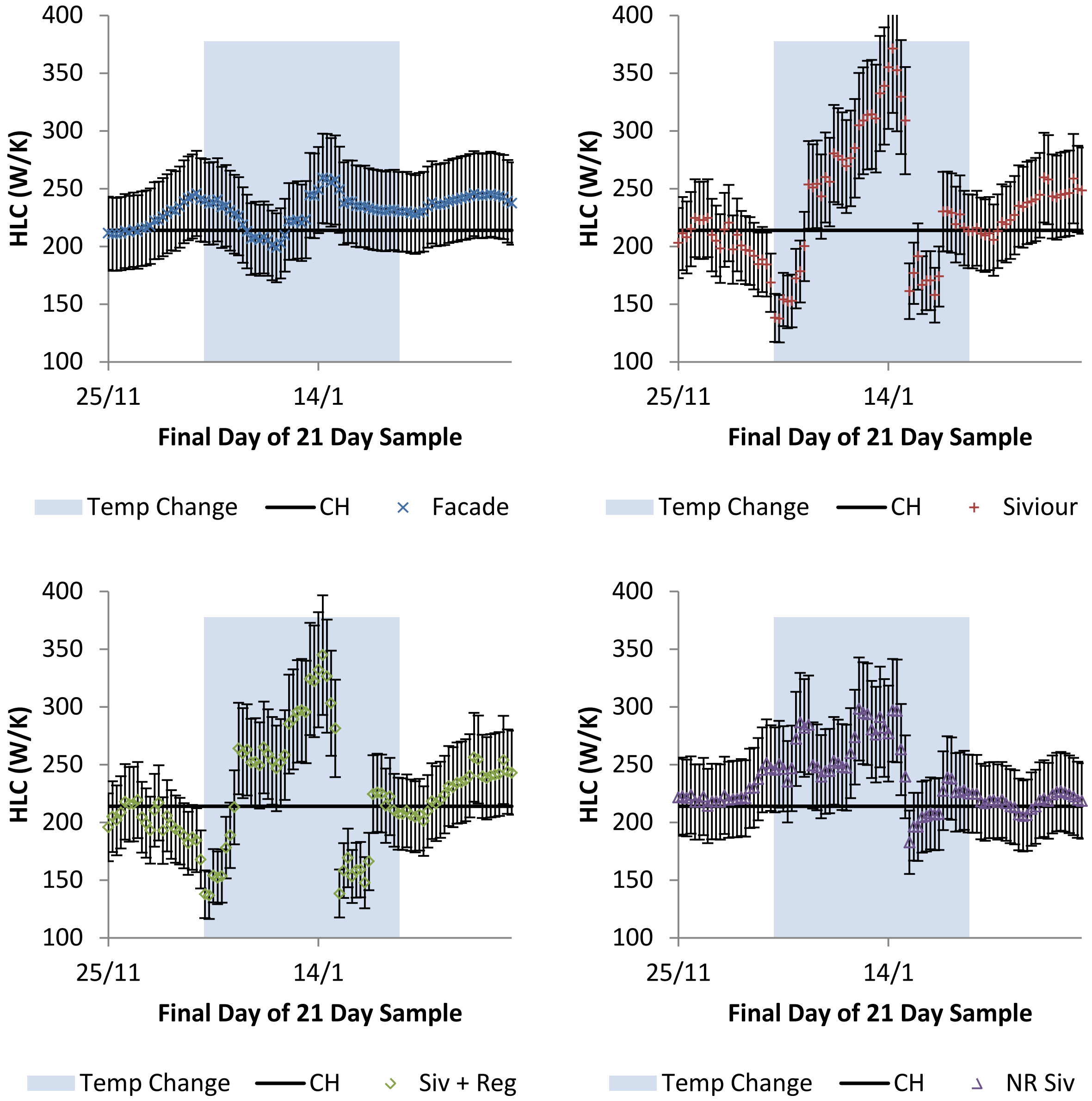


Figure 7-42: Calculated HLC via four data analysis methods applied to 97 21-day samples of the LIUHB occupied house case study dataset. Samples within the shaded area contain data from the period of cooling and warming. (CH – co-heating HLC measurement)

Repeating the findings of the investigation reported in Chapter 6, it can be clearly seen that the facade method results in the most consistent measurement of HLC for these three week samples. It can also be seen that the largest variations from the co-heating baseline HLC occur during the period around Christmas when the house was not occupied and experienced a significant reduction in internal temperature. This is not surprising and is likely to be associated with the low heat input to the house during this period (Figure 7-39), and a longer term charging and discharging of the thermal mass.

The heat input to the house can be considered as the signal input to the house in the measurement carried out in an LIUHB test; During the unoccupied period there was very little heat input to the house (a mean daily average gas + electrical power of only 274W), resulting in very low internal-external temperature differences (Figure 7-38), with daily mean values of less than 10^{o}C (the recommended minimum for co-heating) during this time. Under these conditions there is clearly a reduced heat flow from the house; however the magnitude of some of the key sources of uncertainty in the HLC measurement, particularly quantifying solar gains, are unaffected. The result is that the though the absolute magnitude of the total uncertainty is reduced, it forms a larger proportion of the heat balance, and the measurement is adversely affected.

Due to the time span of several days over which the house cooled down and warmed back up it is likely that there will have been a charging and discharging of the thermal mass of the building which occurred over a period of several days. This will therefore be unaccounted for by the method of using daily averaged values in the analysis which is used to deal with charging and discharging in a normal diurnal cycle. As the house cools the thermal mass will discharge, acting as a positive heat source which is not accounted for in the heat balance, as the discharging only affects the internal, and not external, air temperature. Therefore the calculated HLC is lower for the three-week samples which contain days only from this discharging period, this is apparent in Figure 7-42 for all analysis methods. Then, as the house heats up again the thermal mass is charged, acting as an unaccounted for heat sink, causing the calculated HLC to be higher for the three-week samples which contain days only from the charging period – this trend can be observed for all analysis methods in Figure 7-42. As the moving window into the data moves forwards in time, travelling across the chart from left to right, fewer of the days during which the temperature change occurred are included in the sample, therefore the effect reduces in magnitude at the right hand side of the shaded area.

The results shown in Figure 7-42 are compared statistically to the results of the co-heating test carried out in the house in Table 7-19. The result of the co-heating test as analysed using the facade method was used as the baseline value.

	Analysis Method	Facade	Siviour	Siv + Reg	NR Siviour
Including cooling/ warming period	Samples within ±15%	91	53	55	69
	% within ±15%	94%	55%	57%	71%
Excluding cooling/ Warming period	Samples within ±15%	50	43	46	48
	% within ±15%	100%	86%	92%	96%

Table 7-19: Comparison between the results of the occupied house case study LIUHB and the co-heating test in the same house.

This comparison reaffirms the observation of a successful trial of the LIUHB; using the preferred facade method an HLC within ±15% of the co-heating value was found for 94% of all three week samples (91 of 97 total samples). We can see in Figure 7-42 that the six samples outside of the ±15% boundary all occurred sequentially and included data collected during the re-heating of the house. This period effects calculated HLC using the other three analysis methods to a greater extent, which is reflected in the low number of samples that fall within the ±15% zone using these methods.

In the second section of Table 7-19 the results excluding the cooling down and warming up period are shown. It can be seen that using this filter results in all samples falling within the ±15% zone for the facade method, and high proportions for the three other methods.

The results of the case study show a successful demonstration of the LIUHB, but also highlighted some issues with the method. In particular a rapid change in the use of the house seems to present a problem which is likely to be associated with charging and discharging of thermal mass. It is not possible to be sure how likely this sort of event is to occur during a monitoring period, or what size of change in temperature will cause a significant inaccuracy in the calculated HLC. Though in this case is can be observed that day-day variations in internal temperature, and even a marked change in energy usage, did not cause a significant impact on the measured HLC. This only occurred when there was almost no heat input, an event which can be clearly seen on plots of the internal temperature or energy use (Figure 7-38 and Figure 7-39). Therefore in the first instance a filtering approach, whereby days not meeting predetermined conditions are excluded from the dataset, may prove an effective measure. Possible conditions could be a minimum internal-external temperature difference (e.g. 10^{o}C), a minimum total heat input, or a maximum change in internal temperature compared to the previous day. The disadvantage of the approach is that it may require lengthening the monitoring period to ensure that enough data is collected to carry out the analysis. Analysis of data collected in a number of houses would be required to determine suitable filtering conditions (which could indeed be specific to a particular house), and to determine possible added monitoring time that would be necessary if this approach was adopted.

Data of this type was not available during this study to allow this analysis to be carried out, but it is recommended as essential further work if this method is to be adopted more widely. With further work it may be possible to determine the range of conditions that are necessary to allow a chosen level of certainty in the regression carried out during data analysis. Given remote collection of data this would make it possible to select that date of decommissioning when enough suitable data has been collected, which could reasonably be a shorter or longer than three week period dependent upon the conditions particular to a house and time.

In the longer term a better understanding of how charging and discharging of the thermal mass effects the heat balance is desirable, which should allow methods to account for imbalances on a day-day basis to be developed, and included in the heat balance. It is possible that this could be achieved simply using a different averaging method, either by averaging over a longer time period (i.e. several days) or by using weighted averages so that each daily value for internal-external temperature difference has some weighting to account for the trend over the preceding days. The weighting for these averages could be defined by analysis of the rate of cooling of a house under free running conditions, which is likely to be collected overnight as a part of a normal monitoring regime. Alternatively this analysis may lead to the development a simple method of calculating the amount of energy contributed daily to thermal mass charging or discharging, which could then be directly added to the heat balance.

A weighted average approach may also be applied to solar or net radiation data, to account for charging of the external side of construction elements. Some attempts to test such weighted average analysis methods were applied in this project, but time restraints have meant that no conclusive findings were reached.

7.7. Summary

A method, the Loughborough In-Use Heat Balance (LIUHB), has been developed which allows the HLC of a house to be measured while it is occupied. It has been successfully demonstrated in comparative trials with the co-heating test in several different houses. The method has been demonstrated in an unoccupied test house, in a test house with extreme profiles of synthetic occupancy applied, and finally in an occupied house. In all trials the LIUHB tests resulted in an HLC within a boundary of ±15% of the HLC as measured by a co-heating test. The method has also been successfully applied to test the change in performance resulting from a retrofit.

At present ±15% is the estimated total uncertainty of the test. In order for the test to be applied more widely is it necessary to develop further confidence in this estimate, this can be achieved through a series of comparative trials with co-heating tests in occupied houses. In particular the trials must increase the sample of different occupants and building types to show that the method is robust under different conditions. Given the results gathered in this project, with agreement between in-use and co-heating results typically rather close, it is likely that given a larger body of evidence the estimated uncertainty of the method could be reduced from its current level of ±15%.

The uncertainty in the LIUHB method is derived from several sources which could be categorised broadly into physical issues relating to the building and testing conditions, and those related to the actions of the occupants. It is those related to the occupants that apply specifically to an in-use method, in comparison to co-heating tests. Ideally, an in-use testing method should be able to remove the effects of the occupants in deriving the physical properties of the house, in this case the HLC. The tests carried out so far have shown that the LIUHB method seems to be robust enough to achieve this aim. Though as an aside it is useful to state that even if that wasn't possible, a method which outputs another metric which gave a composite measurement of the house and the occupants would have some value given the paucity of alternatives currently available.

So far the method has been successfully demonstrated in detached and semi-detached buildings, it is likely that uncertainty will be increased in houses with other buildings attached, such as terraced houses and particularly flats. This is because the boundary conditions in these cases are not likely to be known, as a reduced proportion of the perimeter walls will be exposed to the external temperature. It may be necessary to develop additional elements to the method to account for these additional unknowns.

The effect of charging and discharging of the thermal mass has been identified as source of uncertainty in the method in its present form. In particular the data collected in the occupied house case study demonstrated the impact of this phenomenon on the measured result. This is highly recommended as a necessary area of further research, with some potential methods to address the issue suggested in the concluding remarks of section 7.5. The new analysis method for heat flux sensor data described in section 2.2, which seeks to characterise rather than eliminate the effect of thermal mass (Biddulph et al., 2014), clearly shows the potential advantages of a dynamic analysis approach. It is likely that if a similar approach could be successfully applied to the LIUHB method the issues associated with thermal mass would be greatly reduced. This would be likely to reduce the required monitoring time, measurement uncertainty, and necessary internal-external temperature difference.

When considered as a whole the results of these trials clearly show the potential of the LIUHB. Pleasingly, the method itself is rather simple, and yet has proven reliable under a varied set of operating conditions. It has been developed through a deep testing schedule, including many comparative experiments with the co-heating test. The research carried out into the co-heating test, reported in Chapter 5 and Chapter 6, have informed the design of the LIUHB, giving it a well-founded basis. A thorough experimental program was then carried out to test the additional uncertainties in the LIUHB on an elemental basis. It is the combination of these pieces of evidence that give confidence in the promise of the LIUHB method.

Chapter 8 Discussion

This thesis has presented the results of an investigation into measurement of whole-house thermal performance focussing on three key areas:

(i) Establishing the accuracy of the currently most-used testing method, the co-heating test.
(ii) More accurately accounting for solar gains in co-heating tests.
(iii) Developing a measurement method that can be carried out while a house is in-use, with minimal disruption to the occupants.

In this chapter the context for the research findings is discussed, and suggestions are made for suitable applications for these findings and the potential impact they could have. The chapter also includes appraisals of the methods used to undertake this study, and recommendations for further work are made.

This chapter is separated into sections which discuss the co-heating test (section 8.1), and more specifically accurately accounting for solar gains in these tests (section 8.2). The next section contains a discussion on the Loughborough In-Use Heat Balance test, and in-use testing in general (section 8.3). Section 8.4 then moves on to a discussion of suitable applications for fabric performance testing in the future, and what testing methods would be most suitable to meet the demands of these applications. The discussion is summarised in section 8.5, with the main conclusions of the study presented in the following chapter (Chapter 9).

8.1. The Co-heating Test

The co-heating test continues to be the only widely-used test for fabric thermal performance in the UK. It has been invaluable in providing evidence to prove the existence of the 'performance gap', which refers to the common overestimation of the thermal performance of a house, and as a research tool to identify causes for this gap (Stafford et al., 2012). Despite this success, the test has been limited to use in research applications up to this time due to a combination of a lack of confidence in its results by the building industry and the lengthy and invasive nature of the test (Butler and Dengel, 2013). The results presented in Chapter 5 and Chapter 6 provide new insights which contribute to the discussion around these issues.

In Chapter 5 it is shown that across six co-heating tests carried out in the NHBC Co-heating Project, the HLC was measured to within a margin of ±10% of the mean measured HLC. This was despite major variations in data collection and analysis methods, different weather conditions for each test, and the final tests being carried out outside the usual co-heating season. In addition, a sensitivity analysis was used to calculate a measurement uncertainty of ±9% in the co-heating test. The combination of these findings significantly increases the confidence to be expected of the results of co-heating testing, and for the first time allows the resulting HLC to be reported with an empirically defined uncertainty interval. These findings support the confidence in the results of the test that is held by researchers at Leeds Beckett University, whose work has brought the test to more widespread attention and who have significant experience in its use (Stafford et al., 2012).

The variation in data collection and analysis approaches adopted by the teams taking part in the NHBC Co-heating Project show that the co-heating test method is still under development. The methodological comparison undertaken based on that project, which can be found in sections 5.3.1 and 5.3.25.4, has led to a series of recommendations upon best practise method for carrying out co-heating tests (section 5.4). Generally, it is important to appreciate: the value of the time taken to carry out the test, its invasive nature means that a repeat test is unlikely to be possible, therefore every effort must be taken to ensure the success of the test using secondary sensors as a back-up and remote monitoring where possible.

The data analysis method used to calculate the HLC has been under-reported in the past; in order to allow confidence in the results of a test and comparison between the results of tests, it is vital that this is reported in addition to the measured HLC. At present the data analysis consists primarily of accounting for solar gains, with several methods proposed to do so, this is clearly the input to the heat balance subject to most variation and consequently the source of the most uncertainty. Ideally, each of the most commonly used data analysis methods would be applied and the results reported for each co-heating test, this would aid direct comparison between test results and provide further information as to which analysis method gives the most repeatable result.

With further homogenisation of the co-heating method it is certain that the reproducibility of the result would be increased further. The uncertainty of the test is also likely to be further reduced given greater understanding of the effects of other weather conditions such as wind speed, direction and rainfall, which are not currently accounted for in most co-heating analyses. This observation does highlight a limitation of the sensitivity analysis that was used to define the measurement uncertainty of the co-heating test, which is recognised not to be completely exhaustive and did not include the influence of these factors. That was not possible at this time as methods to take account of these other weather conditions have yet to be defined. The effect of varying wind speed, which will change the convective heat transfer rate at the external surfaces, and the effect of evaporative cooling, particularly after rainfall, could perhaps initially be best addressed by laboratory based experiments (as they were by White (2014), as described in section 2.6.1), as they can be investigated at an elemental level, rather than the building as a whole.

It is interesting to note that the conditions during a co-heating test are very different to those in which the building will typically be used, with a higher internal temperature and forced internal air movement (to ensure an even temperature distribution). These factors will influence the heat transfer from the house and could cause a difference between HLC measurements made in co-heating tests and under normal operating circumstances.

Testing in building with attached spaces (such as semi-detached, terraced or apartment buildings) presents a problem in co-heating, particularly if it is not possible to access the adjacent space in order to install sensors. At present, the energy balance in a co-heating test is based upon only the internal-external temperature difference, which clearly does not apply to attached walls. A similar problem applies to heat losses through the ground floor of buildings, which are also likely to be exposed to a different temperature than the external air temperature. Ground temperature is unlikely to vary widely throughout the year, or across the UK, however, heat losses to the ground will vary between houses depending upon construction and insulation levels. Quantifying the possible effect of different temperature conditions at these boundaries would further knowledge of the uncertainty in co-heating measurements carried out in different building types and is recommended as a topic for future research.

That the results of the co-heating test were found to be reproducible to within a margin of ±10%, despite the issues discussed, provides great confidence in the possibility of carrying out whole-house thermal performance measurements, and will help to address the lack of confidence in the co-heating test that is still present in the building industry. Persuading the building industry that the co-heating test offers an accurate and useful way to test the performance of buildings may not be a simple task; it seems natural that there could be a certain resistance to its adoption given the additional cost that testing would entail and the possibility of uncovering routine overestimation of the in-situ thermal performance of buildings.

8.2. Accounting for Solar Gains and other Data Analysis in Energy Balance Tests

Despite the high degree of reproducibility in co-heating results, it is clear that accounting for solar gains during co-heating tests remains an area of debate that requires further research. This issue was addressed in Chapter 6, which described a series of comparative tests between various methods used to account for solar gains in a range of weather conditions and house types. The methods included in the comparative tests were the three currently most commonly used (the Siviour, Siviour plus regression and multiple regression methods), and a new method which has been developed in this research – the 'facade solar gain estimation' method. The results of the comparative tests showed that the new method performed well in comparison to those currently used, providing a more consistent result across a range of weather conditions. A major, unexpected, further advantage of the facade method was also observed; it was shown to be capable of producing accurate HLC measurements using data collected from co-heating tests carried out during summer months which have previously been regarded as unsuitable for co-heating. This addresses one of the major practical limitations to the application of the co-heating test. The same analysis techniques are used to account for solar gains in the Loughborough In-Use Heat Balance test, this research is therefore directly applicable to both testing methods.

All three of the buildings in which the comparative tests reported in Chapter 6 were carried out (the Holywell test house, 209 Ashby Road and building 50.3) were of relatively modest thermal performance. It has been observed that inaccuracy in the calculation of solar gain has less effect on the accuracy of an HLC measurement of a house when the total heat input is higher – simply as the solar gain accounts for a smaller percentage of the total heat input. Therefore, it is likely that in a highly performing, well-insulated, house, where there is a lower total heat input to maintain a given internal temperature, the inaccuracies in calculating the solar gain will have a large impact on the reproducibility of the measurement of HLC (as seen to some extent in the tests carried out at BRE). This would be particularly pronounced in the summer months, with higher external temperatures and solar gain levels. Therefore, it would be useful to repeat these comparative tests in houses with higher thermal performance to investigate this effect.

The comparative success of the facade method versus the traditional methods is likely to be due to its engineering-based approach, rather than the regression techniques applied in the traditional analysis methods. A regression method is rather seductive for a number of reasons: it offers a simple analysis; does not usually require additional on-site measurements (appropriate solar radiation data can usually be sourced from a local weather station); and accounts for solar gains through both glazed and opaque elements. In comparison, the facade method requires either additional measurements of irradiance of the glazed facades or significant additional data analysis to translate global solar irradiance into irradiance reaching each glazed facade; and does not include a method to account for solar gains through opaque elements. However, the regression based methods have been shown to be heavily dependent upon the weather during the monitoring period for providing a suitable range of conditions. If the weather conditions are rather similar during the measurement period, then the data points will be clustered together, so that they almost become several samples of the same data point. This limits the accuracy with which a regression can be carried out, as there isn’t a spread of data points on which to estimate the line of best fit, analogous to trying to guess the slope of a staircase from a single step. This means that the calculation of either the intercept (in the case of the Siviour method) or the gradient (in the case of the Siviour plus regression and multiple regression methods), and hence the HLC, is based upon an extrapolation of regression well away from the actual data points; an approach which is generally not recommended in regression analysis (Montgomery et al., 2001).

This idea is illustrated graphically for the case of a co-heating test in Figure 8-1, which shows a Siviour analysis carried out on a hypothetical sample of 14 days with very similar dull and cool weather, which would ordinarily be thought ideal for co-heating due to the low solar gains (and hence low additional uncertainty in accounting for them). A 95% confidence interval around the regressed line of best fit is shown; it can be seen to fit tightly around the cluster of data points, but then rapidly expands in size away from the data points. The y-intercept of the Siviour plot defines the estimated HLC, and it can be seen that in this crucial area the 95% confidence interval is very wide; in fact it is ±44% of the measured HLC of 125W/K. So it can be seen that the HLC cannot be estimated with a high degree of confidence, despite seemingly ideal testing conditions. Regression-based methods require a spread of weather conditions, which clearly cannot be guaranteed in a limiting available time for testing.

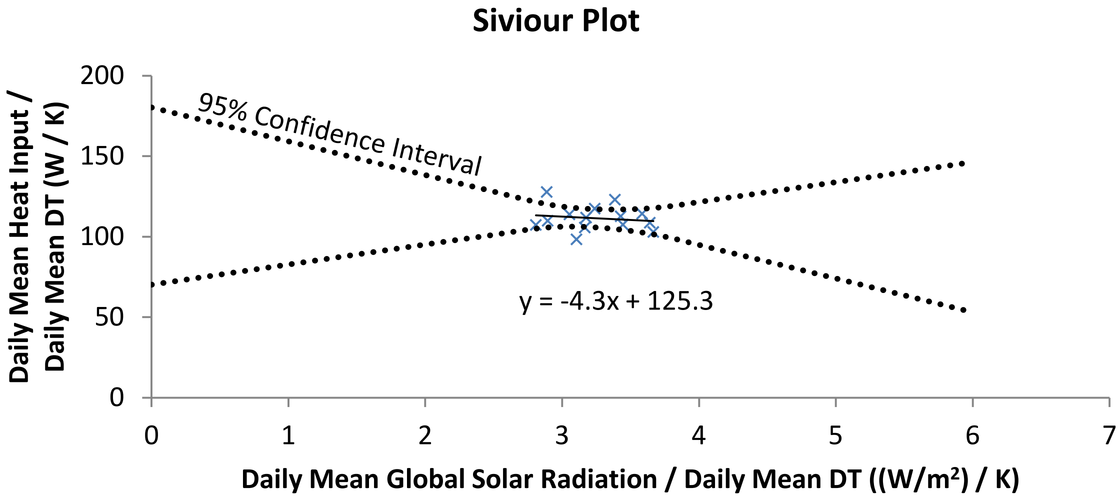


Figure 8-1: Example of the problem of 'clustering' of days with similar weather conditions during a co-heating test.

A less extreme example of this occurred during the winter co-heating test carried out in 209 Ashby Road, as shown in Figure 8-2. In this case the confidence interval is ±20% of the measured HLC of 422W/K, again despite the data being collected during a series of, seemingly ideal, days with low irradiance and external temperature.

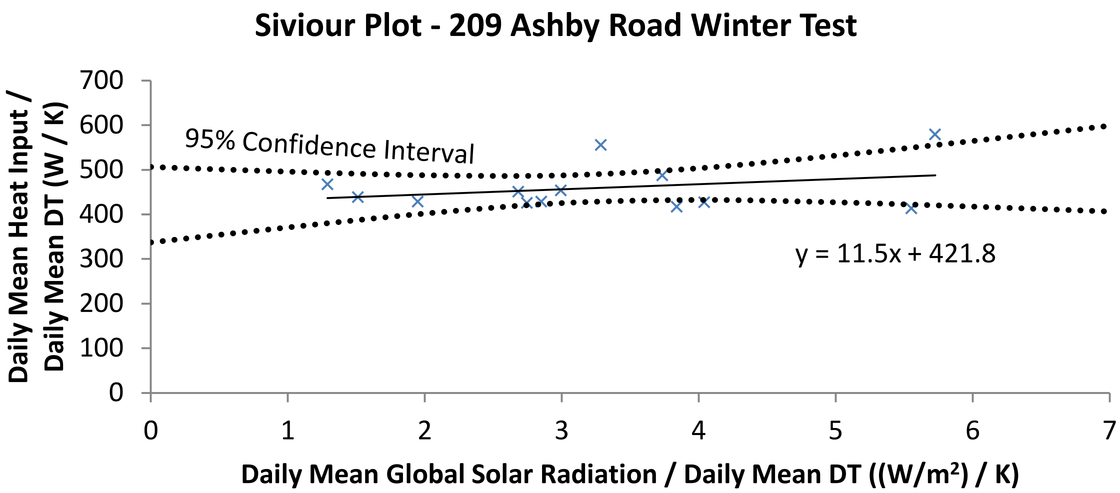


Figure 8-2: Siviour plot from the winter co-heating test in 209 Ashby Road, including a 95% confidence interval around the regression line.

The effect is even more pronounced when looking at a co-heating plot, as shown in Figure 8-3 and Figure 8-4 which are calculated using the Siviour plus regression method for the same data as is used in Figure 8-1 and Figure 8-2, respectively. In both cases the confidence interval around the regression line expands very rapidly away from the cluster of data points.

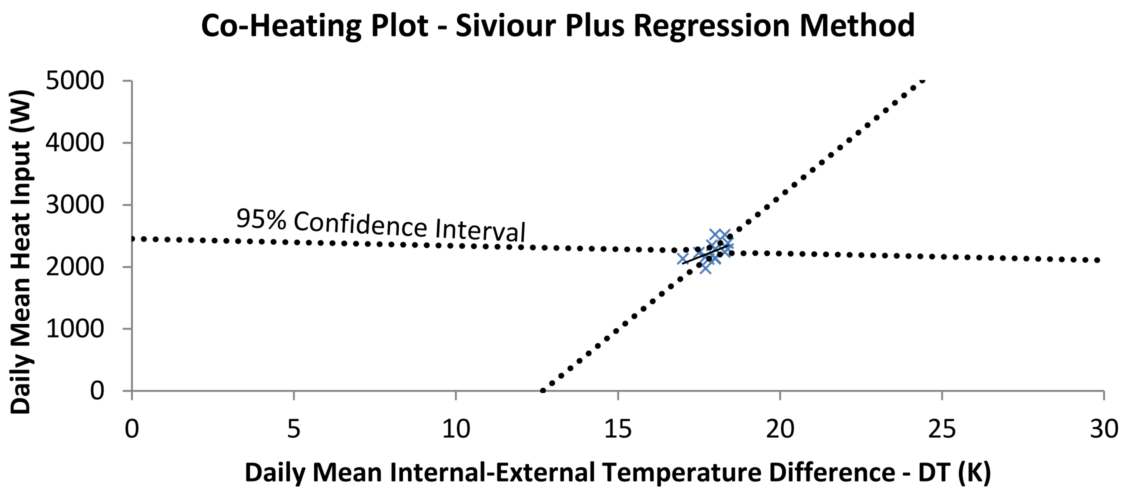


Figure 8-3: Co-heating plot showing the calculated HLC using the Siviour plus regression method for the same data as Figure 8-1, a 95% confidence interval is shown around the linear regression line.

In the case of the winter co-heating test in 209 Ashby Road (Figure 8-4) it can be seen that the commonly used method of assuming a zero-intercept (i.e. that when there is no heat input the internal-external temperature difference will be zero) seems to be invalid as this position falls outside of the 95% confidence interval. This suggests that there are further variables influencing the energy balance; perhaps long-wave radiative heat loss, wind speed, rainfall or some other variables.

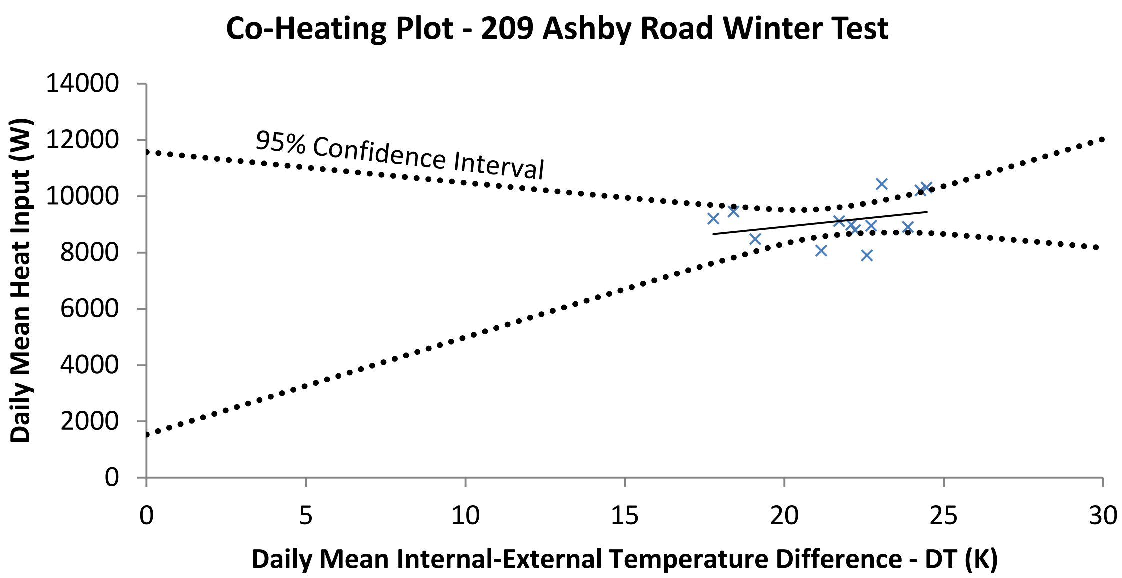


Figure 8-4: Co-heating plot showing the calculated HLC using the Siviour plus regression method for the winter test in 209 Ashby Road, a 95% confidence interval is shown around the linear regression line.

The use of this analysis technique demonstrates that in the winter co-heating test in 209 Ashby Road data was not collected during a suitable range of weather conditions to allow calculation of the HLC to an acceptable level of confidence. The ability of this analysis method to demonstrate this phenomenon opens the door for a possible new ongoing review of co-heating data as it is collected. While in this case a suitable range of weather conditions did not occur, the high level of observed reproducibility in co-heating results shows that in most cases it does; furthermore it is possible that a full sample of 14 days may not be required to collect a suitable dataset. In some cases a suitable range of conditions may occur in a shorter period, even perhaps within a couple of days. If data is collected remotely, then this analysis method could be applied daily to judge whether a suitable dataset has been collected; this would allow an informed decision on whether further data collection is required. This process would enable reduced measurement periods in many cases, and would offer a means to determine when a measurement period must be extended to collect data over a suitable range of weather conditions to allow an accurate estimate of the HLC in others.

Without a process such as described above though, there remains a risk that a suitable range of weather conditions will not occur, meaning that the HLC cannot be accurately estimated using a regression-based analysis method. In addition to this issue with regression-based analysis techniques, there is a more fundamental problem in the contravention of the inherent assumptions of multiple regression analysis caused by the data collected in co-heating tests (which was described in section 3.1.1). By contrast, the facade solar gain estimation method does not suffer from these problems and has been shown to deliver a more repeatable estimate of the HLC for datasets collected in a variety of weather conditions.

The additional solar radiation measurements required to carry out the full version (earlier defined as the ‘measured variant’) of the facade method do add an additional cost, however, this is a one-off cost associated with purchasing the additional pyranometers and logging equipment (the additional time required to fit the sensors to the facades is very small in comparison to the set-up time for a co-heating test as a whole). As the co-heating equipment is moved between houses to carry out tests, the capital cost of the additional equipment is unlikely to be very large in comparison to the labour costs of physically administering the test, and is therefore not considered likely to be a major consideration given the advantages in reproducibility that the method offers. The ‘translated variant’, where the solar irradiation reaching each facade is calculated by a translation of global solar radiation, has also been shown to be superior to existing methods, and does not require additional measurements to be undertaken.

There remains an issue with the facade method in its current form in that it does not include a method to empirically take into account overshading. This is also an issue for the measured variant, as the shading path across the facade is likely to be complex and not fully represented by a measurement taken in one location. It may be possible to adopt a measurement approach to address this issue in a cost-efficient manner. Rather than installing many highly accurate (and expensive) pyranometers, it may be possible to fit an array of much lower cost and less accurate sensors, with one installed on each window (which offers a simple attachment approach). These sensors would then be used simply to judge when each window was shaded, and to what extent. This information could then be combined with the unshaded irradiance, calculated by a translation of accurately measured weather station data, to provide accurate estimates of the irradiance reaching each window whilst taking overshading into account.

Despite these remaining issues, the facade method has been shown to provide the most repeatable method to account for solar gains, and is likely to be improved with further research. Excitingly, it also offers the option of carrying out co-heating tests during the summer months, though it must be noted that this is likely to require an even higher internal temperature which may cause damage by rapid drying out, causing cracks. This is likely to be more pronounced in newly built and refurbished houses. It is recognised that the method can still be further developed; however, the method crucially is not subject to the statistical problems identified with the regression-based models, which have been shown to be insurmountable for tests carried out in some weather conditions.

All current methods have limitations in common; none of them address the influence of other factors which affect the boundary conditions of the house during co-heating tests and will have some impact on the rate of heat loss. Examples of such variables are wind speed and direction, rainfall and finally the interaction between these variables; all of these variables require further research to quantify their possible effect and to account for them in the energy balance. The facade method is likely to be adaptable to such an approach in that it specifically calculates solar gains; in contrast it is unlikely that the influence of each variable could be isolated using a regression-based approach due to the cross-correlations between weather variables. This research would be applicable both to the co-heating test and to the Loughborough In-Use Heat Balance Method.

The ‘net radiation Siviour’ (or NR Siviour) method was proposed in section 7.4.4 as a way to account for long-wave heat losses, and was shown to perform well in comparison to both the traditional regression and the facade analysis methods. The NR Siviour method is therefore worthy of further research, it is however limited by the same issues associated with the assumption in regression analysis which apply to the other regression-based methods. It may be possible to combine net radiation measurements with information about the sky-view factor of a house in order to develop a method which accounts for radiative heat loss in a similar way to that which the facade method calculates solar gains, this is recommended as an area of further research.

Clearly accounting for solar gains remains an ongoing area of research, and it is recognised that the facade method does not represent a conclusive solution to this problem. It has been shown, however, to offer a significant improvement upon existing methods in its current state, and which could be further improved by ongoing development alongside its use.

8.3. The Loughborough In-Use Heat Balance

The Loughborough In-Use Heat Balance (LIUHB) provides a method to measure the HLC of houses with little disruption to the occupants. The application of the test is likely to require only two house visits, one to install the equipment and carry out a basic survey of the house and a second to remove the equipment. As described in Chapter 7, the test has undergone a series of successful comparative demonstrations versus the co-heating test under a number of different scenarios. This testing process has provided a thorough empirical proof of concept for the test, including an investigation of the effect of differing boundary and occupancy conditions. The commercial appeal of the LIUHB has also been thoroughly demonstrated by the collaborative work that has been carried out with the Energy Technologies Institute (ETI), PRP Architects and Mitsubishi Electric; and the article outlining the method that has been published in Innovation and Research Focus (Jack et al., 2015). The combined technical and commercial supporting evidence provides a clear justification to continue use and development of the method.

Continued development of the method is a key statement; while this thesis has provided a thorough proof of concept it must be noted that the method has not been carried out in a wide variety of housing types or with a wide variety of occupants. Comparative experiments versus an accepted measurement method, likely to be the co-heating test, must be carried out in a greater sample of houses to deepen the understanding of the method. The approach of comparing the results of the LIUHB to a measured baseline value provides the only route to properly test its accuracy, particularly in view of the evidence for the fabric performance gap (described in section 2.2). However, it is clear that the LIUHB and the co-heating test share many features in common. This may present an issue when using the co-heating test to provide the baseline measurement in a comparative test, as it is possible that both methods could share a weakness in common, given the similarity between them. This hypothesis is supported to some extent by the difference that was found between the HLC as measured by the co-heating test and the PSTAR test in a comparison of the two methods carried out in the same detached house (Palmer et al., 2011). In this study it was not possible to definitively identify the cause for the difference, indeed the two tests were carried out several months apart, so the HLC of the house may have actually changed (ibid). One possible cause that was suggested was the difference between the dynamic nature of the PSTAR test and the quasi-steady-state approach adopted in the co-heating test. This suggestion is not supported by the close agreement between the results of the LIUHB (which is also applied under dynamic conditions) and the co-heating test observed in this thesis however. In addition, the co-heating test offers the only method to provide a baseline *measurement* for comparison in widespread use at present, and is therefore the natural choice for this application.

Uncertainty in the HLC measurement using the LIUHB is likely to be primarily linked to four sources: weather conditions, occupancy, measurement errors and building characteristics. The occupied house case study, the results of which were reported in section 7.6, was carried out over an extended period and provided evidence of the ability of the facade method to provide a repeatable measurement of the HLC over a variety of weather conditions in conjunction with the LIUHB. Given that the same analysis techniques developed for use in a co-heating test are applied in the LIUHB, it is not surprising that this finding repeats that obtained for the co-heating test. As stated in the previous section (section 8.2), the research carried out investigating the best analysis methods in co-heating is directly applicable to the LIUHB. Further development of those analysis methods, which were discussed in section 8.2, should continue to be fed into the method used for the LIUHB.

The synthetic occupancy tests sought to identify the maximum possible realistic effects of various occupancy variables; however, at this point there is a paucity of research documenting the infinite variety of ways in which a house could be used. It is therefore necessary to carry out further tests in real occupied houses to broaden knowledge of the possible effects of occupancy on the accuracy of the test. The ongoing work with the ETI, in which the LIUHB is being used to test the effect of retrofits in five occupied houses, provides a further demonstration that an HLC measurement can be drawn from data collected while a house in in-use. This work is limited though, as no other testing method has been applied to provide a baseline measurement against which to compare the value from the LIUHB test. The LIUHB results will be compared to those from an RdSAP assessment, but this method has been shown to be prone to significant inaccuracy and does not provide a useful baseline comparison. Further comparative demonstrations versus the co-heating test in a greater sample of houses are likely to provide the only route to a convincing validation of the LIUHB's ability to separate the influence of occupation from the measurement of the HLC.

The measurement error inherent in an energy balance analysis such as that used in the LIUHB was investigated via a sensitivity analysis, the results of which are reported in section 5.2. As for the investigation into the effects of varying weather conditions carried out using co-heating data, due to the similarity between the tests these findings are considered to be directly applicable to the LIUHB. There are some important differences between the two tests however, particularly the effect of sensor placement and the measurement of the heat input provided by a typically gas fuelled central heating system.

The results of an investigation into the effects of sensor placement were reported in section 7.2. The investigation found that as long as temperature sensors can be placed at approximately mid-height in a room and away from heat sources the mean air temperature within the room can be discretely measured with an acceptable degree of accuracy. It also demonstrated that measuring the temperature in each room is important in carrying out an accurate measurement of the volumetrically-weighted mean temperature within a whole house. This is likely to become increasingly important with a greater penetration of zonal heating controls, where rooms are not heated continuously if they are unlikely to be unoccupied. The results did show some success, however, in measuring a reasonable approximation of the mean volumetrically-weighted air temperature within a house using a single sensor located at the mid-point of the whole house. This possibility should be investigated further as a reduction in the number of temperature sensors necessary would help to reduce the cost and invasiveness of the method.

The measurement of the heat input from a typical gas-fired central heating system will naturally be prone to more uncertainty than heat delivered entirely from electrical sources (as in co-heating); however, uncertainty from this source is likely to reduce over time due to a number of factors:

- Boilers are becoming increasingly more efficient and well characterised.
- In houses of higher thermal performance (such as new or retrofitted houses), there will be a lower total heat demand. As electrical loads (which can be accurately measured with ease) in houses are likely to stay constant or increase in the future (due to additional appliance

use), the proportion of the total heat input from the heating system is likely to decrease, and hence the measurement accuracy of the total heat input increase.

- As described in the introduction (Chapter 1), CO_2 emissions due to heating homes contribute around 22% of total CO_2 emissions in the UK (DECC, 2012; Parker and Cooper, 2011). In order to meet the target of an 80% reduction in CO_2 emissions (H.M. Government, 2008) this portion of the total emission must clearly be addressed. This is likely to be achieved both through an increase in the thermal performance of houses, and electrification of heating – the output of which can be measured with more accuracy that that of a gas boiler.

The performance of currently typical heating systems has been addressed in some detail in previous research (Orr et al., 2009) and the boiler efficiency testing reported in section 7.3. This evidence shows that the heat output of most boilers is rather constant and similar to the listed efficiency (within ±7%), which means that this source of uncertainty is not large enough to invalidate the results of the LIUHB. The estimated uncertainty from this source has been accounted for in the total reported uncertainty of the LIUHB, ±15%.

Having discussed the possible effects of weather conditions, occupancy and measurement uncertainty, one of the four sources of uncertainty remains: the building characteristics. This is an area particularly in need of further research due to the limited sample of houses in which the method has been applied to date. Although the uncertainty of the LIUHB has been reported as a percentage of the HLC up until this point, it is likely that the total uncertainty will be comprised of elements that vary with the HLC and elements that have an absolute effect. For example, the additional heat loss due to opening a window to the same area and for the same length of time will not vary for houses of different thermal performance. However, the percentage change in the total heat loss from the house caused by a given additional heat loss is clearly directly linked to the HLC of the house. Similar relationships are likely with other variables; in general the heat input will be lower for a given internal-external temperature difference in higher performing houses, therefore the effect of each variable will be relatively higher and the uncertainty a larger percentage of the HLC. In this way there is likely to be some relationship between the HLC and the measurement uncertainty. An example of a possible distribution of this relationship is shown in Figure 8-5. Note that the figure is not based upon any measured data, and is merely an illustration by the author.

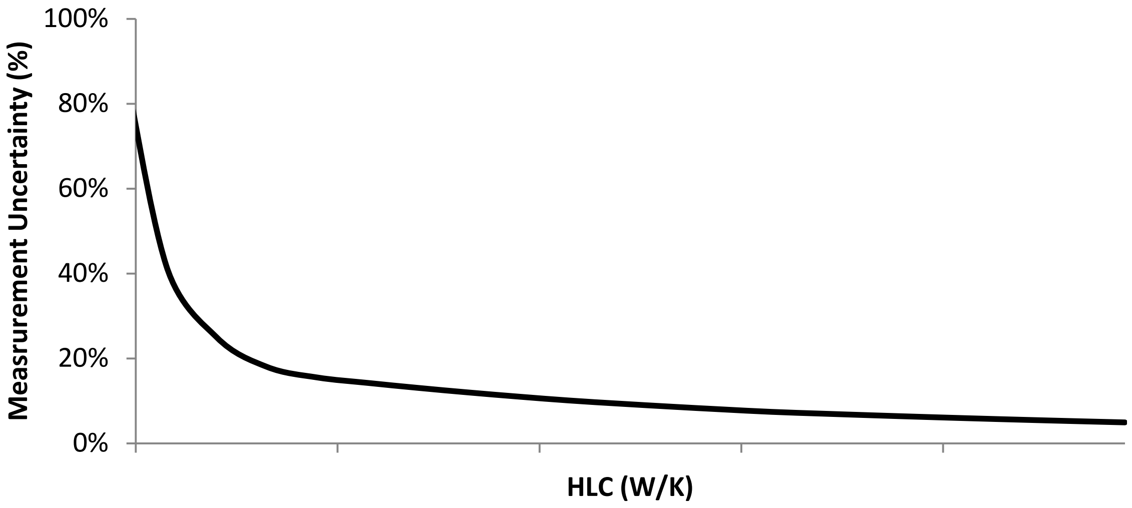


Figure 8-5: Example of a possible relationship between the HLC of a house and the measurement uncertainty of the LIUHB method.

Populating a chart such as that shown in Figure 8-5, and developing an understanding of when the LIUHB can be applied is a vital next step in establishing the range of houses in which the method can be used and to what degree of accuracy. It is likely that there is some maximum level of thermal performance for a house (that would correspond to a low HLC) after which the test cannot be applied with an acceptable level of accuracy. A validation process for the LIUHB, including comparative tests versus the co-heating method in houses of a variety of HLCs, is required to understand this relationship.

8.3.1. Possible Future Developments

The recent development of the QUB method (described in section 2.6.2) and the lumped mass method for carrying out U-value measurements of individual elements proposed by Biddulph et al. (2014) (described in section 2.3), have shown the potential of dynamic methods to allow reduced measurement periods and yet obtain accurate measurements of thermal performance. It seems likely that a similar approach, possibly using a lumped element resistor-capacitor style model that is used in electrical engineering, could be successfully applied to the LIUHB, reducing the necessary monitoring time. While the non-invasive nature of the test largely removes one practical constraint to longer testing periods, reducing the necessary measurement period would reduce the cost of the method as sensors would not need to be committed to each building for as long. This would be particularly pertinent to encourage testing on a mass scale.

The LIUHB method has been designed to be utilised in combination with emerging data streams, such as smart meters. It has been mandated by the government that all energy meters (gas and electricity) should be replaced by smart meters (DECC, 2014), with the aim that they should be installed in all houses by 2020 (H.M. Government, 2015). These meters are capable of two-way communication, so that in future records of the gas and electricity consumption of every house in Britain on a half-hourly basis will be available, thereby providing a significant proportion of the data required to carry out the LIUHB test. It is expected that smart meters will be the first of a series of sensing technologies installed in houses, so that eventually methods to log the energy performance of houses will be as common as those currently used to measure the performance of cars. The LIUHB will be well placed to take advantage of these data streams. In order to take full advantage of them it will be necessary to digitise the LIUHB analysis method, so that it can be carried out automatically. This would enable testing on a truly massive scale; opening the door for a series of new markets associated with quality assurance or retrofit targeting, or new ways to design government policies for example.

Application of the LIUHB using embedded sensing technologies would allow both very widespread testing, and testing on a continuous basis. This could be used to provide instant feedback to occupants on the energy performance of their homes, along with more accurate estimates of the energy savings that may be possible due to a variety of retrofits and eventually the effect that any completed retrofits have had. A continuous analysis would also allow a record of how the measured HLC changes over time, which may enable a whole series of further analysis methods to be developed. For instance, opening windows causes an additional heat loss from the building. By monitoring the changing HLC in a house it may be possible to highlight periods when the HLC is lowest, and infer periods when all windows and openings were closed. Methods such as this, to isolate and quantify the effect of different occupant actions, would enable feedback to be provided to occupants about how they use their house and what effect this has on energy consumption. The availability a large dataset created by continuous monitoring would also allow filters to be applied, so that data collected on days with sub-optimal weather conditions, such as particularly high wind speeds or levels of solar radiation, could be removed. This would be likely to decrease the uncertainty of the LIUHB test, and may enable application of the LIUHB to higher thermally performing houses.

The energy balance approach adopted in the LIUHB is adaptable, and is not limited therefore to testing the performance of houses in the UK. The method would be directly applicable in houses in any country with a similar climate and a measurable heating input; it may also be possible to apply an energy balance approach where a house is cooled rather than heated. In fact, as cooling is most frequently provided from electrical sources, the cooling load could be accounted for more accurately than the heat output of a typical boiler. However, the internal-external temperature difference may be smaller than in a typical heating situation, which may increase uncertainty. Research into this application would increase the range of climates in which the LIUHB could be applied. Indeed, there is no reason why the method should be limited to domestic buildings, and it may be possible to apply it in larger non-domestic buildings, further increasing the total number of situations in which the method could be applied.

8.4. Applications for Whole House Fabric Thermal Performance Measurement

The co-heating test remains the most commonly used method to test the fabric thermal performance of a whole house. Although it is likely to be too invasive and expensive for very widespread use, it remains a powerful research tool, both for providing a measurement of a house's performance, but perhaps more importantly providing ideal conditions for a series of other diagnostic tests to be carried out. For example, the raised internal temperature caused by the co-heating test is helpful for thermographic surveys and elemental U-value measurements. This thesis has demonstrated that the co-heating test is capable of providing a measurement of a house's HLC to within an accuracy of ±10%, and that with the new facade solar gain estimation method it can be successfully applied at all times of the year in the UK. This addresses the doubts that have been raised about the accuracy and reproducibility of the method, which make it suitable for use in a quality assurance role. This quality assurance process would allow house builders to demonstrate the performance of their product, providing a competitive market advantage, empower occupants by providing more information about their property, and may allow a route for measured compliance testing with building regulations. This would enable a shift in analysis from 'designed' to 'as-built' performance, helping to address the performance gap.

The LIUHB offers a much less invasive method to measure the HLC with an estimated accuracy of ±15%; this opens up a whole new series of possible applications that are not practically possible for the co-heating test. It is clear that the method is very well suited for testing the effects of retrofits, again providing quality assurance for all parties. This would also allow more accurate estimates of energy savings resulting from retrofits; this plays directly into the 'golden rule' inherent to the Green Deal but is more widely applicable to informing retrofitting decisions at all levels, from occupants to policy designers. More accurate predictions of energy savings due to retrofits would allow the development of better business cases for retrofitting; this would allow the effect of mass-retrofitting measures to be compared to costly supply-side emission-reducing measures by policy developers.

Performance measurement of houses on a mass scale, which could be enabled by integration with smart metering as discussed earlier, would allow accurate evaluations of the performance of housing stocks to be carried out. This would allow better targeting of retrofit measures, so that the lowest performing houses are treated first and would be of direct benefit to groups that manage large portfolios of buildings, such as housing agencies or policy makers. This would also allow houses at risk of fuel poverty or which could be detrimental to the health of the occupants to be identified.

Both the co-heating and LIUHB tests output the HLC of a building, which is not at present a widely known metric. In order for the results of the tests to have value, awareness of the HLC must be raised, or HLC measurements need to be combined with a basic model of the house in order to predict energy consumption, which is a more commonly used metric in policy design. It is also questionable quite how useful the HLC is as a metric, it is certainly valuable in directly comparing the performance of houses, but it may not be particularly informative to the occupant. This is an area which requires more research to ensure that the most useful information is drawn from the results of LIUHB testing. It may be that this leads to the development of other metrics, for instance a version of the HLC which includes an adjustment for the efficiency of the heating system and could therefore be reported as a rate of energy consumption which could then be converted into cost to the occupant. This could be extended further to give a metric which is a composite measurement of the fabric and system performance, and also the effect of the particular occupants in a house; which may in fact lead to more accurate estimates of energy consumption. Interestingly, these metrics would actually be simpler to calculate than the HLC, and would remove many of the uncertainties associated with the LIUHB.

8.5. Summary

This chapter has discussed the key findings of the thesis, including appraisals of the methods that have been used, suggestions of suitable applications for the research findings, and for suitable further work.

This thesis has been focussed on building performance measurement methods. It demonstrates clear contributions to the body of knowledge on the co-heating test, including: a unique calculation of the uncertainty and reproducibility of the test, and the development of a new analysis method to account for solar gains which shows a distinct improvement over existing analysis methods.

The research culminates with the development of the Loughborough In-Use Heat Balance, which was informed and strengthened by the research carried out into the co-heating test. The LIUHB method has been shown to be capable of providing accurate, yet non-invasive and relatively low-cost, measurements of houses' fabric thermal performance, meeting the overall aim of the project. Further validation work is required to establish the full operating range of the LIUHB by assessing the suitability of its use in a range of different house types, and with different occupants.

Chapter 9 Conclusions

The aim of this work was to ‘develop and validate non-invasive domestic building thermal performance measurement methods suitable for application on a mass scale’. Three objectives were defined to lead to the fulfilment of this aim: 1) to define the uncertainty of the co-heating test, 2) to develop a method to better account for solar gains, and 3) to develop a non-invasive measurement method which could be applied while the occupants remained in place. This aim and objectives have been largely met by the study, leading to contributions to knowledge including: the calculation of the accuracy of HLC measurements resulting from co-heating tests, recommendations for the best practise method of carrying out co-heating tests, advancements in the understanding of co-heating data analysis methods to accurately account for solar gains, and the development of the Loughborough In-Use Heat Balance method to measure the fabric thermal performance of houses with little disruption to the occupants.

The following conclusions have been drawn:

- Provided testing and data analysis is carried out according to the best practise method, the HLC measurement by a co-heating test can be reported with a precision of ±10%. This calculated precision is based upon a sensitivity analysis used to summate inherent measurement uncertainties, and a reproducibility study. The reproducibility of a measurement refers to the precision of a test, given that it is carried out in different locations and with different operators and equipment (BSI, 2000).
- A methodological comparison of the co-heating method of seven organisations has been completed, informing a series of recommendations for the best practise co-heating data collection and analysis methods (given in section 5.4). They include guidance on the required number, specification and placement of equipment and sensors, infiltration measurement, and data analysis methods and reporting.
- A new method to account for solar gains has been developed, called the ‘facade solar gain estimation’ method, which enables accurate HLC measurements to be carried out in many houses during the UK summer.
- Existing regression-based co-heating data analysis methods have been shown to be prone to significant inaccuracy. This is due to contravention of inherent statistical assumptions and extrapolation errors occurring in cases when a suitable range of weather conditions does not

occur during a test. It is recommended that regression-based analysis methods should not be used unless these causes of inaccuracy have been accounted for.

- The 'Loughborough In-Use Heat Balance' (LIUHB), has been developed and successfully demonstrated. It can be used to measure the HLC of houses with an accuracy of ±15%, while they are occupied and used as normal. The method has undergone a thorough proof of concept process, including successful comparative tests versus the co-heating test with extreme yet realistic examples of synthetic occupancy applied, before and after a thermal performance increasing retrofit and in a single occupied house. The method now requires thorough validation in order to define the range of applications in which it can be accurately applied.
- The LIUHB has already been used in practise to measure the performance increase resulting from retrofits of existing houses, in association with the Energy Technologies Institute.

The co-heating testing analysed in this thesis, in particular the testing carried out by different teams upon the same building as part of the NHBC project, form a unique dataset, which has allowed a uniquely robust analysis of the reproducibility of the method to be carried out. The structure of the NHBC project allowed the first direct comparison of co-heating test results, revealing for the first time the amount of variation which different testing and analysis methods can cause. The fact that very consistent HLC measurements were returned, despite variations in data collection and analysis methods and weather conditions across the tests, provides a significant increase in confidence with which the results of co-heating tests can be interpreted.

Further to the analysis of the NHBC project, a comparison of existing methods for estimating solar gains during co-heating test has been carried out based upon testing in three different test houses, over a wide variety of weather conditions in each case. This has added to the understanding of how best to deal with solar gains, which have been shown to be the largest source of uncertainty in co-heating tests and the largest source of variety in co-heating method. The comparison has shown that reproducible HLC measurements can be made in any season in the UK, for three different houses, though it has been shown that this may be problematic in highly performing houses. This work has addressed one of the most significant limitations to the co-heating test's wider use: it's limitation to a short period of the year.

The development of the LIUHB, has addressed the other major hurdle to widespread building performance testing, namely the invasiveness of the testing methods such as co-heating. The testing investigating the additional uncertainty in HLC measurements caused by the presence of occupants has shown that it is possible to accurately determine a building's thermal characteristics based upon data collected while a building is in-use. This work is of course applicable directly to the LIUHB method, but also has a wider relevance to post-occupancy evaluations of building performance in general. This is likely to become an area of increasing interest given the rich streams of data that are emerging from smart meters, and are likely to become available from zonal heating controls and Home Energy Management Systems (HEMS). It is clear that combination of these data sources and methods such as the LIUHB could allow routine, accurate, assessment of as-built thermal performance at very low cost in the future.

Measurement of building performance on a mass scale would provoke a dramatic change in thinking about energy use in buildings. It could provide quality assurance for retrofitted and newly built assets (including assessing compliance with building regulations), which would drive performance improvement; it would allow accurate assessment of the effect of demand side policies, which could then be compared directly with supply-side equivalents; and it would also empower homeowners and property managers, such as local authorities, to make informed decisions about improving the performance of their buildings. The findings of this thesis provide both confidence in measurements of whole-house thermal performance, and demonstrate the possibility of much more convenient and low-cost testing; thus delivering the means to accurately assess the real performance of buildings on mass scale.

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