White, Jennifer A. (2014) An investigation into the parameters that contribute to the gap between the designed and as-built thermal performance of British housing. PhD thesis, University of Nottingham.

Infrastructure, Geomatics and Architecture Research Division
Faculty of Engineering

AN INVESTIGATION INTO THE PARAMETERS THAT CONTRIBUTE TO THE GAP BETWEEN THE DESIGNED AND AS-BUILT THERMAL PERFORMANCE OF BRITISH HOUSING

Jennifer Anne White BSc(Hons), MSc(Res), MA

Thesis submitted to the University of Nottingham

for the Degree of Doctor of Philosophy

APRIL 2014

ABSTRACT

The UK Government has placed the need to reduce national energy demands and carbon emissions at the forefront of the political agenda, with a commitment made to meet EU targets of 20% reductions in greenhouse gas emissions and primary energy consumption, alongside a 20% improvement in overall energy efficiency, across all EU Member States, by 2020.

Building performance has been identified as a key area where significant progress towards meeting these ambitions can be made. It is fundamental to ensure that the building fabric of a property functions correctly in order to achieve high levels of thermal effectiveness, which should result in lower energy demands and carbon emissions. However, research to date shows that a gap exists between predicted and actual performance levels.

This research utilises the dwelling Heat Loss Coefficient (HLC) as a common output in design stage and post-construction evaluation techniques, that can be used to compare predicted and measured fabric performance. The Standard Assessment Procedure (SAP), coheating tests, air pressure tests and thermal imaging are used to evaluate in-situ buildings. Sensitivity analysis and controlled conditions experiments are utilised in order to investigate the reliability of the assessment techniques used.

The key findings from the study include the demonstration, through novel coheating test, that post-installation mechanically ventilated heat recovery (MVHR) system efficiency levels can have a pronounced effect on the measured HLC, and, in conjunction with use of assumed theoretical efficiency levels, can cause divergence in theoretical and measured data of 10-15%. This can largely be resolved through correct design, installation and commissioning. Environmental conditions, both notional and site-specific, can also cause divergence in the HLC data, including wind speed (15%) and solar gains (10-26%). In addition, it has been shown that, when considering thermal bridging values, inaccurate calculation at the design-stage and poor attention to detail during construction could cause underperformance in this element by up to 50%. This is of significance as there are currently no mandatory procedures to assess post-construction compliance with thermal bridging levels specified within the UK Building Regulations.

PUBLICATIONS TO DATE RESULTING FROM THIS RESEARCH

Published:

Banfill, P., Simpson, S., Gillott, M., White, J., (2011) The potential for energy saving in existing solid wall dwellings through mechanical ventilation and heat recovery, ECEEE 2011, 6-11 June, Belambra Presqu'ile de Giens, France.

Banfill, P., Simpson, S., Gillott, M., White, J. (2011) Mechanical ventilation and heat recovery for low carbon retrofitting in dwellings. Proceedings of the World Renewable Energy Congress 2011, 8-11 May, Linkoping, Sweden.

White, J., Gillott, M, Gough, R. (2012) Investigation Of A Combined Air Source Heat Pump And Solar Thermal Heating System Within A Low Energy Research Home. Proceedings of the 11th International Conference on Sustainable Energy Technologies (SET-2012), September 2-5, 2012, Vancouver, Canada

White, J., Gillott, M., Wood, C. (2013). The Impact of MVHR Systems on Space Heating Levels in Dwellings. 12th International Conference on Sustainable Energy Technologies (SET-2013). 26-29th August 2013. Hong Kong.

White, J., Gillott, M., Wood, C.J., An Analysis of Influencing Factors Within Coheating Test Methodology (accepted for inclusion at 13th International Conference on Sustainable Energy Technologies (SET-2014). 25th-28th August 2014, Geneva)

ACKNOWLEDGMENTS

Whilst the last three or so years have been both challenging and fascinating, none of it would have been possible without the support and guidance of a wonderful group of people, some of whom have been instrumental in my studies and others who probably do not even realise they have been there for me.

Firstly, I will always be grateful to Professor Mark Gillott for taking a chance and choosing to let me study for my PhD and awarding me a funded programme. His support and advice has been invaluable, and without his foresight I may never had the opportunity to complete this work. Many thanks to the Accelerating Low Carbon Economies project for providing my finance, and to Melanie Watts (the Project Manager) for her advice and friendship during my studies. Professor Saffa Riffat has also been a source of sound advice.

Dr Lucelia Taranto-Rodrigues has provided excellent feedback on my work at annual reviews and beyond, whilst Dr Christopher Wood has given many hours of support in terms of technical and experimental guidance. All of these people, along with Zeny Amante-Roberts, have helped me through the difficult times, and been there to celebrate when progress has been made. A special mention should be made to David Oliver, who has provided an abundant amount of practical and emotional support, and who I will never

My family has kept me going when I needed encouragement, and provided a safe place to relax when a break from the books was required. I realise that my thesis will not be widely read, but my mum had the painstaking task of proofreading the draft copies – thank you for the hours you gave up and the comedy comments!

I will not name all of the friends who ignored my rants and cheered me up when experiments were not working or data was corrupted. They know who they are – thanks for forcibly dragging me off to the great outdoors when I needed it most. And a special mention should be made to the great British countryside – whilst finances were limited, trips to the mountains, lakes and coasts of the UK certainly didn't seem like second best to journeys further afield, and never ceased to relax and rejuvenate me.

Finally, I will answer the question that my father asked me when I left my well-paid permanent job to return to the world of student wages and endless days of reading and writing, with frequent frustration interspersed with occasional euphoria. Why did I want to do a PhD? It is simple really – why not? I am not sure I will ever stop wanting to learn more. As I find myself close to the end of another journey of discovery and learning, I am already looking forward to the next chapter and what challenges that may bring.

TABLE OF CONTENTS

APPENDICES

LIST OF EQUATIONS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ACH: Air Changes per Hour (unit)

AECB: Association for Environmentally Conscious Building

BRE: Building Research Establishment

BREDEM: Building Research Establishment Domestic Energy Model

BSI: British Standards Institute

CEH: Creative Energy Homes

CERT: Carbon Emissions Reduction Target

CERO: Carbon Emissions Reduction Obligation

CESP: Community Energy Saving Programme

CfSH: Code for Sustainable Homes

CO_2*: Carbon Dioxide*

COP: Coefficient of Performance

CRC EES: Carbon Reduction Commitment Energy Efficiency Scheme

CSSO: Carbon Saving Community Obligation

DABE: Department Architecture and Built Environment

DCLG: Department of Communities and Local Government

DEC: Display Energy Certificate

DECC: Department of Energy and Climate Change

DER: Dwelling Emissions Rate

DHA: Domestic Hot Water

DSA: Differential Sensitivity Analysis

EACR: Effective Air Change Rate

EC: European Commission

ECO: Energy Companies Obligation

EED: Energy Efficiency Directive

EI: Environmental Impact

EHS: English Housing Survey

E.On House: E.On 2016 Research House

EPBD: Energy Performance of Buildings Directive

EPC: Energy Performance Certificate

EPSRC: Energy and Physical Sciences Research Council

ESOS: Energy Savings Opportunities Scheme

EST: Energy Saving Trust

EU: European Union

FEES: Fabric Energy Efficiency Standard

FITS: Feed In Tariff Scheme

ICF: Insulating Concrete Formwork

GHA: Good Homes Alliance

gWh: Gigawatt Hours (unit)

HCA: Homes and Communities Agency

HLC: Heat Loss Coefficient

HLP: Heat Loss Parameter

HHCRO: Home Heating Cost Reduction Obligation

K: Kelvin (unit)

kWh: Kilowatt Hours (unit)

LEED: Leadership in Energy and Environmental Design

l/s: litres per second (unit)

MCA: Monte Carlo Analysis

m/s: metres per second (unit)

MEV: Mechanical Extract Ventilation

Mt: Megatonnes (unit)

Mtoe: Million Tonnes of Oil Equivalent (unit)

MVHR: Mechanically Ventilated Heat Recovery

NES: National Energy Services

NHBC: National House Building Council

NHER: National Home Energy Rating

NRSA: Nominal Range Sensitivity Analysis

Pa: Pascal (newton/m^2*) (unit)*

PHPP: PassivHaus Planning Package

POE: Post Occupancy Evaluation

PSTAR: Primary and Secondary Terms Analysis and Renormalization

Project CALEBRE: Consumer-Appealing Low Energy Technologies for Building Retrofitting

RCUK: Research Councils UK

RdSAP: Reduced Data Standard Assessment Procedure

RHI: Renewable Heat Incentive

RIBA: Royal Institute of British Architects

RUSFA: Really Useful Software for Architects

SAP: Standard Assessment Procedure

SIPS: Structural Insulated Panels

SME: Small Medium Enterprise

STEM: Short Term Energy Monitoring

Tarmac House: Code Level 6 Tarmac Masonry Research Homes Dwelling

TAS: Thermal Analysis Simulation

TER: Target Emission Rate

TSB: Technology Strategy Board

UK: United Kingdom

NOMENCLATURE

A: area of exposed surface (m^2)

C: specific heat capacity (j/kgK)

COP: coefficient of performance

F: total ground floor heat loss (W)

G_i: internal gains (W)

G_s: solar gains (W)

H : required heating input (W)

H value: thermal convection (W/m^2K)

H_t: transmission heat loss (W)

K value: thermal conductivity (W/mK)

L: steady state heat loss coefficient

L_t: transmission losses (W

L_v: ventilation losses (W)

Ms: supply mass flow rate (kg/s)

n50: dwelling air leakage rate (ach @ 50Pa)

n: background ventilation rate (h^{-1})

N: nominal value

N_i: initial set value

η_t: temperature efficiency of the MVHR system

P: renormalized parameters

P: total power input (W)

Q: Total measured power (W) or heat flux (W)

Q_s: Total measured power corrected for solar gains (W)

q50: dwelling air permeability ($m^3/(h.m^2)$ @ 50Pa)

r_{ext}: External wall surface resistance

r_{hf} : Heat flux sensor surface resistance

r_{int}: *Interior wall surface resistance*

R: *solar aperture* (m^2)

R value: thermal resistivity (m^2K/W)

S: *total south facing solar radiation* (W/m^2)

S_i: *normalised sensitivity coefficient*

$U.A$: *total fabric heat loss* (W/m^2)

T_1: *temperature of intake air* (°C)

$T_{2:}$ *temperature of supply air* (°C)

$T_{3:}$ *temperature of extract air* (°C)

t_e: *external air temperature* (^oC)

t_i: *inside air temperature* (^oC)

t_o: *outside air temperature* (^oC)

ts_i: *inside surface temperature* (^oC)

ts_o: *outside surface temperature* (^oC)

U value: thermal transmittance (W/m^2K)

V: *Internal volume of the dwelling* (m^3)

V_1: *operational infiltration rate* (m^3/s)

V_{50}: *air leakage value from air pressure test* (m^3/s)

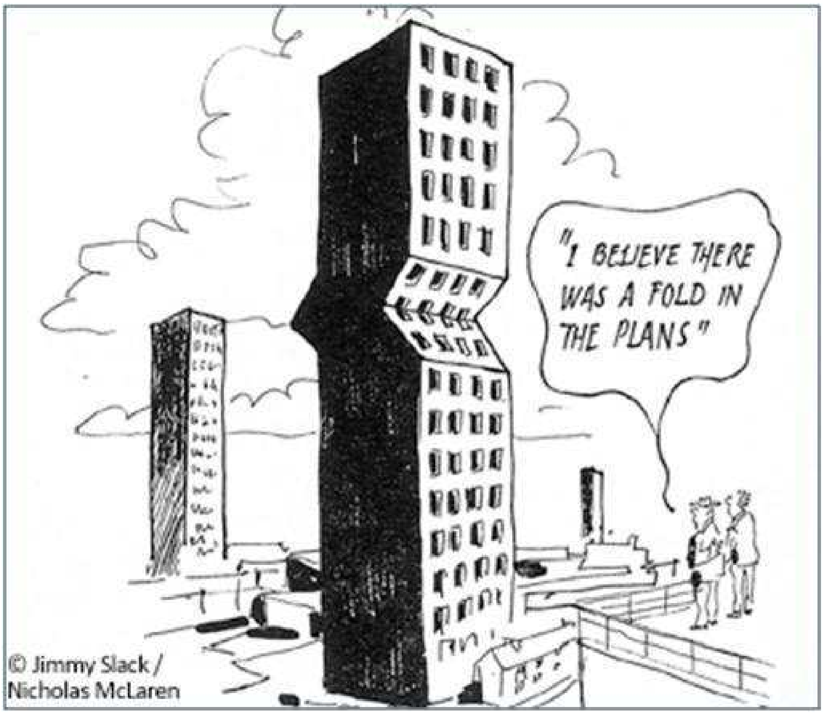
Y: estimation of heat losses through building junctions (thermal bridging)

ΔT: *temperature difference between the inside and the outside of the dwelling* (K)

$\sum$: *sum*

INTRODUCTION

At some points in life, reality does not always correspond with expectations. Often, this merely leads to disappointment and there are no far-reaching consequences. However, in the case of building design and construction, the impact of underperformance in terms of energy efficiency and carbon emissions can have repercussions at an individual building, national and international level.



A Light-Hearted Example of a Divergence Between Design and Construction Expectations
Source Data: (Nathaniel Lichfield & Partners, 2012, web)

Consider the energy demand of the standard UK home. This is not an insignificant amount, at an average single-rate electricity consumption and cost of 4226 kWh and £510 per year per dwelling (Department of Energy and Climate Change (DECC), 2013b; 2013e web data). It is the equivalent of approximately 111,140 million kWh and £13,410 million when multiplied by the estimated 26.3 million occupied homes in the UK today (Utley *et al.*, 2012, p. 6). There can be little doubt that reducing the energy demand and carbon emissions of housing can make a considerable contribution to achieving EU targets of 20% reductions in energy consumption and carbon emissions by 2020 (European Commission, 2013a).

Evidence presented in several studies suggests that a gap currently exists between the design-stage and post construction performance of dwellings (Bordass *et al.*, 2004; Bordass *et al.*, 2001; Demanuele *et al.*, 2010; Technology Strategy Board, 2011; Zero Carbon Hub, 2010, 2013b) . Research shows that measured energy demand and fabric efficiency can exceed predicted values by between 5% and in excess of 100% (Stafford, A. *et al.*, 2012, p. 8), depending on dwelling type and construction materials/methods used. Whilst actual energy consumption data from utility bills can be compared to calculated energy usage generated by modelling software, this may not consider some of the aspects relating to the fundamental function of the physical building.

Occupant behaviour will affect the level of energy used within a home, yet this is directly influenced by factors connected to the way the property reacts to the external environmental and user intervention in systems such as heating and lighting. Space heating is the largest single contributing factor within domestic carbon emissions, accounting for up to 66% of all energy usage in the average UK home (Department of Energy and Climate Change (DECC), 2013a). Therefore, if the level of heating requirement can be reduced then some progress towards Government targets may be made.

Improving the fabric performance of both new-build and existing dwellings, through increased airtightness and thermal enhancements (such as insulation and high quality glazing) can result in lower energy demands. This, in turn, could potentially lead to reduced energy consumption and lower carbon emissions, thus contributing greatly to the achievement of the Government’s targets.

Within design stage housing energy models, such as the UK Government endorsed Standard Assessment Procedure (SAP), the Heat Loss Coefficient (HLC) provides the first indication of the thermal performance of a dwelling. This is a measurement in W/K representing the energy (W) required to heat a building per degree of difference in temperature between the internal and external environment (ΔT in K) (Wingfield, J. , 2011, p. 3). It presents a direct indication of the fabric and thermal effectiveness of a dwelling.

Following the construction of a house, a number of techniques can be used to evaluate physical performance. These include air pressurisation tests, thermal imaging surveys, in-situ measurement of heat flows/u-values associated with individual building elements, and whole house heat losses. The coheating test is most commonly used to investigate the last of these aspects, and the calculation of a post-construction HLC forms the final output of the experiment and subsequent data analysis. This value can be compared to the HLC obtained from the theoretical SAP model, in order to assess the actual fabric performance of a property as compared to design-stage expectations.

The ability of the SAP methodology to provide a true indication of predicted performance has been questioned, due to uncertainty as to the appropriateness of the assumptions and embedded data/calculations within the energy assessment model. The quality of available input data, and the level of skill and understanding of assessors relating to the impact that different selected options may have on final outputs, may also affect the resultant data. (Association for Environmentally Conscious Building (AECB), 2008; MacDonald, 2002; Menezes *et al.*, 2012; Quigley, 2010; Zero Carbon Hub, 2013a).

This issue is compounded by uncertainty regarding the accuracy and reliability of information obtained through use of post-construction testing techniques. Whilst a certain level of mandatory testing is required to meet Building Regulations compliance in the form of a standardised procedure for air pressurisation testing, at present this provides the sole compulsory validation that a property performs to design-stage standards. Even then, assessment by this means is limited to a small sample of dwellings within a larger development. In more comprehensive studies, the coheating test can be used to further evaluate fabric performance, although it is recognised that the data derived from this methodology may be affected by the lack of a fully defined methodology, experimental error and environmental conditions (National House Building Council (NHBC) Foundation, 2013; Wingfield, J. *et al.*, 2011b; Zero Carbon Hub, 2013a).

There is a large body of evidence that suggests that it is more common for the actual performance of housing in different to that calculated at the design stage (AIMC4 Partners in Innovation, 2013; Bell, M. *et al.*, 1998; Blueprint, 2013; Johnston *et al.*, 2004; Menezes et al., 2012; National House Building Council (NHBC), 2011a; Randall *et al.*, 1979; Sonderegger *et al.*, 1980; Stephen, 1998, 2000; Technology Strategy Board, 2011; Technology Strategy Board (TSB), 2013; Warren *et al.*, 1980; Webster, 1987; White *et al.*, 2013; Wingfield, J. *et al.*, 2006; Wingfield, J. *et al.*, 2010; Wingfield, J. *et al.*, 2011a; Wood, C., 2013; Zero Carbon Hub, 2011c, 2011d, 2013a).

However, it should be mentioned at this stage that not all properties underperform, and that it is possible to achieve zero carbon housing in practise. Recent examples include a development of 6 zero-carbon homes in Oldham, 9 homes at the SHINE ZC development in Derby, and 10 properties at Greenwatt Way, Slough (The Guardian, 2013; Zero Carbon Hub, 2011c, 2011d). Unfortunately such developments are not generally the norm, and it requires a great level of commitment and precision from design-stage through the construction process to handover procedures to attain such high standards of performance.

Failure for a home to deliver the expected levels of energy efficiency and carbon emissions could have potential repercussions throughout the whole supply chain. At a Government level, inaccurate predictions of energy demands could lead to underestimation of future national energy needs and failure to meet national legally binding carbon emission reduction targets. Consequently, measures put in place to protect and maintain adequate energy supply levels may not be sufficient to ensure energy security. At an individual dwelling level, higher than expected energy bills could lead to dissatisfaction of occupants and, in extreme cases, inability of the residents to afford to pay increased unexpected charges.

It is therefore critical to fully understand the factors that could potentially contribute to the performance gap, and to isolate the areas that need to be addressed throughout the design and post-construction stages of fabric efficiency evaluation. This will enable the acquisition of a more accurate awareness of housing energy demands and carbon emissions. These issues form a largely underdeveloped area of research, and will provide the focus of this study in order to better equip the housing supply chain to design and deliver high quality new-build homes, and make successful improvements to existing dwellings, to meet the expectations of all parties concerned.

Research Aims and Objectives

Following extensive research into previous work undertaken in this area, as detailed in Chapter 4, three key themes have been identified, relating to the contribution that the housing sector could have in helping to achieve increased energy efficiency and reductions in carbon emissions, namely:

1. Competent design, construction, installation and operation of building fabric and mechanical/electrical systems in new-build housing developments;

2. Effective retro-fit solutions for fabric improvements and systems installation in existing housing stock (both at individual homeowner and wider development (e.g. social housing level); and

3. Requirement for a greater understanding of the key factors contributing to the apparent performance gap between designed and actual performance of building fabric and mechanical/electrical systems installed in new and existing properties.

The overarching aim of this research project is to investigate the potential reasons why a significant difference exists between the designed and actual performance of the UK housing stock, in order to inform industry of the consequences of inaccurate design stage assessments and the underperformance of key construction and systems elements.

In order to ensure that the strategic aim of the project is met, several objectives have been defined to enable the research to be focussed on four key areas. These are:

- To investigate the reasons why a gap exists between designed and actual performance of homes, through evaluation of data derived from design stage models and post-construction testing;
- To assess which elements of the building fabric have the greatest impact on the calculated and measured HLC, as a benchmark for fabric performance;
- To examine the impact of designed ventilation strategy and installed systems within the performance gap; and
- To evaluate the data collected from all of the experimental work undertaken to meet the first three objectives, and use it to assess the individual contribution of various parameters to the level of thermal performance achieved by a dwelling.

Through meeting these key themes and objectives, the research work presented here will contribute to the existing evaluations that have been undertaken in this area, whilst also interrogating the methods used to evaluate design stage and post construction fabric performance.

Research Structure and Key Outcomes

The programme of research involved a detailed literature search in order to gain a full appreciation of the context of the subject of housing energy efficiency and carbon emissions, including the characteristics of the UK housing stock and household energy trends. The legislation supporting EU and Government targets was also assessed. This led to a sound understanding of the factors that could potentially contribute to the documented divergence between design stage and post-construction thermal performance.

Analysis of the approved SAP 2009 methodology provided an insight into the sensitivities and limitations associated with design-stage energy models. Selected dwellings were used to assess the magnitude of divergence that could exist between the two sets of data, with interrogation of the SAP information for each property being undertaken alongside in-situ experimental evaluation of fabric performance. Techniques such as air pressurisation tests, thermal imaging surveys, heat flux monitoring and coheating tests were used to gain information relating to the physical effectiveness of the final constructed dwelling. A specifically designed and instrumented thermal chamber was used to further assess the sensitivities of the coheating test to variations in environmental conditions.

The information gained was finally combined to produce a novel risk ranking technique, that could be used to evaluate the significance of individual design stage and post-construction factors that may contribute to the apparent divergence in calculated and measured data.

In terms of structure of the thesis, following this introductory chapter, the work is presented in the following sections:

Chapter 1: This section describes the context of the study, including the characteristics of the UK housing sector and household energy trends. Furthermore, relevant legislation and Government targets are explained, with justification provided for the focus of this work on building fabric performance.

Chapter 2: Theory relating to building physics and thermal properties is included in this section, with detailed consideration of relevant analytical techniques employed to evaluate design-stage and as-built fabric performance.

Chapter 3: This chapter presents an original synopsis of the research that has been undertaken to date in relation to the magnitude and impact of contributing factors associated with the apparent divergence between predicted and actual housing fabric performance.

Chapter 4: A summary of the primary methods utilised within the experimental and analytical stages of research is included in this section.

Chapters 5 and 6: Two dwellings (the E.On House and Tarmac House) are presented, with an overview of construction type, materials used and design-stage predicted performance levels. A detailed evaluation of design stage drawings and specifications is used to adjust the SAP 2009 model for each dwelling to reflect as-built characteristics. Data obtained from experimental work (coheating tests and other diagnostic techniques) is used to assess post-construction performance, with focus on the effects of ventilation strategy and environmental conditions on the final HLC values.

Chapter 7: Detailed sensitivity analysis is used to further interrogate the sensitivity of the calculated SAP 2009 HLC to changes in a number of parameters, including input data and several embedded assumptions and protocols. Controlled tests undertaken in a thermal chamber are used to obtain a more comprehensive understanding of the variances that may be observed in coheating data as a result of the impact of environmental conditions. The data from all desk-based and experimental work is combined to provide a novel representation of the significance of contributing factors to the recognised performance gap via use of a risk index.

Chapter 8: Conclusions are presented, including recognition of the limitations of the current work and recommendations for further study.

The intention of this work is to enable the reader to gain an understanding of the theoretical principles underpinning all aspects of the research undertaken, before presenting the main experimental sections. Analysis and discussion leads to the generation of a simplified and clear approach to presenting the significant contributing factors that need to be addressed in order to reduce the gap that appears to exist between designed and as-built performance.

The scope includes assessment of inaccuracies in data input and default calculations/data embedded within the SAP methodology, and extends to investigation of site-based factors associated with coheating tests. Whilst there is still potential to extend this analysis further, the work presented here provides a baseline analytical approach that can be applied to other projects in order to increase the volume of information available to drive future research.

Whilst it is acknowledged that work has previously been undertaken by other parties to provide evidence to support the existence of a gap between the designed and actual performance of UK homes, there has been little or no work that focuses on the evaluation of the significance of the potential factors that may impact upon the observed divergence in HLC values. The primary contributions to knowledge arising from this work include:

- Employment of the coheating test to investigate both passively ventilated and mechanically ventilated dwellings, including consideration of the impact of ventilation on the derived HLC and comparison to predicted data;

- Evaluation of key factors that can influence measured and predicted building performance and outputs from modelled and measured data, concluding that wind speed can have a major effect on the magnitude of the performance gap;

- Assessment of the in-situ efficiency of mechanically ventilated heat recovery (MVHR) systems, leading to the testing of product improvement proposed by the manufacturer and subsequently incorporated into the mainstream system design;

- Determination of the point where MVHR becomes an effective means of ventilation as compared to natural ventilation; and

- Evidence to suggest that thermal bridging levels are an area where poor attention to detail can have a large effect on both predicted and measured thermal performance.

It is envisaged that the knowledge gained as a result of this research will be useful in informing the construction industry and home-owners of the main contributing factors to underperformance of new and existing housing stock. There is potential for certain aspects of the findings to be applied in practise, through helping to guide policy and common standards, in order to meet wider Government targets and enable delivery of more energy and carbon efficient homes.

Indeed, work by the author relating to the E.On 2016 Research House was presented at Government level in 2011, as part of the E.On/EPSRC funded Project CALEBRE (Loughborough University, 2014). The research findings formed part of a consultation response relating to the Green Deal mechanism and the potential for such a scheme to contribute towards energy efficiency in dwellings. This policy has now been adopted and is central to current energy legislation and regulations, which clearly demonstrates the relevance of the project and the high level of demand for information relating to this area of building energy performance.

1 ENERGY AND HOUSING

Energy is central to the lifestyles of the modern western world, providing comfortable living and working environments, means of transport, technological solutions and industrial infrastructure. For most individuals and businesses, life with no electricity is almost inconceivable, meaning that economic stability is reliant on a constant and sufficient power supply.

Traditionally, the main fuels used in power stations and mass energy generation have been derived from non-renewable sources such as coal and other fossil fuels. It was not until the 1980's that the impact of pollution and potential lack of available fuel became an area of topical debate, as climate change and sustainability came to the forefront of the political agenda (World Commission on Environment and Development (WCED), 1987). In more recent years, increasing consideration has been given to both reducing energy demand and finding less polluting and more efficient means of providing power through renewable sources (Department of Energy & Climate Change (DECC), 2013). As populations continue to grow, and energy use intensifies, the concern that one day there will not be enough energy to meet worldwide demands is intensifying, as evidenced by responses to a House of Commons consultation on future energy security (Energy & Climate Change Committee, 2011).

Figure 1-1 (European Commission, 2013b, p. 13 & 17) shows that, at a global level, the EU, China and the United States are the three highest users of energy and generators of carbon dioxide (CO_2) emissions. Together, they accounted for approximately 50% of the total 8,918 mtoe (million tonnes of oil equivalent) of energy consumed and 31,342 $mtCO_2$ produced by the world in 2011. Of this total energy consumption, almost 18% (1,578 mtoe) was provided by electrical means (International Energy Agency, 2013, p. 30 & 45).

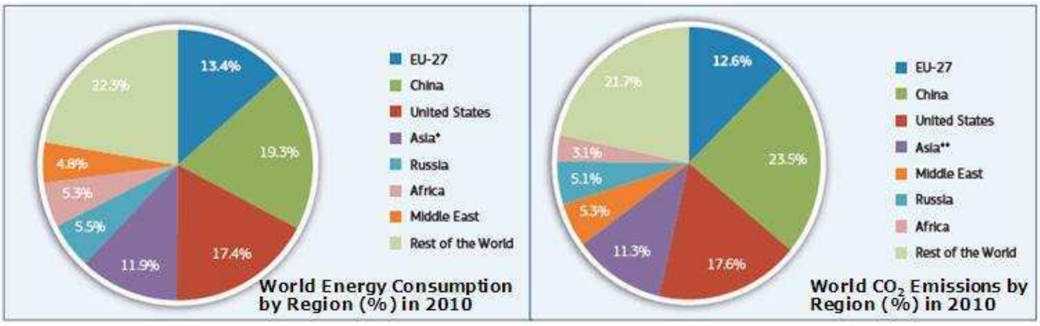


Figure 1-1 - World Gross Inland Energy Consumption and CO_2 Emissions (% contribution in 2010)

Source Data: (European Commission, 2013b, p. 13 & 17)

The European Economic Community was formed in 1957, through a treaty agreed between Germany, France, Italy, the Netherlands, Belgium and Luxembourg. The vision was for people to move, and goods and services to be transferred, across country borders more easily. The UK joined the group on 1st January 1973, along with Ireland and Denmark (Wallace, 2012). The agreement between these nine countries has evolved into an economic and political partnership formed between 28 Member States, which has been known as the European Union since 1993 (EU Observer, 2013).

Figure 1-2 shows the profile of electricity consumption across the EU Member States. Unsurprisingly, the highest consumers are those in colder climates, where space heating is required for a longer period. When compared to other major world energy users, the EU per capita consumption is much higher than the world average, with only the US and Russia exceeding EU levels. The UK position is in line with other countries that have similar heating and cooling needs, and has an average overall electricity consumption within the context of the EU, as observed in Figure 1-2. However, several Member States, such as Norway and Finland provide a large proportion of their energy requirements through renewable sources whilst, at the present time, this is not the case in the UK.

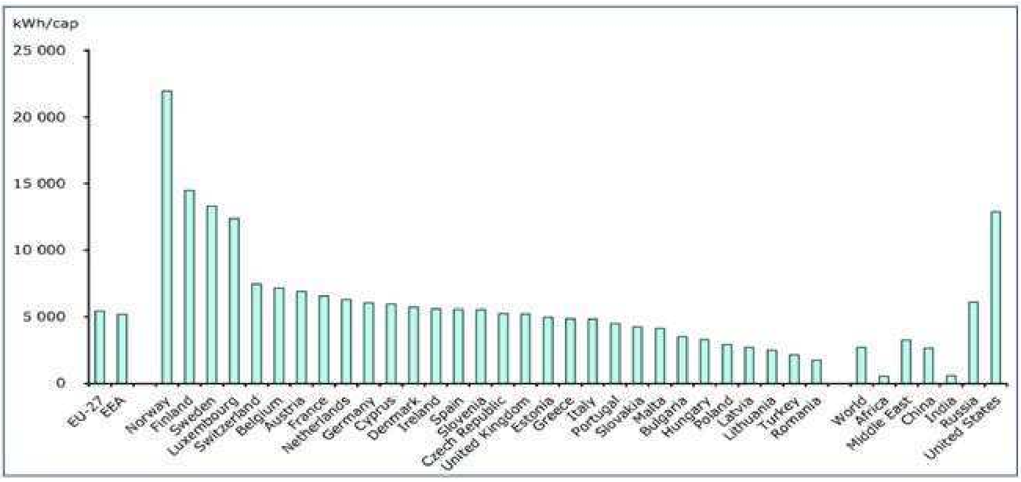


Figure 1-2 – EU Member State Electricity Consumption 2009 (kWh/capita)
Source Data: (European Environment Agency, 2012)(Web)

In recent figures from 2010, total energy consumption from housing across the EU Member States amounted to 842,663 gWh of a total 2,836,637 gWh (Bertoldi *et al.*, 2012, p. 18 & 19). When considering electricity consumption alone, this amounted to almost 177 mtoe across all sectors, with 50% being attributed to domestic use (European Environment Agency, 2013a). With regard to greenhouse gas emissions, in 2011, CO_2 accounted for 82% of a total of 4550 mt, with the domestic sector being responsible for approximately 14% of all emissions (European Environment Agency, 2013b), as shown in Figure 1.3 (European Environment Agency, 2013a, 2013b).

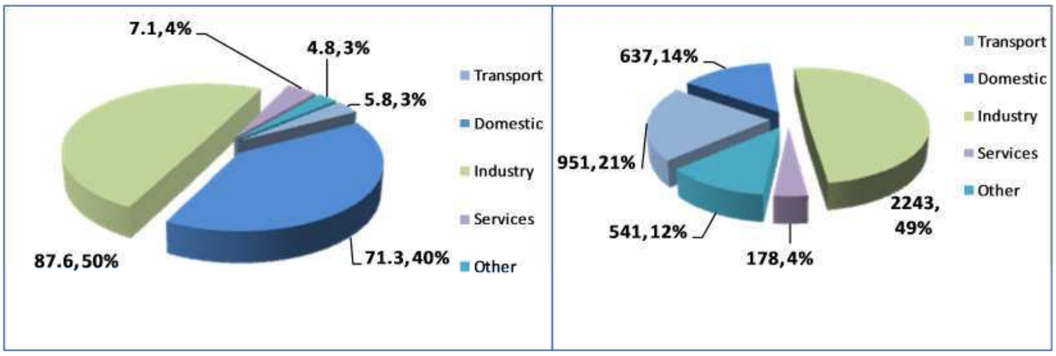


Figure 1-3 - EU Final Electricity Consumption and Emissions by Sector (2011, mtoe, mt, %)
Compiled From Source Data: (European Environment Agency, 2013a, 2013b)

Evidence shows that, in 2010, energy efficiency in housing across all Member States had improved by 15% as compared to data from the year 2000 (Odyssee Mure, 2012, p. 1). The main factors contributing to the average annual 1.6% reduction in household energy demand include the improvement of building fabric, and the use of highly efficient boilers and A+/A++/A+++ rated electrical goods (Odyssee Mure, 2012, p. 2).

The domestic sector is considered to be an area where further considerable reductions in energy demand and greenhouse gas emissions can be made, in order to achieve overall targets set by the EU at international level. The remainder of this chapter aims to outline the relevant application of legislation at an EU and UK level, whilst placing this in the context of achieving more energy efficient housing stock.

1.1 The UK Housing Sector

The UK total primary energy consumption amounted to 206.3 mtoe in 2012 (Department of Energy and Climate Change (DECC), 2013a, p. 1). Building stock accounts for approximately 40% of total usage (MacKenzie *et al.*, 2010, p. 1), and approximately 30% (74.3 mtoe) (Utley *et al.*, 2008, p. 3) emanates from the domestic sector. UK greenhouse gas emissions are in the region of 571.6 mt CO_2 equivalent, with carbon dioxide accounting for 82% (479.1 mt) of this total (Department of Energy and Climate Change (DECC), 2013d, p. 4). The contribution across sectors is illustrated in Figure 1-4.

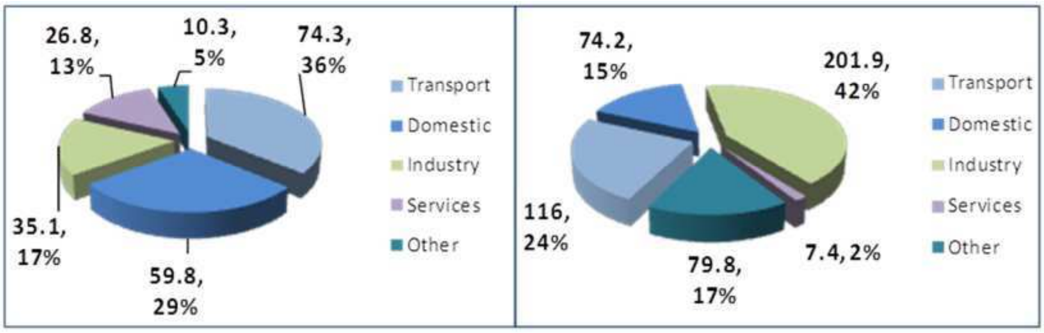


Figure 1-4 - Total UK Energy Consumption and CO2 Emissions by Sector (2012, mtoe, mt, %)
Compiled From Source Data: (Department of Energy and Climate Change (DECC), 2013a, 2013d)

It can be seen that the domestic sector is responsible for a large proportion of both energy consumption and greenhouse gas/carbon emissions at an international level, which is also seen in the UK context. With UK Government targets to reduce carbon emission levels to 80% below 1990 levels by 2050 still in place (Department of Energy and Climate Change (DECC), 2008, p. 1), there is a renewed drive to lower energy use in buildings.

The UK housing stock totalled almost 28 million dwellings in 2012 across a range of different tenures, including vacant dwellings, as derived from source data and shown in Figure 1-5 (various sources). Private sector ownership and rentals form the majority of housing tenure type (90%), with public sector ownership accounting for the remaining 10%.

	Private Sector						Public Sector				TOTAL
	Owner Occupied		Rented Privately or With a Job/Business		Vacant Private Dwellings and Second Homes		From Housing Associations		From Local Authorities		
	Number ('000)	%	Number ('000)	%	Number ('000)	%	Number ('000)	%	Number ('000)	%	
England	18,990	80%	2,359	10%	inc	inc	73	3%	1,689	7%	23,111,000
Wales	975	70%	191	14%	inc	inc	135	10%	88	6%	1,389,000
Scotland	1,507	60%	305	12%	99	395%	277	11%	319	13%	2,508,000
Northern Ireland	488	64%	115	15%	39	510%	29	4%	88	12%	759,000
TOTAL UK	21,960	79.1%	2,970	10.7%	138	0.5%	515	1.9%	2,185	7.9%	27,767,000

Figure 1-5 - Housing Tenure Profile in the UK in 2012
Compiled From Source Data: (Department for Communities and Local Government (DCLG), 2013a; Northern Ireland Statistics and Research Agency, 2013; The Scottish Government Housing and Regeneration Department, 2013; Welsh Assembly Government, 2013)

Several studies suggest that tenure can have a large impact on the attitude and ability of households to implement energy saving measures and upgrades to promote energy efficiency (Brechling *et al.*, 1992; Wood, G. *et al.*, 2012). Indeed, home improvements (such as insulation and replacement of windows) are more likely to be implemented by owner-occupiers than landlords or private/public tenants. This is partly due to the limited ability of tenants to directly implement changes to a building, but is mainly due to cost concerns – either the inability of a person to finance work/materials, or the unwillingness of a landlord to expend funds on a project that will not directly benefit themselves (Dowson *et al.*, 2012).

It is also important to consider changes in domestic energy demand trends. As illustrated in Figure 1-6 (Department of Energy and Climate Change (DECC), 2013b, p. 3), in 2012, space heating demands accounted for 66% of household energy consumption (Department of Energy and Climate Change (DECC), 2013b, p. 3). This proportion has slowly increased over time, with unusually cold winters such as that experienced in 2010 leading to a peak in space heating energy use. In 2012, water heating accounted for 17%, appliances/lighting for 15% and cooking for the remaining 3% of energy used (Department of Energy and Climate Change (DECC), 2013b, p. 3).

Figure 1-6 - Profile of Energy Use in UK Homes: 1970 – 2012
Source Data: (Department of Energy and Climate Change (DECC), 2013b, p. 3)

Yohanis (2008) undertook a study of energy usage in 27 houses in Northern Ireland, and found that the evening demand level of a larger higher income home can be double that of a smaller less affluent family unit. This is largely attributed to use of televisions, computers and other 'gadgets', alongside a general trend towards later evening meals. Firth (2007) presented research relating to 72 dwellings over a two year period, which demonstrates an increase in energy usage of 4.5% between data from Year 1 and Year 2. It was identified that the overall increase in consumption was due in part to greater use of televisions and electronic equipment, with a significantly less proportion assigned to lighting, kitchen appliances and use of showers. This supports the situation apparent within the data shown in Figure 1-6.

Figure 1-7 shows energy demands as measured against baseline 1970 levels through use of a comparative energy intensity index (energy consumption per unit of output) (Department of Energy and Climate Change (DECC), 2012a, p. 37).

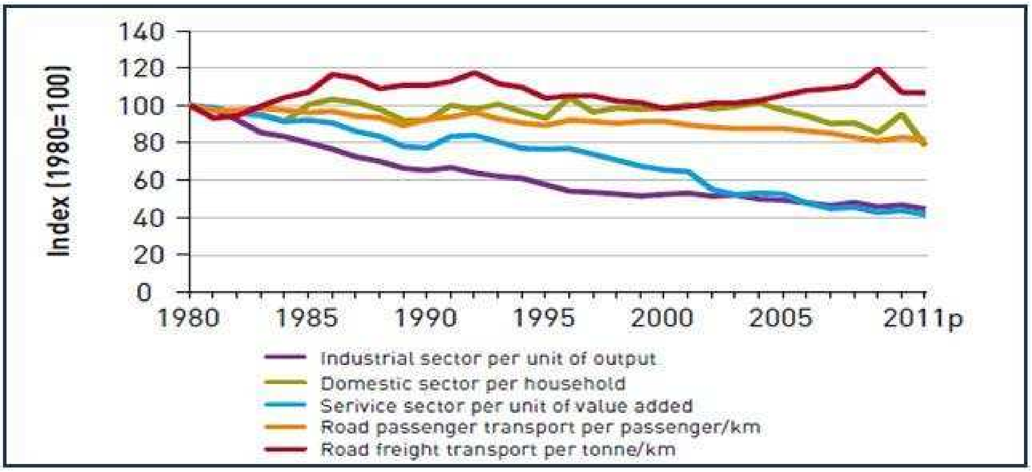


Figure 1-7 - Energy Intensity of UK Sectors
Source Data: (Department of Energy and Climate Change (DECC), 2012a, p. 37)

It can be seen that progress has been made in many sectors (for example industry and transport) in order to reduce the overall energy demand. Yet, conversely, energy use in the domestic sector has appeared to increase by 11% since 1990 (Department of Energy and Climate Change (DECC), 2010b, p. 2). It is evident that progress has been inconsistent, and reasons for this could be due to the cyclical nature of the construction industry, a sector specific response to poor economic conditions, year to year climate variations, and lack of coherent targets or poor implementation of policy in practise (Lowe *et al.*, 2008; Pérez-Lombard *et al.*, 2008).

The UK Government has set the target that all new-build homes should have zero net carbon emissions by 2016, with all non-domestic buildings expected to achieve the same zero carbon standard by 2019 (Department for Communities and Local Government (DCLG), 2011d). It is only recently that a full understanding and common definition of zero carbon has been developed, and the current framework is shown in Figure 1-8 (Zero Carbon Hub, 2013e, p. 4).

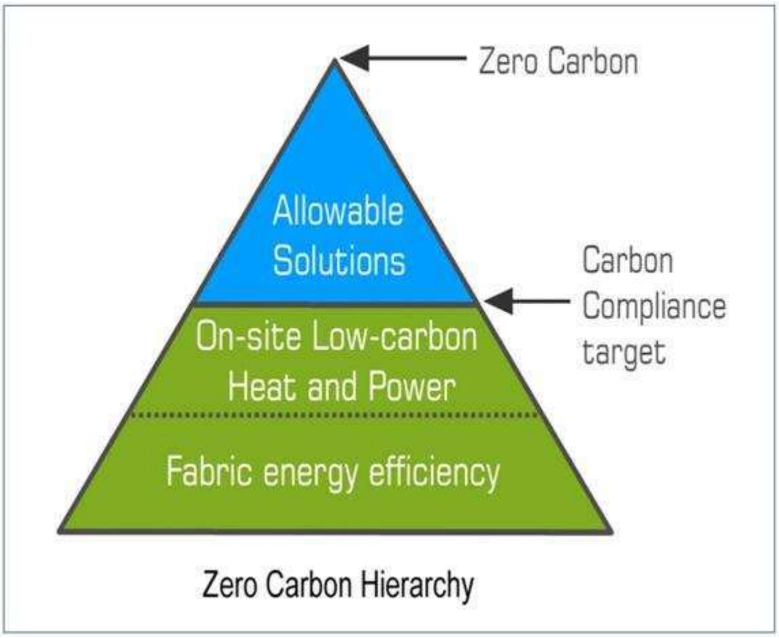


Figure 1-8 - Zero Carbon Hierarchy
Source Data: (Zero Carbon Hub, 2013e, p. 4)

The first step is to meet a minimum standard of fabric energy efficiency, either through design and compliance in new buildings, or improvement measures such as insulation and double glazing in existing homes. A mandatory Fabric Energy Efficiency Standard is being introduced with Building Regulations updates in early 2014 (Department for Communities and Local Government (DCLG), 2012a). The second level relates to on-site micro-energy generation to meet a Carbon Compliance target. However, there is concern that up to 80% of homes in the UK will not be able to achieve zero carbon status by this means (McLeod, R. *et al.*, 2012, p. 26). The final tier relates to residual emissions and involves carbon off-setting through investment in carbon-neutral and community projects, although this is only necessary where zero-carbon cannot be achieved through the first two levels of the hierarchy (Zero Carbon Hub, 2012a).

Through this process, it is expected that a building will achieve net zero carbon emissions over a whole year, with reference to space and water heating, ventilation, lighting and appliances (Laustsen, 2008). It has been argued that the scope of zero-carbon, as defined in Figure 1-8, is not fully comprehensive and does not account for embodied energy in construction materials or the carbon load associated with the transport of goods, labour and services (Hillyard, 2009). There are also concerns that, in reality, the allowable solutions aspect of the hierarchy may be prioritised over building fabric, leading to a situation where emissions from a dwelling could actually increase and yet still manage to meet overall reduced emissions targets through off-setting (McLeod, R. et al., 2012). The three tier hierarchy has been developed by the UK Government through consultation, but there is concern that it is still not fully defined and this could delay implementation in 2014 (Heffernan *et al.*, 2013).

Whilst a zero-carbon approach may be suitable for new build dwellings, it should be emphasised that, as demonstrated in Figure 1-9, only 13% of the English housing stock has been constructed since the introduction of more stringent building regulations implemented in the last two decades (Department for Communities and Local Government (DCLG), 2013b, p. 53).

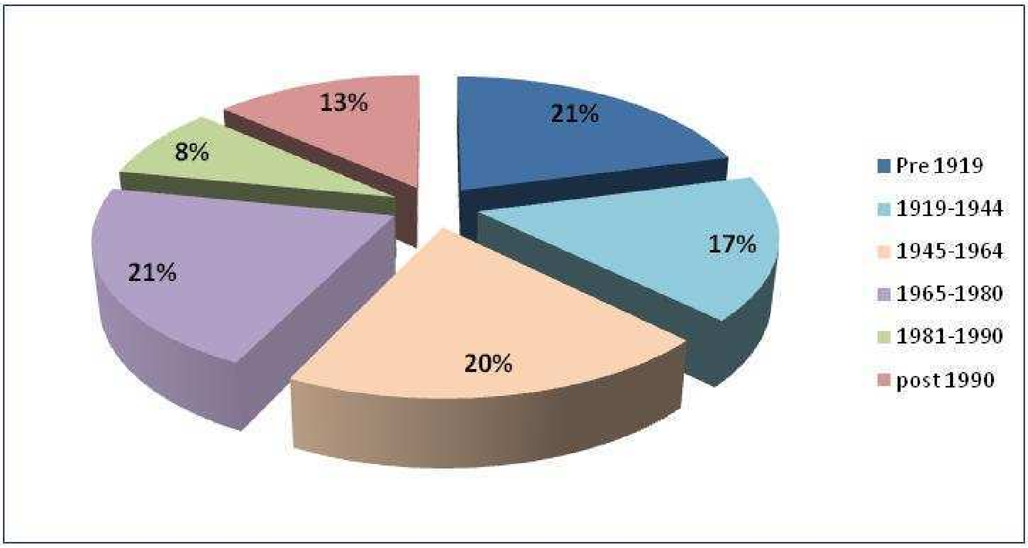


Figure 1-9 - Age Profile of English Housing Stock 2010
Compiled From Data: (Department for Communities and Local Government (DCLG), 2013b, p. 53)

With one house being demolished for every new home constructed (Kelly, M., 2010, p. 1084), and current target new-build construction rates forecast to provide only an additional 9 million homes over the next 15-20 years, it is estimated that approximately 70% of the total building stock that will exist in 2050 already exists today (Power, A., 2010, p. 206). There is evidence that the emissions level associated with new housing almost equates to the savings realised by the current rate of improvement of existing buildings (Royal Institute of British Architects (RIBA), 2009, p. 4). Therefore, whilst zero carbon can be imposed as the standard quality for new build construction, the issue of improving energy efficiency in existing housing is of equal or greater concern and cannot be underestimated in terms of importance (Royal Institute of British Architects (RIBA), 2009).

The complexity of the problem of retro-fitting energy saving measures in the extensive and diverse aging housing stock is further compounded due to the number of 'hard to treat' properties that exist and comprise 43% of homes in the UK (Building Research Establishment (BRE), 2008, p. 1). This includes solid walled, flat roofed, timber framed and high rise buildings, as well as tenements, park homes and those with limited services connections or no loft space (Roaf *et al.*, 2008). In such properties, it can be difficult to improve building fabric performance through standard measures such as cavity wall or loft insulation due to the building structure.

In addition, listed buildings and those in conservation areas can also be difficult to alter to improve thermal properties due to planning restrictions. The UK Government has recognised that the issue of hard to treat homes is a sub-sector that needs to be specifically addressed, through recent changes in policy and financial support schemes as explained in detail in Section 1.2.3. However, there is already concern that without more pro-active communication and enhanced incentives, many of the properties in this category will still not be thermally efficient in 2050 (Dowson et al., 2012).

It is evident that actually achieving a substantial reduction in energy use and carbon emissions in the UK housing sector is a complex and challenging issue. As acknowledged by Pearson (2012), it is extremely difficult to predict the future of energy supply, demand and pricing levels, and the speed of transfer from production of coal powered generation to alternative and more renewable sources. This leads to uncertainty in the future situation for the UK in terms of energy security, which can only be managed through legislation, policy and collaboration between all sector stakeholders (Winzer, 2012).

1.2 The Legislative Context

Energy is fundamental and central to modern industry, transport systems and personal lifestyles, including use in the home. It is not surprising, therefore, to find that the sector is governed by a complex legal framework, covering aspects such as supply, demand, efficiency and carbon emissions. Such laws exist at international (European Union) and national level, supported by industry led best practise standards, as shown in Figure 1-10.

Figure 1-10- Hierarchy of Regulation Framework (Produced by Author)

As emphasised by work undertaken by Sovacool (2009), a comprehensive approach to the implementation of statute and policy at all levels is necessary to ensure that the objectives of strategic aims are achieved. This requires communication between Member State Governments at international level, alongside integrated plans and schemes generated by Governmental Departments and individual Ministries at national level. More locally, a holistic approach is required by Local Governments to deliver consistent policies at regional level. It is also necessary to engage with and work with industry specialists in order to ensure that legislative requirements are realistic and achievable through implementation of standardised methods and a coherent approach (Watson *et al.*, 2012).

There is considerable legislation at all levels governing the area of energy generation (including renewable sources), energy efficiency and carbon emission levels. The remainder of this chapter does not aim to provide an exhaustive review of the many Acts, Regulations and instruments that are used to manage the energy production and consumption in the EU and the UK. Rather, it seeks to provide a political context for the remainder of the research, by providing an overview of those most relevant to this work.

1.2.1 EU Legislation

The Climate and Energy Package (European Commission, 2013a) provides an overarching umbrella for the energy policies developed by the European Union Member States to work together in a cohesive way. This helps to channel resources and communications in order to achieve the fundamental ’20-20-20’ overall objectives by the year 2020, which are to:

- Reduce total EU greenhouse gas emissions by 20% against 1990 levels;
- Raise the share of EU energy consumption produced from renewable resources to 20%; and
- Improve the energy efficiency of the EU by 20% (European Commission, 2009).

The primary pieces of EU legislation relating directly to energy use and energy performance of buildings are summarised in Table 1-1.

Whilst it is anticipated that the EU as a whole will meet the target of a 20% reduction in emissions by 2020, there is concern that up to half of the 28 Member States will not achieve their individual obligations (Keeting, 2012). The revised Energy Efficiency Directive 2012 has helped to refocus the attention of Member States on the real concerns surrounding this area.

The key elements of the new Directive will be for there to be a legal obligation to implement energy saving schemes, for public bodies to take the lead in procurement and use of energy efficient products and services, for energy efficiency to be taken into account by regulators when setting fuel tariffs, and for incentives to be introduced relating to energy audits for small medium enterprises (SMEs) (European Commission, 2011). This recent reassessment of EU strategy demonstrates the scale of the challenge that energy efficiency and reduction of carbon emissions presents at a national, European and global level.

Table 1-1 - Key EU Legislation

(Compiled from Source Data: (ARUP, 2010; Leach *et al.*, 2012; Makuch *et al.*, 2012; Pereira *et al.*, 2012))

EU Directive	Key Dates	Overall Aim	Secondary Objectives	Impact on UK Legislation/Regulation
Directive on Energy Performance in Buildings (EPBD) (European Union (EU), 2003, 2010)	Introduced 2003, Enacted 2007, Recast 2010	To tackle climate change through reduction of carbon emissions from buildings	Common methodology for energy performance calculations and energy certification; minimum standards for energy performance of new/existing buildings	Standard Assessment Procedure Calculation Methodology (SAP) Display of Energy Performance Certificate (EPC) or Display Energy Certificate (DEC) Building Regulations Part L amendments
European Commission Directive on Renewable Energy (European Union (EU), 2009)	Introduced 2009, Enacted 2010	To set renewable energy targets for all member states to achieve by 2020	National Action Plans to be submitted by each State demonstrating strategy to achieve targets	UK target of 15% energy from renewable sources by 2020 via Renewable Energy Strategy and 2010 National Action Plan
Energy Efficiency Directive (EED) (European Union (EU), 2012)	Introduced 2012 Adoption by June 2014	To put in place the means to achieve 15% energy savings by 2010, with targets set by each Member State	Long term strategy for all building renovations 3% of Central Government buildings to be renovated each year to 2020 Energy supplier efficiency obligations schemes to save 1.5% on end user sales cumulatively year on year to 2020 Establishment of finance mechanisms for efficiency improvement measures	Green Deal, Renewable Heat Incentive, Feed in Tariffs, Smart Meters Energy Savings Opportunities Scheme (ESOS) for businesses Other strategies are likely to be developed

Indeed, due to the good progress towards meeting the 2020 emission reductions target, discussion has been held between EU Member States to evaluate the possibility of achieving a 30% reduction level (European Commission, 2012). Consultation on the related EU Green Paper entitled ‘A 2030 Framework for Climate and Energy Policies’ (European Commission, 2013c), closed in July 2013, and a formal announcement and proposals relating to a draft 2030 framework are expected in early 2014.

1.2.2 UK Legislation

The EU Directives outlined in the previous section are implemented in the UK through several key pieces of legislation. The two most relevant to this research are the Climate Change Act 2008 and the Energy Act 2011.

The Climate Change Act 2008 (Department of Energy and Climate Change (DECC), 2008) is a fundamental piece of energy related legislation, as it is this Act that documents the ways in which the UK intends to meet its obligations relating to the EU 20-20-20 target. Moreover, it also states the ambitious target that the UK will reduce greenhouse gas emissions by 80% by 2050 and carbon emissions by at least 20% by 2020 against a 1990 base level (Department of Energy and Climate Change (DECC), 2008, p. 1).

The UK Energy Act 2011 (Department of Energy and Climate Change (DECC), 2011a) received Royal Assent in October 2011, providing a framework to enable households and businesses to access increased opportunities in terms of achieving energy efficiency and utilising renewable technologies. The 'Green Deal' forms an integral part of the Act, which is essentially a mechanism by which private companies and energy providers provide the capital cost of approved energy efficiency improvements, and those benefitting from the savings from the system repay the 'loan' through instalments added to their energy payments (Department of Energy and Climate Change (DECC), 2010a). The Green Deal will work alongside the Renewable Heat Incentive (RHI) framework, which offers subsidies to support the domestic sector in integrating approved renewable energy sources into existing properties (Department Of Energy And Climate Change (DECC), 2011e).

The Energy Act provides new direction in terms of achieving UK and EU energy efficiency targets, with added focus on the improvement of both new and existing homes. This is of great importance, as only 1% of total UK housing stock comprises of new build developments, and up to two-thirds of existing houses will still be occupied in 2050 (Department of Energy and Climate Change (DECC), 2009, p. 10). It can therefore be seen that improving the energy performance of new and existing housing stock is required in order to realise overall energy and carbon targets.

1.2.3 Supplementary Schemes and Instruments

In order to ensure progress is made towards EU and UK legislative requirements and obligations, a number of orders, regulations, strategies and standards have been developed to support the primary legislation.

Several such initiatives relate directly to energy production and the supply chain. The Energy Companies Obligation (ECO) was introduced in January 2013, and replaced the Carbon Emissions Reduction Target (CERT) and Community Energy Saving Programme (CESP) (OFGEM, 2013). Energy companies are required to commit to the Carbon Emissions Reduction Obligation (CERO), Carbon Saving Community Obligation (CSSO) and Home Heating Cost Reduction Obligation (HHCRO). These schemes place a requirement on energy companies to provide insulation measures and district heating systems to hard to treat homes and low income households, and methods for low income and vulnerable households to heat their homes efficiently (e.g. boiler repairs or replacements) (Department of Energy and Climate Change (DECC), 2011b).

The Green Deal, which was also implemented in January 2013, is a complementary scheme that works in conjunction with ECO in order to improve the performance of domestic housing. The basic intention of the scheme is to enable homeowners to fund improvements (such as insulation, heating and hot water systems, glazing and micro generation systems) within their dwelling using the savings realised on their energy bills. It involves energy suppliers, Green Deal assessors, approved installers and specialised finance bodies working together in order to ensure that the balance is achieved between initial payment for improvements and pay back over time (Energy Saving Trust (EST), 2013).

The Green Deal and ECO essentially work towards the same goal – to improve the energy efficiency of homes through fabric and systems improvements. The difference is in their target recipient – ECO focuses on hard to treat homes and low income households, whilst the Green Deal primarily concentrates on households that can afford to fund all or part of the required improvement work.

In order to promote and support the installation of local level renewable energy schemes, the Feed In Tariff Scheme (FITS) was introduced in 2010 and works in conjunction with the 2011 Renewable Heat Incentive (RHI). The FITS concentrates on renewable electrical production up to 5 MW, through eligible sources such as photovoltaics, small scale combined heat and power systems, bio gas and small scale hydro and wind installations (Feed In Tariffs Ltd, 2013). The RHI relates to heating systems utilising biomass, geothermal, ground source heat pumps, water source heat pumps and solar thermal fuel sources (Renewable Heat Incentive Ltd, 2013). Both schemes provide mechanisms by which the UK aims to achieve 15% of total energy generated by renewable sources by 2020 (Department of Energy and Climate Change (DECC), 2012b, p. 4).

1.2.4 Building Regulations and Best Practise

Prior to the Great Fire of London that occurred in 1666, very little consideration was given to the planning and design of buildings and developments. The extent of destruction resulting from the fire that spread quickly through the timber buildings clearly demonstrated the danger associated with fire in closely positioned properties. The London Building Act 1667 provided the first guidance on minimum standards of fire resistance in buildings, and was utilised during the rebuilding programme (Ley, 2000).

Since that era, the regulation of building standards has become increasingly important, as guided by the political and industry focus at various points in time. The first formal mandatory regulations were introduced via the 1966 Building Control Act (UK Parliament, 1966), and were mainly concerned with ventilation and protection against damp. The Building Regulations have increased in scope and have been revised on a number of occasions, and compliance monitoring has become more rigorous.

With growing concern regarding energy conservation and efficient use of resources, and well documented EU and national targets relating to reduction of energy demand and carbon emissions, the performance requirements in terms of building fabric and thermal efficiency have incrementally increased.

The most relevant section of the Building Regulations to this course of study is Part L, as this relates directly to the conservation of fuel and power in properties (residential and non-residential), with specific details given on standards and evaluation of new and existing homes (Department for Communities and Local Government (DCLG), 2010b, 2010c). Part L forms a key policy driver for delivering Government carbon and energy targets, with further more stringent amendments being proposed for implementation in 2016.

Table 1-2 (Department for Communities and Local Government (DCLG), 2006a, p. 19; 2010b, p. 15; Energy Saving Trust (EST), 2004, p. 3) demonstrates the limiting fabric parameters required to meet historic Building Regulations Part L standards, demonstrating the trend towards more demanding fabric performance targets. A u-value is a measure of the heat loss properties of a material, and can be used to describe the thermal performance of building elements (Ibstock, 2011).

The next amendments to Part L of the Building Regulations are expected to be released in April 2014. A major change to the Regulations will be the introduction of a Fabric Energy Efficiency Standard (FEES). This will set a capped limit on acceptable energy demand for maintaining comfortable living temperatures throughout a home (commonly 39 – 46 kWh/m^2/annum) (Zero Carbon Hub, 2012b, p. 1). In addition, new homes will be required to achieve Code for Sustainable Homes (CfSH) Level 4 in order to meet 2014 Building

Regulations minimum standards (Osmani *et al.*, 2009), increasing again to CfSH Level 6 in 2016.

Table 1-2 - Building Regulations - Thermal Standards
Sources: (Department for Communities and Local Government (DCLG), 2006a, p. 19; 2010b, p. 15; Energy Saving Trust (EST), 2004, p. 3)

Year	**U-values (W/m^{2}K)**				**Air Permeability**	**Glazing**	
	Wall	**Roof**	**Floor**	**Windows**		**Area**	**Draught Stripping**
1965	1.70	1.42	n/a	5.7	n/a	12% Wall Area	n/a
1974	1.00	0.60	n/a	5.7	n/a	12% Wall Area	n/a
1981	0.60	0.35	n/a	5.7	n/a	12% Wall Area	n/a
1990	0.45	0.25	0.45	5.7	n/a	15% Floor Area	n/a
1995	0.45	0.25	0.45	3.3	n/a	22.5% Floor Area (inc. doors)	Required
2002	0.35	0.25	0.25	2.2	12 m^3/m^2/h	25% Floor Area (inc. doors)	Required
2006	0.35	0.25	0.25	2.2	10 m^3/m^2/h	25% Floor Area (inc. doors)	Required
2010	0.30	0.25	0.20	2.0	10 m^3/m^2/h	25% Floor Area (inc. doors)	Required

Part F of the Building Regulations relates to ventilation in buildings. As the airtightness of building envelopes is increased in order to achieve compliance with Part L, ventilation strategy becomes a primary concern in maintaining a sufficient supply of fresh air and removal of stale air. The lack of background infiltration can cause moisture build up and elevated relative humidity levels.

This can result in stale air accumulating, and poor indoor air quality, affecting the health of the occupants (World Health Organisation, 2010).

The current version of Part F (dated 2010 and now with 2013 amendments) (Department for Communities and Local Government (DCLG), 2010a), focuses on four main ventilation strategies: intermittent fans with background ventilation, passive stack ventilation, mechanical extract ventilation (MEV), and mechanically ventilated heat recovery system (MVHR). For mechanical systems, minimum efficiency levels and system element performance requirements (such as specific fan power) are specified (Vent-Axia, 2010), and contained within the Domestic Building Services Compliance Guide (Department for Communities and Local Government (DCLG), 2011b).

One of the key elements of the 2010 Part F amendments was the introduction of the Domestic Ventilation Compliance Guide. Prior to this date, there had been little requirement for those involved in the design and installation of ventilation systems to evaluate the performance of the system once set-up (Dorer *et al.*, 1998; Zero Carbon Hub & NHBC Foundation, 2013) The Guide provides detailed coverage of procedures for testing and commissioning the various elements required for the four main ventilation strategies previously identified (Department for Communities and Local Government (DCLG), 2011c).

1.2.5 Code for Sustainable Homes and Standard Assessment Procedure

The Code for Sustainable Homes (CfSH) was introduced into the UK in Spring 2007 (Department for Communities and Local Government (DCLG), 2006b), replacing the EcoHomes scheme, and it became mandatory for new homes to be given a Code rating from May 2008 (Department for Communities and Local Government (DCLG), 2008). The CfSH was developed by the Building Research Establishment (BRE) in order to provide a standardised benchmark for understanding the predicted design performance of a property, based on six compliance levels. These range from 1 to 6, with Code Level 3 being the equivalent of 2013 UK Building Regulations and Level 6 being zero-carbon.

The Level of the Code applicable to a property is based on the overall sustainability performance assessed against nine key design categories, namely energy and carbon dioxide (CO_2) emissions, water, materials, surface water runoff, waste, pollution, health and well-being, management, and ecology, as shown in Table 1-3 (Department for Communities and Local Government (DCLG), 2010d, pp. 13-15).

Whilst all of the issues included in the CfSH are of high importance, clearly the theme of energy and carbon dioxide emissions is the most relevant to this research project. This also accounts for over one third of the available credits within the CfSH evaluation criteria. The Technical Guide to the Code for Sustainable Homes (Department for Communities and Local Government (DCLG), 2010d) identifies several key compliance criteria within this category:

- Dwelling Emission Rate (DER): the estimated CO_2 emission rate ($KgCO_2/m^2$/year) for the dwelling as designed, accounting for heating, fixed cooling, hot water and lighting (m^2 refers to total useful floor area)

- Target Emission Rate (TER): the calculated target CO_2 emission rate in $kgCO_2/m^2$/annum (m^2 refers to total useful floor area)

- Net CO_2 Emissions: the dwelling CO_2 emissions in $kgCO_2/m^2$/annum from space heating and cooling, water heating, ventilation, lighting, cooking and other appliances (m^2 refers to total useful floor area)

- Fabric Energy Efficiency: the energy demand for space heating and cooling (kWh/m^2/annum) (m^2 refers to total useful floor area)

The existing mandatory TER level set by the 2010 Building Regulations seeks to ensure that all new homes are designed to achieve CfSH Level 3 standards. The DER of each dwelling as designed must meet or outperform the notional calculated TER level of CO_2 emissions and obtain a minimum overall points score (from all categories and criteria), as specified in Table 1-4 (Department for Communities and Local Government (DCLG), 2010d, p. 12&18).

Table 1-3 - CfSH Category Credits and Weightings

Source Data: (Department for Communities and Local Government (DCLG), 2010d, pp. 13-15)

Code Categories	Available Credits	Category Weighting Factor
Energy & CO_2 Emissions		
Dwelling Emissions Rate	10	
Fabric Energy Efficiency	9	
Energy Display Devices	2	
Drying Space	1	
Energy Labelled White Goods	2	
External Lighting	2	
Low & Zero Carbon Technologies	2	
Cycle Storage	2	
Home Office	1	
Category Total	**31**	**36.40**
Water		
Indoor Water Use	5	
Outdoor Water Use	1	
Category Total	**6**	**9.00**
Materials		
Environmental impact of materials	15	
Responsible sourcing of materials – basic building elements	6	
Responsible sourcing of materials – finishing elements	3	
Category Total	**24**	**7.20**
Surface Water Runoff		
Management of surface water runoff from developments	2	
Flood Risk	2	
Category Total	**4**	**2.20**
Waste		
Storage of recyclable/non-recyclable household waste	4	
Construction Site Waste Management	3	
Composting	1	
Category Total	**8**	**6.40**
Pollution		
Global Warming Potential (GWP) of Insulants	1	
NOx Emissions	3	
Category Total	**4**	**2.80**
Health & Wellbeing		
Daylighting	3	
Sound Insulation	4	
Private Space	1	
Lifetime Homes	4	
Category Total	**12**	**14.00**
Management		
Home User Guide	3	
Considerate Constructors Scheme	2	
Construction Site Impacts	2	
Security	2	
Category Total	**9**	**10.00**
Ecology		
Ecological Value of the Site	1	
Ecological Enhancement	1	
Protection of Ecological Features	1	
Change in Ecological Value of Site	4	
Building Footprint	2	
Category Total	**9**	**12.00**
OVERALL TOTAL	**107**	**100**

Each level of the CfSH stipulates minimum standards relating to energy and CO_2 levels, and if the design does not comply, it must be modified until the required level is achieved for the desired ranking. In order to aid the assessment of fabric performance and carbon emission levels, the CfSH framework currently includes two fundamental tools for evaluation and communication of key information – The Energy Performance Certificate (EPC) and Standard Assessment Procedure for Energy Performance of Dwellings (SAP).

Table 1-4 - Minimum Levels of Compliance for CfSH Levels
Source Data: (Department for Communities and Local Government (DCLG), 2010d, p. 12&18)

Code Level	Minimum Percentage Improvement in DER over TER	Maximum Indoor Water Consumption (litres/person/day)	Required Total % Points Score
Code Level 1	0%*	120	36
Code Level 2	0%*	120	48
Code Level 3	0%*	105	57
Code Level 4	25%	105	68
Code Level 5	100%	80	84
Code Level 6	Net Zero CO_2 Emissions	80	90

** - 0% requires compliance with Building Regulations Part L Only*

The EPC describes the energy performance and carbon emissions of a property in simple terms, with a rating from A (highly efficient) to G (poor efficiency). Indications are also provided of the levels that the dwelling could achieve if recommendations are implemented. Using this information, it is possible to understand the limitations of a house and what changes could be made to make it more efficient. It is mandatory for an EPC to be provided for all new build dwellings and existing properties when sold.

The Standard Assessment Procedure (SAP) (Department of Energy and Climate Change (DECC), 2011c) is an approved energy performance assessment methodology, and it is mandatory that it is undertaken by an approved assessor if the results are to be given to a homeowner. It results in a standardized output schedule, which provides indicators of the energy performance of a dwelling in terms of:

- SAP Rating – energy costs associated with space heating, water heating, ventilation and lighting, adjusted for floor area (Rating of 1 – 100, with 100 being lowest running costs)
- Environmental Impact (EI) Rating – annual CO_2 emissions associated with space heating, water heating, ventilation and lighting, adjusted for floor area (Rating of 1 – 100 with 100 being best standard)

The final outputs are reliant upon completion of a series of sections, requiring accurate data input and correct use of standard calculations. The first part of the worksheet concentrates on key details relating to the fabric of the property, location and environment, basic design matters (dimensions and type of dwelling) and ventilation. From this information, heat losses from the building can be calculated, which then affect much of the data in the remainder of the model. Other areas considered include energy required for water and space heating, solar gains, internal gains, and energy from renewable sources. When combined, the final outputs of the model are the SAP and EI ratings and the calculation of primary energy requirements (measured in kWh/year).

As shown in Figure 1-11, (English Housing Survey (EHS), 2012, p. 8), the use of SAP as a compliance evaluation tool in conjunction with increasingly stringent Building Regulation requirements has led to a tangible improvement in housing energy performance in recent years.

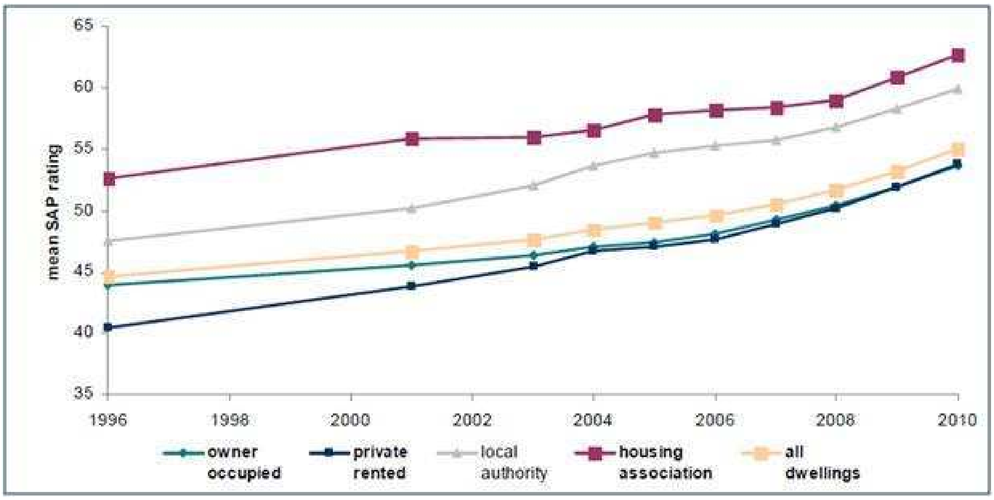


Figure 1-11 - Mean SAP Ratings for UK Housing Stock
Source Data: (English Housing Survey (EHS), 2012, p. 8)

In order to support and incorporate the forthcoming amendments being made to the Building Regulations, consultation has been undertaken regarding modification of the current SAP methodology (from SAP 2009 to SAP 2012). In order to maintain the improvement in housing quality demonstrated in Figure 1-11, it is almost certain that additional updating of the SAP model will be required again in the future (circa 2015). The proposed changes include (Department for Communities and Local Government (DCLG), 2012a):

- More stringent standards for new build dwellings, working towards zero carbon
- Increased energy efficiency standards for existing buildings
- Introduction of FEES into the methodology and calculated outputs
- Use of regional weather data and longer term projections of carbon emissions
- Revisions to assessment of renewable energy systems (default parameters and extension of database to include more manufacturer products)

- More detailed analysis of thermal bridging, insulation of hot water pipework, revised default data inputs

An initial summary of the responses to the consultation was released in October 2013, and a draft version of SAP 2012 (Version 9.92) was published in 2011 (Department of Energy and Climate Change (DECC), 2011c). The aim of the amended model, which was released to coincide with the new 2014 Building Regulations on 6th April 2014, will be to continue the trend of substantial reductions in carbon emissions whilst also addressing the importance of fabric performance and the efficiency of installed systems (Department of Energy and Climate Change (DECC), 2013c).

1.3 Conclusions

The general shift in focus in UK policy relating to domestic energy efficiency is from the support of renewable energy technology installations to a 'fabric first' approach. Feed in tariff payment levels have decreased incrementally over recent years, with more Government funding being targeted at building envelope issues. The intention is to support homeowners and landlords to afford improvements such as enhanced insulation and glazing, working in conjunction with energy supplier schemes and obligations.

'Fabric first' is not a new phenomenon – indeed in 2007, the UK set out an intention to achieve zero carbon in all new build homes by 2016, primarily through improvements to the building envelope (Department for Communities and Local Government (DCLG), 2007). This involves the reduction of building energy demand and carbon emissions through improvement of insulation, reducing thermal bridging through simplified designs, and increasing airtightness levels to minimise infiltration (Energy Saving Trust (EST), 2010).

It can be seen that the Government has placed considerable importance on high fabric performance of new dwellings, and the facilitation of improvements to existing homes, in order to achieve increased energy efficiencies and lower carbon emission rates. The SAP methodology, as it currently exists and in the form of the modified 2012 version, will be integral to the assessment process. It will incorporate the FEES as a mandatory measure for measuring building fabric standards compliance with Building Regulation requirements.

The concept of using a fabric first approach is supported by key stakeholders in the design and construction industry. Several long term projects exist, involving designers, construction companies and research bodies, to investigate the impact that high thermal performance can have on the overall reduction of energy demand and carbon emissions of dwellings (AIMC4 Partners in Innovation, 2013; Bell, M. et al., 1998; Blueprint, 2013; Johnston et al., 2004; Menezes et al., 2012; National House Building Council (NHBC), 2011a; Randall et al., 1979; Sonderegger et al., 1980; Stephen, 1998, 2000; Technology Strategy Board, 2011; Technology Strategy Board (TSB), 2013; Warren et al., 1980; Webster, 1987; White et al., 2013; Wingfield, J. et al., 2006; Wingfield, J. et al., 2010; Wingfield, J. et al., 2011a; Wood, C., 2013; Zero Carbon Hub, 2011c, 2011d, 2013a).

In essence, the concepts of low carbon housing and high levels of fabric performance are synonymous in terms of achieving higher standards of housing in the UK. CfSH Level 3 is currently the minimum legal standard for all new build homes, and this is expected to raise to Level 4 in 2014 and Level 6 (zero carbon) in 2016. The concept of the zero carbon hierarchy, as outlined in Section 1.1, has three tiers – fabric energy efficiency, on-site low/zero carbon energy (and connected heat), and allowable solutions.

Evidence suggests that it is possible to achieve compliance with at least CfSH Level 4 (a 44% improvement in dwelling emissions rates above Building Regulations Part L 2006 or 25% above Part L 2010) solely with a fabric first approach, and without the need for additional renewable technologies (Smith, 2013). However, to achieve higher levels of the CfSH, it is generally necessary to introduce micro-energy generation systems and more innovative low carbon means of water and space heating.

Clearly, there is justification for the current research project to focus on the fabric performance of housing as a means to improving the overall efficiency of dwellings. Should this fundamental element of a building not function as it is predicted to do so, this will have a considerable detrimental impact upon the ability of the UK housing industry to meet the ambitious targets for reductions in energy demand and carbon emissions being stipulated at EU and Government level.

2 FABRIC PERFORMANCE – THEORY AND EVALUATION

Within the mountaineering community, the matter of understanding the principles of heat losses and gains can be the difference between a life and death situation. In conditions of extreme cold, thermal clothing can lessen the effects of low body temperature and help to maintain an adequate level of warmth to enable survival.

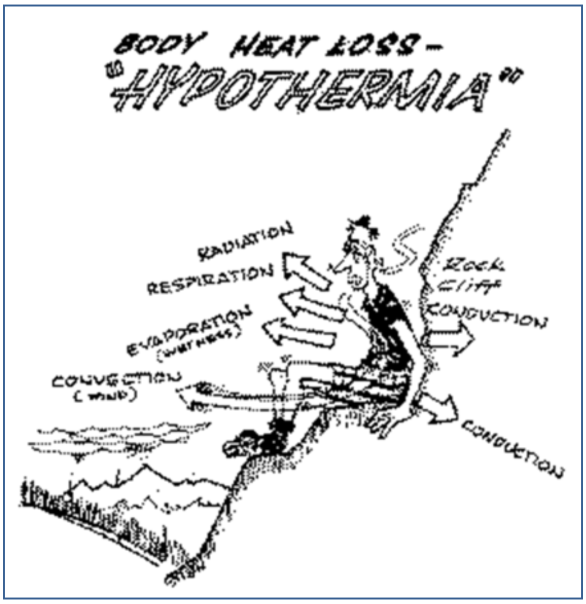


Figure 2-1 - Heat Loss Pathways from the Human Body
Source Data: (Expedition Samoyeds, 2012)(Web)

As illustrated in Figure 2-1, the main heat transfer pathways are convection, conduction, and radiation, with evaporation and respiration also acting as contributing factors. All of the heat is flowing away from the body by various means, in accordance with the principles of the Second Law of Thermodynamics. In the absence of any intervention, heat will flow in a hot to cold direction and cannot flow backwards (Equation 2-1 (Baehr et al., 2011, p. 10).

$$H_t = AU\,(T_{inside} - T_{outside})$$

Equation 2-1 – An Application of the Second Law of Thermodynamics (Baehr et al., 2011, p. 10)

Where:
H_t = *transmission heat loss (W)*
A = *area of exposed surface* (m^2)
U = *overall heat transmission coefficient* (W/m^2K)
t_i = *inside air temperature* (^oC)
t_o = *outside air temperature* (^oC)

Heat losses from the human body in a cold environment can be reduced in several ways. Wearing wind proof, breathable, wicking, thermal clothing adds an insulative layer by maintaining a barrier of warm air between the body and the external elements whilst avoiding moisture build up. Ensuring that extremities such as the head, hands and feet are kept covered and warm, and avoiding contact with cold and wet surfaces helps to conserve body heat (LaRusso, 2013). All of these intervention methods have the aim of maintaining core body heat temperature away from the external temperature in order to prevent heat flow, whilst also ensuring that there is no moisture build-up inside clothing which would effectively act as a cooling system and compromise thermal effectiveness.

In a similar way to the example of a person trying to maintain body heat in a cold environment, so the building envelope must be of a certain standard in order to reduce heat losses and stabilise heat gains. This needs to be balanced against the requirements for heating and adequate ventilation, in order to maintain good indoor air quality whilst avoiding moisture build-up and issues such as damp and condensation.

The remainder of this chapter seeks to identify the key heat flow pathways and mechanisms that need to be minimised in order to achieve high standards of housing fabric efficiency. The coverage extends to a discussion relating to techniques used to evaluate and quantify heat transfer mechanisms at both the design and post-construction stage, and approaches utilised to improve the overall thermal performance of homes.

2.1 Principles of Heat Flow in Buildings

In order to be able to assess the fabric and thermal performance of a dwelling, it is necessary to first appreciate the theory and principles that govern the processes occurring within the materials used and the building as a whole. This is fundamental to understanding the application of a fabric first approach to energy efficiency, where minimisation of building heat losses and reduction in energy demand are of key importance.

It is also important to consider the thermal comfort of building users during the design process. The primary purpose of a dwelling is to provide a healthy, energy efficient living environment (Haghighat, 2012). As such, the current guidelines for acceptable internal temperatures are 21°C for living rooms (as included in SAP) and 18°C for all other rooms (World Health Organisation, 2007, p. 4), with an adequate ventilation rate (by natural or mechanical means) being specified as 13-29 l/s depending on the size of the property (Department for Communities and Local Government (DCLG), 2010a, p. 11).

The internal environment provided within a dwelling will be dependent upon the interaction of building fabric, ventilation and heating systems (Boardman *et al.*, 2005). The properties of these elements will influence the temperature of the air and material surfaces, and also humidity, air movements (draughts) and air circulation/ventilation (Ormandy, 2011).

As buildings become more airtight and high performance insulation and glazing is used in order to reduce energy demand, the risk of overheating and poor ventilation levels increases (Banfill *et al.*, 2011a). This may have health implications for the occupants, and could also cause damage to the building fabric through condensation and subsequent mould growth and dampness (World Health Organisation, 2010). The heat balance of the building is central to both the estimation of energy demand and to thermal comfort, and is discussed further in the remainder of this chapter.

2.1.1 Fabric Heat Transfer Mechanisms

There are several ways in which heat energy can be lost or gained in a building, and, when considering the energy demand of a building, it is important to consider all possible sources of heat losses and gains, as identified in Figure 2-2 (Department of Energy and Climate Change (DECC), 2005, p. 3).

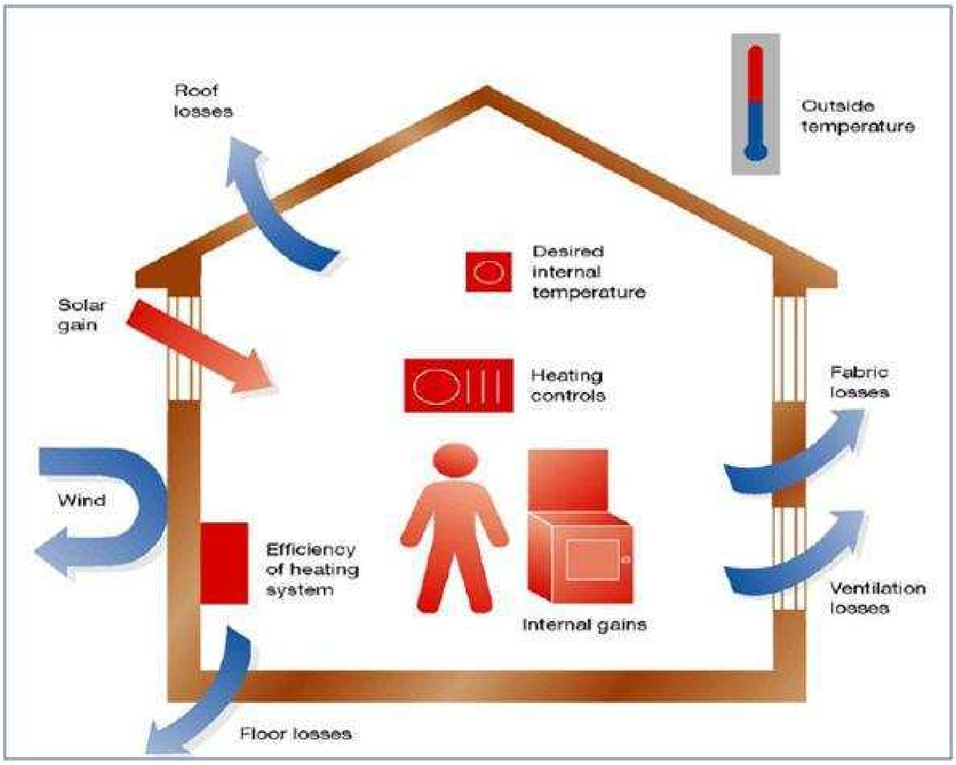


Figure 2-2 - Energy Balance of a Home - Heat Losses and Gains
Source: (Department of Energy and Climate Change (DECC), 2005, p. 3)

In a situation where there is no temperature difference between internal and external temperatures and no intervention from occupants or external environmental factors (wind or solar radiation), the heat losses and gains to/from a building should balance. However, in most circumstances this is not the case, due to a combination of factors such as:

- Transmission Losses (L_t) - internal to external heat flows through the building fabric via conduction or heat transfer;
- Ventilation Losses (L_v) – exchange of warm internal air with cold external air, through either passive or active means;

- Solar Gains (G_s) – additional energy gained through solar irradiance transmitted through windows and other non-opaque building elements; and
- Internal Gains(G_i) – additional energy gained from body heat, lighting, appliances and other electrical devices (Baehr et al., 2011; Pohl, 2011).

The space heating requirements of a dwelling are dependent upon the contribution of these factors, as shown in Equation 2-2 (Feist, 2006), where the majority of terms are identified previously, and H is the required heating input.

$$H = (L_t + L_v) - (G_s + G_l)$$

Equation 2-2 - Heating Demand Formula (Feist, 2006)

The main heat transfer pathway in a building is conduction - the movement of heat through opaque solid matter. As heat energy is absorbed, it generates kinetic motion between adjacent molecules. This occurs due to the presence of a temperature gradient, with energy passing from the hot to the cold side of the material until an equal distributed temperature is achieved. Heat transfer by conduction is also possible in liquids and gases, but due to the less stable structure it is often accompanied by convection and radiation processes (Baehr et al., 2011).

A second process, convection, is familiar to most people, and can be explained by the simple statement ‘hot air rises’. Natural convection occurs when a mass of liquid or gas is mixed, and warmer areas of the substance expand and rise while cooler areas sink, due to differences in density. The process continues in this pattern of circulation until an equal temperature is achieved in the gas or liquid mass.

Convection requires a medium in order for the transfer to take place, and in buildings it occurs at wall and floor surfaces and at heating/cooling units, and also at points where materials are exposed to different temperatures (Pohl, 2011). When an external source, such as a fan, is used to increase circulation, this is known as forced convection. In all convection processes, the inherent movement of and contact between molecules leads to the presence of additional heat transfer via conduction.

Radiant heat transfer occurs due to the emission of energy in the form of multi-directional heat from a warm body such as the sun. Unlike conduction and convection, it does not rely upon direct interaction between the heat source and the receiving object in order to occur. Heat energy within the emitting body is converted into electro-magnetic radiation, which flows in a straight line until it is obstructed by another mass. Upon contact, part of the energy is transferred into absorbed heat by the object or substance (via conduction), whilst some of the original radiation may be reflected or transmitted. The proportion of radiant energy absorbed (stored), reflected (bounced back) or transmitted (passing through) the receiving body is dependent upon the material characteristics and temperature of the entity, and the nature of the wavelengths of radiation (short or long) that are incident upon it (Annaratone, 2010).

The way in which building fabric responds to changes in temperatures and the associated heat flows is dependent upon specific properties of the construction materials used. It can be evaluated via three key measures, namely:

- Thermal Conductivity (k Value measured in W/mK) – this can be described as the quantity of heat that passes through a defined thickness of material per 1K difference in temperature between two (often internal and external) surfaces;

- Thermal Resistivity (R Value measured in m^2K/W) – this property is the reciprocal of thermal conductivity, and relates to the ability of a material to reduce or prevent heat transfer;

- Thermal Transmittance (u-value measured in W/m^2K) – this refers to the heat flow through a given area of structure, divided by the difference in environmental temperatures on either side of the structure in steady-state conditions (Building Standards Institute (BSI), 2008a). (Annaratone, 2010; Baehr et al., 2011; Pohl, 2011).

Ventilation strategy can also have a large effect on the heat transfer mechanisms in a building. Infiltration/exfiltration is a passive ventilation mechanism where air passes through joints or gaps in the building fabric in an outward or inward manner respectively. This provides an uncontrolled background air change rate in many buildings, although it can be difficult to quantify as it varies with localised environmental conditions such as wind speed, wind direction and external temperature (Lash, 2011). A large number of existing UK homes have high levels of infiltration and exfiltration, as the building envelope is not airtight (Dowson et al., 2012).

However, as Building Regulations require more stringent levels of airtightness, the ventilation rate attributable to background infiltration will reduce. Some form of additional ventilation may be needed in order to maintain good internal air quality and to prevent the build-up of moisture, bad odours and, in some circumstances, excessive heat (World Health Organisation, 2010).

As shown in Figure 2-3 (Grun Eco Design, 2013), good cross ventilation can be achieved via background infiltration and additional natural ventilation in the form of opening windows or trickle vents. Natural ventilation in housing often requires user intervention, and so is distinct from the background air movement provided by the passive air permeability of the building envelope. In taller buildings, stack ventilation can be utilised, where the principles of convection are employed in order to maintain circulation of hot and cold air via vents (Pohl, 2011).

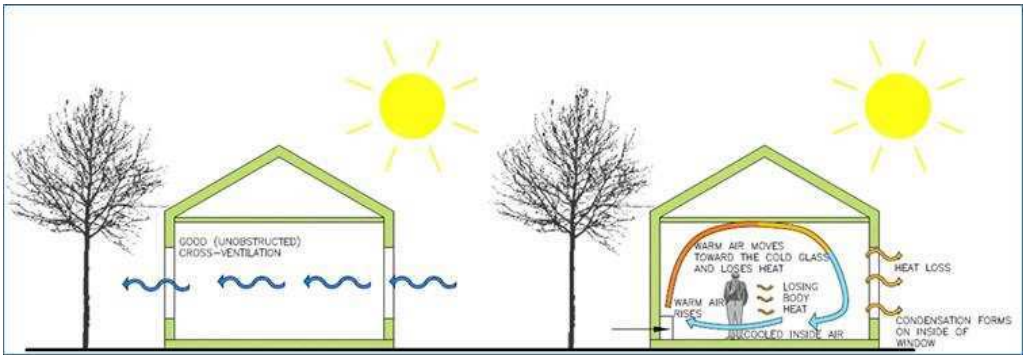


Figure 2-3 - Basic Ventilation Principles
Source Data: (Grun Eco Design, 2013, Web)

In the context of new housing, and improved existing dwellings, the integrity of the building fabric is critical to high levels of energy performance, and a draft-free environment is needed to minimise heat losses through the building envelope. It is becoming increasingly necessary and common place to install a mechanical system to maintain a good standard of indoor air quality and to prevent deterioration of the building fabric due to moisture damage (Banfill et al., 2011a).

Many homes incorporate mechanical extract ventilation in localised areas, such as bathrooms or kitchens, in order to remove moisture and odours and reduce humidity at the point of source. When this is not adequate in conjunction with passive ventilation, it could become necessary to install a whole house ventilation system. This is a mechanical system that uses a control unit to supply fresh air and remove stale air via individual supply and extract ducts situated throughout the property. It becomes particularly effective when the control unit incorporates a heat recovery exchanger, as the heat from the warm extract air is recovered and used to supply pre-heated air to the property. In this way, space heating demand can be reduced (Pollet *et al.*, 2013).

]

2.1.2 Preventing Heat Transfer

The need for heating is a reaction to heat losses – no heat losses will result in a zero heating requirement. Therefore, it seems logical to try to reduce the amount of energy passing through the building fabric in order to decrease space heating requirements. An uninsulated house will lose heat in a similar way to a poorly equipped person exposed to cold temperatures. Large amounts of heat are able to move in and out of the property via infiltration and exfiltration, as quantified in Figure 2-4, for a house built to meet the requirements relevant to Part L of 2010 Building Regulations. (Woodford, 2014).

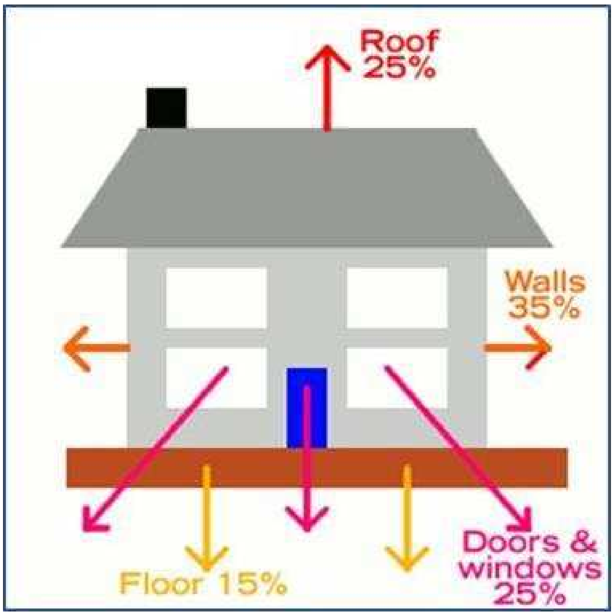


Figure 2-4 - Contribution of Building Elements to Whole House Heat Losses (%)
Source Data: (Woodford, 2014, Web)

There are three key ways in which building fabric can be used as a vehicle to improve thermal efficiency, namely by reducing the thermal transmittance (u-value) of materials, by reducing the effects of thermal bridging, and through employing a holistic airtightness and ventilation strategy (Energy Saving Trust (EST), 2010).

The choice of materials used to construct the building envelope will have a major impact on thermal performance. As insulation levels are increased, u-values (transmittance levels) are decreased and the thermal resistance (R value) increases. Low thermal conductivity (K value) usually indicates greater insulating properties in proportion to thickness (Ibstock, 2011). Insulating materials generally work by reducing levels of conductive and convective heat transfer, and may also act as thermal stores, or reflectors of radiation to reduce solar gains. The resistance of the insulating layer enables a temperature difference to be maintained between the internal and external environments (Pohl, 2011).

It is not uncommon to insulate the roof and walls (filled cavity, solid cavity, internal wall or external wall solutions) of a house. Whilst it is relatively simple to incorporate insulation into upper floors, the ground floor can be problematic to treat as it requires isolation from the earth that supports it. It should also be noted that the calculation of heat losses to the ground is a complex issue due to the unique behaviour of earth as a thermal store, and is governed by standard procedures detailed in EN ISO 13370 (International Organisation for Standardisation, 2007).

In more modern properties, the foundations of the house will generally incorporate insulation to mitigate against heat loss. In older buildings, suspended timber boards can be thermally enhanced by incorporating insulation. Where there is a cellar, insulation can be added between joists from below, and in the case of solid floors a damp proof membrane with an insulative overlay may be a possible solution (English Heritage, 2012a, 2012b).

It has been suggested that heat losses through the floor of a building may account for up to 15% of the total energy balance (Claesson *et al.*, 1991, p. 195), so a strategy to prevent this pathway should be incorporated at the design stage. There has also been counter evidence presented that suggests that savings attributable solely to improvements to ground floor insulation could be as negligible as 3%, raising the question of whether the cost and invasive work required to install floor insulation in older properties is actually worthwhile (George *et al.*, 2006, p. 28).

Whilst insulation is important, other elements of building design may increase heat losses or lower the overall u-value of a building. Thermal bridges are areas or points within a structure where materials with a different thermal conductivity either fully or partially penetrate the building envelope, where there is a change in fabric thickness, or where there is a difference between internal and external areas (for example at junctions between walls, ceilings and floors) (European Committee for Standardization, 2007a). It is estimated that anywhere between 15% and 30% of total fabric heat losses can be attributed to poor detailing at thermal bridge junctions (Energy Saving Trust (EST), 2008b; 2010, p. 4 & 41). However, it is also possible to almost eliminate thermal bridge effects through careful design and attention to detail during construction (Chartered Institution of Building Services Engineers (CIBSE), 2006; Kalousek *et al.*, 2013).

The effect of solar radiation may also influence the heat energy balance. Direct energy can enter a building via transmittance through glazing (predominantly on the south side), and then be absorbed by thermal mass provided by construction materials, or by other objects within the property. When the temperature of the materials falls below that of the internal environment, the stored heat is released due to conduction or convection processes. Whilst this process can be beneficial in terms of reducing space heating demand, it can also lead to overheating in buildings and uncomfortable living conditions. Solar shading can be used to prevent excessive solar gains in the summer months, and when installed at the correct angle will also allow sunlight to reach the building in winter months when it may be useful as a heating aid (Figure 2-5 (Reardon, 2008)).

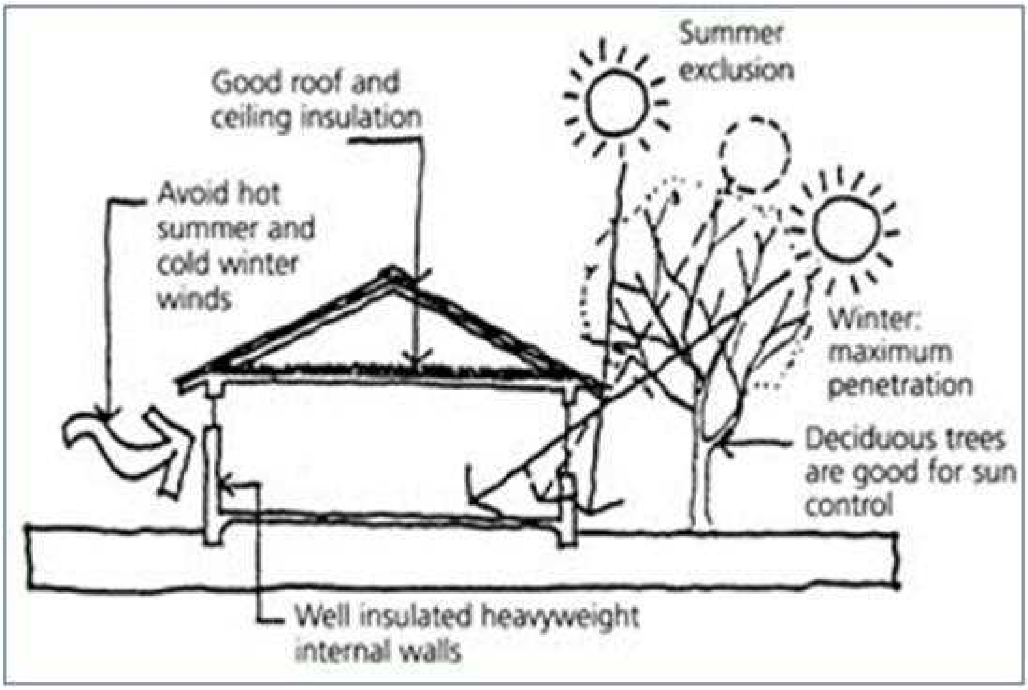


Figure 2-5 - Designing to Mitigate Solar Effects
Source: (Reardon, 2008, Web)

Ventilation strategy is central to the design of a thermally efficient home, as this directly influences the nature of air flow in terms of temperature, velocity and circulation flow rate (Roulet, 2008). When internal gains and solar gains are accounted for, it is possible that, in an airtight house, background infiltration rates alone will not be sufficient to maintain an adequate air change rate to provide a healthy environment for residents (National House Building Council (NHBC), 2009).

Banfill (2011a) suggests that several key measures are required to reduce dwelling space heating demand, namely increased airtightness, high levels of insulation, and installation of a mechanically ventilated heat recovery system (MVHR). The savings are achieved due to a decrease in infiltration levels, in conjunction with an elevated base air temperature obtained via the preheating of supply air using recovered heat from the extracted air. However, this is balanced against the energy costs associated with the running of the MVHR system. The effectiveness of an MVHR system is directly dependent upon the correct balance between the efficiency of system fans, efficiency of the heat recovery unit, air flow rate, and building airtightness (Banfill *et al.*, 2011b).

There is considerable debate concerning the level of air tightness at which it becomes necessary and cost effective to install such a system. Part L of the current UK Building Regulations (Department for Communities and Local Government (DCLG), 2010b, p. 15) specifies a minimum air tightness level of 10 $m^3/(h.m^2)$ @ 50Pa for new build domestic dwellings. However, best practice standards seek to achieve a value as low as 3 $m^3/(h.m^2)$ @ 50Pa (Energy Saving Trust (EST), 2007a, p. 3). Research suggests that the latter value should be adopted as a minimum in order to observe sufficient MVHR operational efficiency levels to realise overall energy savings from such a system (Banfill et al., 2011b).

When considering the UK housing stock, it is characterised by a wide range of air tightness levels, as shown in Figure 2-6 (Stephen, 2000).

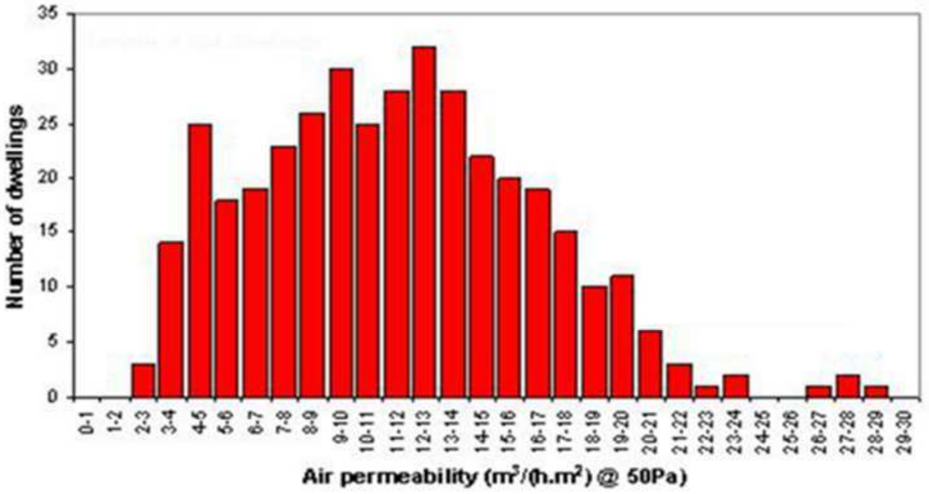


Figure 2-6 - Air Leakage Rates for Survey of 471 UK Dwellings
Source Data: (Stephen, 2000)(Web)

Stephen (1998, 2000) undertook a detailed survey of 471 UK dwellings, and found that those constructed between 1900 and 1930 had mean air permeability values of approximately 10 $m^3/m^2/h$ @ 50pa, those constructed between 1930 to 1960 exceeded 15 $m^3/m^2/h$ @ 50pa, and in properties after that date the value had returned to 10 $m^3/(h.m^2)$ @ 50Pa. This is far in excess of the 3 $m^3/(h.m^2)$ @ 50Pa that may be required in order to achieve efficient function of an MVHR system. The emergence of more energy efficient designs, more stringent minimum requirements for building airtightness, and increased rates of retrofit projects to improve existing housing, could gradually lead to a more widespread need for installation of such systems in order to provide adequate ventilation in dwellings (Zero Carbon Hub, 2012c).

2.2 Design Stage Energy Assessments

Data modelling is used in many contexts in order to assess the predicted performance of a scenario or concept. As has been presented in Section 2.1.2, attention to detail at the design stage of a building can decrease heat losses and space heating requirements, and therefore promote energy efficiency and lower carbon emissions. Various models have been developed in order to allow assessment of the energy performance of buildings at the design stage. Different models may be based upon varying fundamental principles and assumptions, but the general aim is to estimate, as accurately as possible, the potential final as-built and in-use performance levels of a property.

In the UK, the Government has endorsed the use of the Standard Assessment Procedure (SAP) (Department of Energy and Climate Change (DECC), 2011c). This is based upon the Building Research Establishment Domestic Energy Model (BREDEM). Other models in widespread use include the PassivHaus Planning (Design) Package (PHPP), and the US Green Building Council’s Leadership in Energy and Environmental Design (LEED). Of these, PHPP is perhaps the most rigorous assessment procedure and has been described by promoters as the leading international low energy design standard (Passivhaus Trust, 2011).

SAP and PHPP are both essentially steady state energy performance models. This means that the passage of time is not included in the assessment, so standard monthly or seasonal average environmental data is used within the calculation methodology (Building Research Establishment (BRE), 2013). Dynamic modelling software, such as DesignBuilder (http://www.designbuilder.co.uk/), and Thermal Analysis Simulation (TAS) (http://www.edsl.net/main/) include consideration of time factors and so a more detailed analysis of energy demand may be obtained. However, the data derived from many post-construction tests is based upon a dwelling when it is in conditions more comparable to those included in steady state modelling tools, and so SAP and PHPP output provides a more analogous indication of the design-state predicted energy demand.

This section aims to provide the reader with a summary of the key principles of modelling, and also to identify the characteristics of the UK Standard Assessment Procedure (SAP). This tool will be used throughout the remainder of the work to evaluate design stage fabric performance of a new-build and a retrofitted house, through use of specific identified parameters within the model.

2.2.1 Types of Energy Assessment Model

There are two main types of model that are used to evaluate energy use in the residential sector, as outlined in Figure 2-7 (International Energy Agency (IEA), 1998, p. 6) – namely top down (policy led to determine supply requirements) and bottom up (technology led to ascertain demand requirements) (Natarajan *et al.*, 2011).

Essentially, top down models use parameters at an aggregated level (the ‘big picture’), such as macroeconomic indicators, climate and rates of new build housing and demolition, in order to investigate the interaction between the energy sector and a definable key influence (for example, the economy or technology industry). Conversely, a bottom up approach is able to calculate the predicted energy consumption of a complete entity, whether that be an individual dwelling or a large housing development (Natarajan et al., 2011; Swan, L. *et al.*, 2009).

Top down models are useful to assess the impact of policy on the interactions between different sectors, but lack enough detail to be effectively applied to the estimation of individual household energy requirements and do not take account of technological demand shifts and product obsolescence. Bottom up models, including most building energy models, require detailed information relating to the subject being assessed, such as building dimensions and construction/system installation details, and so are very time intensive and often involve complex technical calculations. They are, however, extremely effective when assessing the impact of different scenarios or solutions on final energy consumption (such as varying insulation levels or applying a range of heating system types) (Kavgic *et al.*, 2010; Mhalas *et al.*, 2013; Swan, L. et al., 2009).

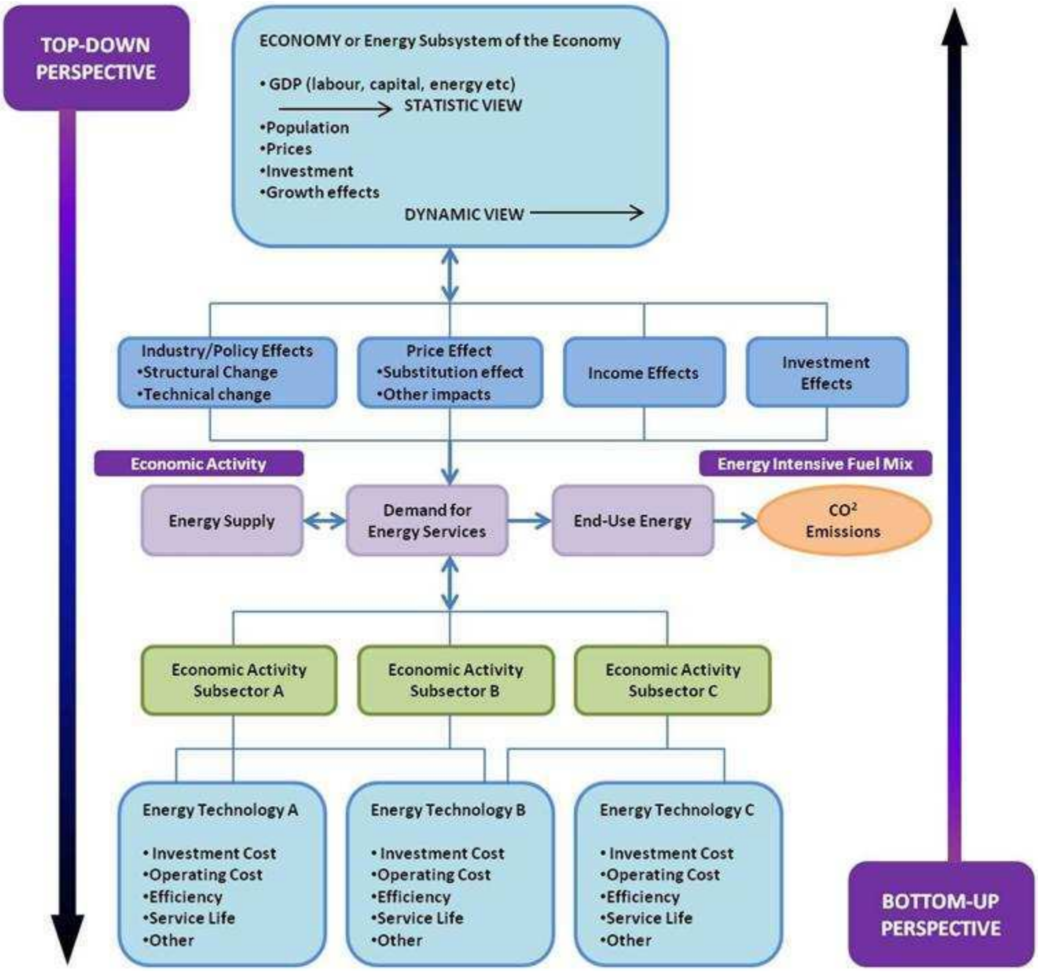


Figure 2-7 - Approaches to Energy Demand Modelling – Top-Down & Bottom-Up
Adapted from Source Data: (International Energy Agency (IEA), 1998, p. 6)

In some cases, such as when assessing the impact of policy on individual households or technological solutions, it may be appropriate to use a combined top down and bottom up model (Frei *et al.*, 2003) . The inclusion of detailed bottom up data in a top-down model can reconcile the generality of the aggregated information and lead to more realistic estimation of future energy needs and the degree of impact that decisions may have on an end user or system (Böhringer, 1998; Koopmans *et al.*, 2001).

2.2.2 Design Stage Energy Assessment Modelling in the UK

When assessing energy demand at the design stage of a building, a building physics bottom up approach is the most commonly used. It is important that the model has the capacity to calculate energy demands and carbon emissions, whilst also taking into account the effect of different building designs and installed technologies on the quality of the indoor environment (Kavgic et al., 2010). Figure 2-8 shows the strengths and weaknesses of this type of model.

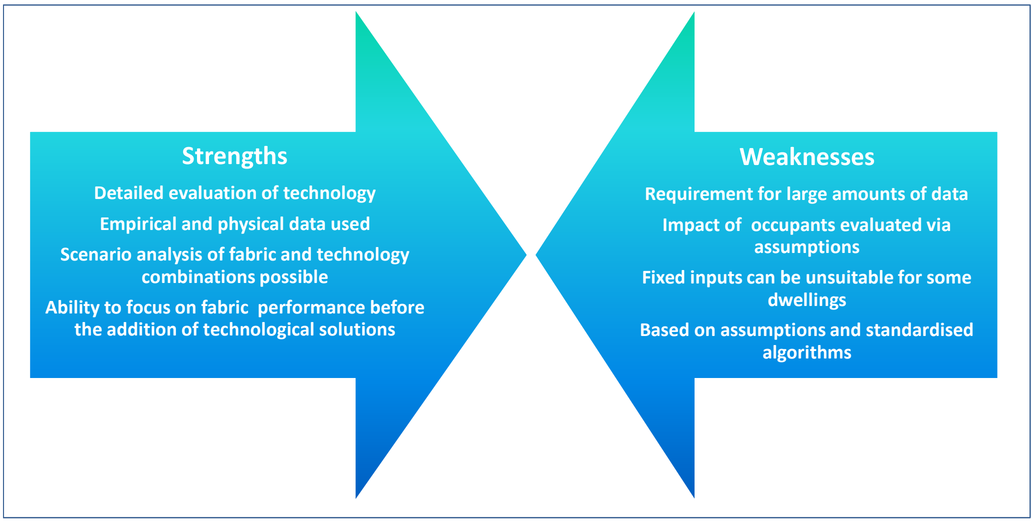


Figure 2-8 - Strengths & Weaknesses of Building Physics Approach
Based on Source Data: (Kavgic et al., 2010)

In the UK, most energy models are based on the Building Research Establishment Domestic Energy Model (BREDEM), which complies with EU requirements for domestic energy models (Building Standards Institute (BSI), 2008b). Whilst BREDEM has been updated a number of times, including as recently as 2012, (Building Research Establishment (BRE), 2013), the Standard Assessment Procedure 2009 (SAP 2009) is based on an older version (BREDEM 12). This model is currently embedded in UK Building Regulations as a compliance evaluation tool, but is due to be updated in 2014. After this date, SAP 2012 will be integrated into policy, and will utilise the most recent BREDEM model (BREDEM 2012). The development of BREDEM and SAP is shown in Figure 2-9 (Kelly, S. *et al.*, 2012, p. 18).

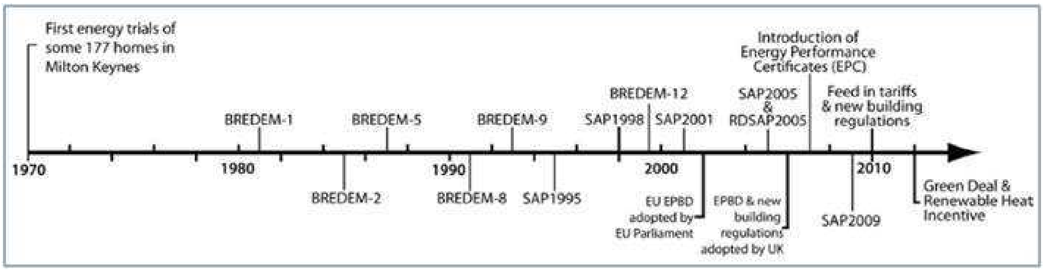
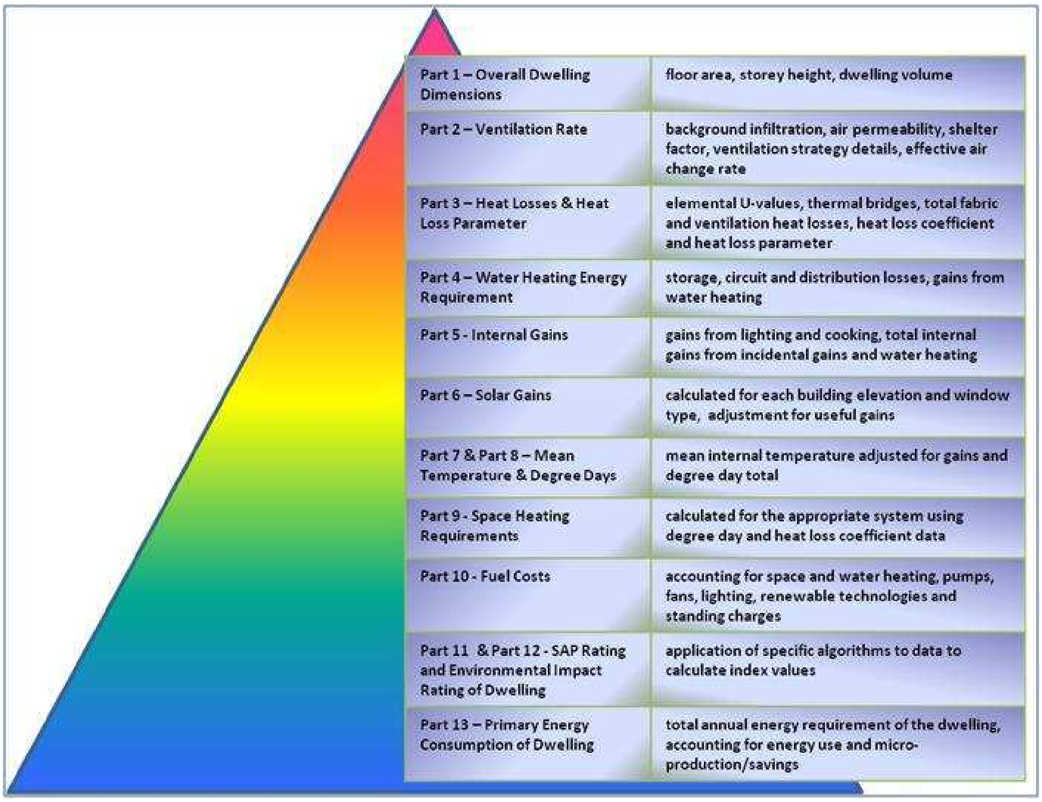


Figure 2-9 - Development of SAP and BREDEM in the UK
Source: (Kelly, S. et al., 2012, p. 18)

BREDEM requires extensive input data relating to the dwelling construction and installed systems, and this is used, via a series of algorithms, to calculate the energy demands associated with space and water heating, lighting and cooking. When good quality data is inputted correctly it can provide an accurate prediction of dwelling energy demands (Natarajan et al., 2011). Essentially, the inputs and underlying calculation methods and algorithms for both BREDEM and SAP are largely identical. However, SAP includes more assumptions and fixed values for certain parameters to ensure standardisation in use, whilst BREDEM allows more flexibility in input data. RdSAP is a further simplified version of the model that is used to evaluate existing buildings (Kelly, S. *et al.*, 2011).

A summary of the parameters utilised in the SAP 2009 methodology is given in Figure 2-10, with an example of a blank example worksheet provided in Appendix 1 (Department of Energy & Climate Change (DECC), 2011).

It has been suggested that other methods of assessment, such as the PassivHaus Planning (Design) Package (PHPP), may be more rigorous and detailed in their approach and thus produce more reliable predictions of household energy demand than that derived from SAP (Association for Environmentally Conscious Building (AECB), 2008).



Part 1 – Overall Dwelling Dimensions	floor area, storey height, dwelling volume
Part 2 – Ventilation Rate	background infiltration, air permeability, shelter factor, ventilation strategy details, effective air change rate
Part 3 – Heat Losses & Heat Loss Parameter	elemental U-values, thermal bridges, total fabric and ventilation heat losses, heat loss coefficient and heat loss parameter
Part 4 – Water Heating Energy Requirement	storage, circuit and distribution losses, gains from water heating
Part 5 - Internal Gains	gains from lighting and cooking, total internal gains from incidental gains and water heating
Part 6 – Solar Gains	calculated for each building elevation and window type, adjustment for useful gains
Part 7 & Part 8 – Mean Temperature & Degree Days	mean internal temperature adjusted for gains and degree day total
Part 9 - Space Heating Requirements	calculated for the appropriate system using degree day and heat loss coefficient data
Part 10 - Fuel Costs	accounting for space and water heating, pumps, fans, lighting, renewable technologies and standing charges
Part 11 & Part 12 - SAP Rating and Environmental Impact Rating of Dwelling	application of specific algorithms to data to calculate index values
Part 13 – Primary Energy Consumption of Dwelling	total annual energy requirement of the dwelling, accounting for energy use and micro-production/savings

Figure 2-10 - Summary of SAP Structure and Key Parameters
Produced by Author

The development of the PassivHaus Standard began in 1991, but it was not formalised until 1995 (Feist *et al.*, 2007). It is essentially a steady state energy modelling tool, with assessments carried out using the standardised PHPP software and methodology (McLeod, R. S. *et al.*, 2012).

The key criteria for compliance with PHPP, defined within the current version of the standard, are (Passivhaus Institute, 2009, p. 1):

Specific Heating Demand:	≤15 kWh/m^2/yr
Specific Cooling Demand:	≤15 kWh/m^2/yr
Specific Heating Load:	≤10 W/m^2
Specific Primary Energy Demand:	≤120 kWh/m^2/yr
Air Changes Per Hour:	≤0.6@n50 (0.4 m^3/(h.m^2) @ 50Pa)

Limiting performance levels are also applied to element u-values, thermal bridging and air change rates, with recommendations made for specification of white goods and integrated systems (PassivHaus Trust, 2014a). When the requirements and principles of the PHPP framework are applied correctly, the primary aim of the concept can be achieved, which is to design and construct

> *'a building, for which thermal comfort can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air'* (PassivHaus Trust, 2014b Web)

Several studies have been undertaken to assess the fundamental differences between SAP and PHPP and the way in which they calculate outputs (Association for Environmentally Conscious Building (AECB), 2008; Moutzouri, 2011; Passivhaus Trust, 2011; Scottish Building Standards Division (SBSA), 2009). The main areas of divergence include:

- SAP is a compliance tool whilst PHPP is a design tool – this affects the philosophy that is used in the calculation methodology for energy and carbon demands. PHPP includes a fixed target energy usage of 15kWh per m^2 of useful floor area, per year, while SAP incorporates the use of a notional Part L compliant building for comparison with the proposed design.

- SAP uses internal measurements (including stairwells) in calculations while PHPP uses external measurements (excluding stairwells), which results in the SAP model being more prone to underestimations of heat loss. PHPP is able to inherently incorporate thermal bridges into the calculations, and enables them to be resolved within the physical design. SAP has the functionality to either include detailed definition of individual junctions between elements or to insert default values, which may increase the likelihood of error in the assessment process.

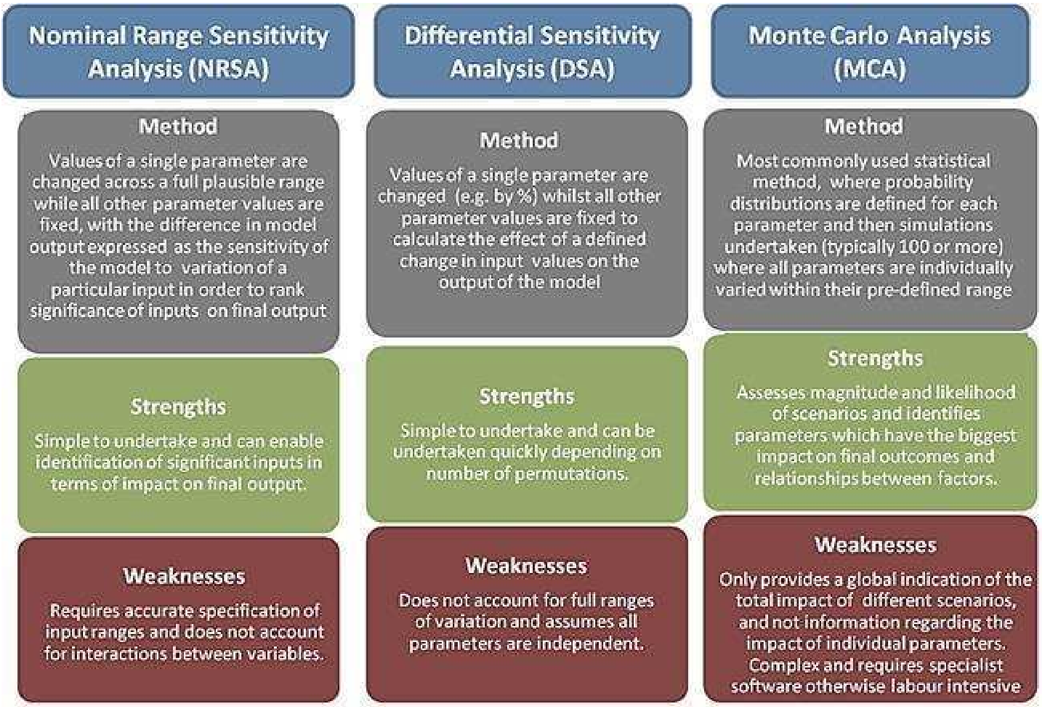
- Within SAP, there is potential to trade-off occupant comfort against use of renewable technologies and other ‘credits’. PHPP is more focused on the end user and the ability of the property to meet their needs.
- The treated floor area defined in PHPP does not include consideration of flights of stairs with in excess of three steps, while SAP takes account of all stairways (Feist et al., 2007).
- Both models take into account orientation and shading, but weather data is standardised within the SAP model (generally using degree data for the East Pennines). PHPP uses monthly degree data, and more localised weather datasets are utilised.
- PHPP assesses individual window units and excludes evaluation of window effect on lighting requirements, whilst SAP uses a total area of glazing for each facade and considers daylight effects.
- SAP does not specifically account for the effect of passive solar gains in terms of effect on heating/cooling requirements, whilst PHPP facilitates dynamic modelling.

There are numerous other subtle differences between the two techniques, although they are both basically steady state heat loss models that utilise a degree day climate approach, and then deduct internal/solar gains. However, the AECB (2008) and The University of Strathclyde/Scottish Building Standards Division (2009) found that if an identically designed house is modelled using both PHPP and SAP methodology, it will produce different results in terms of heating demands and carbon emissions.

SAP generally underestimates both of these values, and McLeod (2012) raises concerns that the use of SAP rather than PHPP may be concealing the true extent of carbon saving that could be achieved in the UK. Thermal performance as a contributing factor to this will be further investigated within the scope of this research project.

2.2.3 SAP Sensitivity and Uncertainty Analysis

A number of studies have been undertaken in order to assess the sensitivity and uncertainty of the input parameters within building energy assessment models. Due to the need to standardise procedures in order to ensure consistency across the evaluation of different buildings by individual assessors, several simplifications and assumptions are used, in addition to fixed calculation methods. This can lead to uncertainty in the model itself, which can impact upon the ability of the model to provide truly accurate outputs (de Wita *et al.*, 2002). Figure 2-11 summarises the main techniques used in sensitivity analysis.



	Nominal Range Sensitivity Analysis (NRSA)	Differential Sensitivity Analysis (DSA)	Monte Carlo Analysis (MCA)
Method	Values of a single parameter are changed across a full plausible range while all other parameter values are fixed, with the difference in model output expressed as the sensitivity of the model to variation of a particular input in order to rank significance of inputs on final output	Values of a single parameter are changed (e.g. by %) whilst all other parameter values are fixed to calculate the effect of a defined change in input values on the output of the model	Most commonly used statistical method, where probability distributions are defined for each parameter and then simulations undertaken (typically 100 or more) where all parameters are individually varied within their pre-defined range
Strengths	Simple to undertake and can enable identification of significant inputs in terms of impact on final output.	Simple to undertake and can be undertaken quickly depending on number of permutations.	Assesses magnitude and likelihood of scenarios and identifies parameters which have the biggest impact on final outcomes and relationships between factors.
Weaknesses	Requires accurate specification of input ranges and does not account for interactions between variables.	Does not account for full ranges of variation and assumes all parameters are independent.	Only provides a global indication of the total impact of different scenarios, and not information regarding the impact of individual parameters. Complex and requires specialist software otherwise labour intensive

Figure 2-11 - Sensitivity Analysis - Main Techniques
Produced from Source Data: (Frey *et al.*, 2003; Kavgic et al., 2010; Saltelli *et al.*, 2000)

Following a detailed study of input parameters in building energy models, Lomas (1992) recommended that DSA was most suitable for evaluating uncertainty in individual input parameters (local impact), with MCA providing a better tool for assessing total/overall sensitivity of the model to cumulative changes in parameters (global impact). However, whilst the practise of varying one parameter whilst fixing all others (one factor at a time DSA) is commonplace in the evaluation of building energy models, there is concern that this may not provide a reliable assessment of the accuracy of the model (Saltelli *et al.*, 2010). This is largely due to the assumption within DSA that all inputs are independent and have no impact upon one another, which is clearly not the case in the context of building performance (Lomas et al., 1992).

MacDonald (2002) and Booth (2012) have assessed the aspects of building energy models that may potentially lead to inaccurate analysis of building energy demands, and suggest that the main areas of concern are:

- Ability of the model to represent reality;
- Accuracy and appropriateness of derived/assumed data in the absence of true measured data for input parameters;
- Assumptions regarding climate, occupancy and behaviour, system installations and use;
- Appropriateness of default values, fixed parameters and base calculations;
- Accuracy of data input; and
- Effect of late design changes on final predictions.

Detailed assessment of the UK BREDEM model has also been undertaken in response to concerns regarding the robustness of the model, including many of the issues identified previously in more general studies. Palmer (2012) used a one at a time DSA approach in order to ascertain the parameters in BREDEM 9 that can have the most significant impact on final outcomes.

Table 2-1 (Palmer et al., 2012, p. 137) shows, in descending order, the most influencing factors, ranked using a normalised sensitivity coefficient. These values reflect the absolute effect of a change in each parameter on the final calculated energy consumption. For example, a 1°C rise in internal demand temperature will result in a 1.54% rise in energy consumption. This study suggests that many of the highest ranking sensitive parameters form part of the heat losses and ventilation section within the model (as highlighted by shading in Table 2-1).

Table 2-1 - Significant Parameters Identified in BREDEM 9 Following Differential Sensitivity Analysis
Source: (Palmer et al., 2012, p. 137)

Input Parameter	Initial Set Value Used (N_i)	Normalised Sensitivity Coefficient (S_i)
Internal Demand Temperature(°C)	19.0	1.54
Main Heating System Efficiency (%)	80.5	-0.66
External Temperature (°C)	7.5	-0.59
Total Floor Area (m^2)	96.4	0.53
Storey Height (m)	2.5	0.46
Daily Heating Hours (hrs)	11.0	0.27
DHW System Efficiency (%)	76.6	-0.19
Wall U-value (W/m^2K)	1.2	0.18
Effective Air Change Rate (ach)	1.0	0.18
Wind Factor Parameter	4.0	-0.17
Wind Speed (m/s)	4.8	0.17
Infiltration Rate (ach)	0.8	0.17
Appliances Energy Coefficient (TFAxN)	0.47	0.17
Shelter Factor	0.9	0.16
Main Heating Responsiveness	0.9	-0.15
Total	**998**	**908**

Similarly Quigley (2010), undertook a detailed sensitivity analysis of BREDEM 8 as applied to several case study building scenarios, and concluded that fabric u-values, air permeability data and heating technologies had the greatest influence on final outputs. Work undertaken by Firth et al. (2010) also found that the characteristics of heating systems and building heat losses had the most impact on energy demands and carbon emissions calculated by a bespoke base model derived from a BREDEM 8 foundation.

Kavgic (2010) observes that the main limitations of building energy models are their lack of transparency due to hidden algorithms, inability to alter certain data inputs and outputs, and uncertainty surrounding assumptions used. The evidence suggests that, whilst the limitations of BREDEM and subsequently SAP, are acknowledged, actual quantification of the impact of individual parameters on final outputs is limited.

Within SAP, there are a large number of input parameters, assumptions and underlying calculation formulae that ultimately influence the output data. It can be seen from the studies undertaken to date that fabric heat losses and ventilation rates are identified as some of the most significant areas of the model in terms of their ability to affect final energy demand values.

There are a number of key items within the SAP 2009 methodology that contribute to the calculation of a HLC output value, as shown in Figure 2-12. This provides a measure of the whole house heat losses in terms of W/K, that is, the required energy (W) required to heat the building per degree of difference between the internal and external temperatures (K).

The calculation is derived from BS EN ISO 12831 (Building Standards Institute (BSI), 2003), where Total Design Heat Loss is equal to the sum of the design transmission heat loss for heated space (W) and design ventilation heat loss for heated space (W). Element u-value multiplied by element surface area data provides a value of fabric heat loss for each aspect of the building (floors, walls, roof, windows and doors). The contribution of thermal bridging losses, background infiltration and additional ventilation losses are summed, together with fabric heat loss, to calculate the HLC (W/K) under steady state conditions. This provides a measure of the required energy (W) required to heat the building per degree of difference between the internal and external temperatures (K).

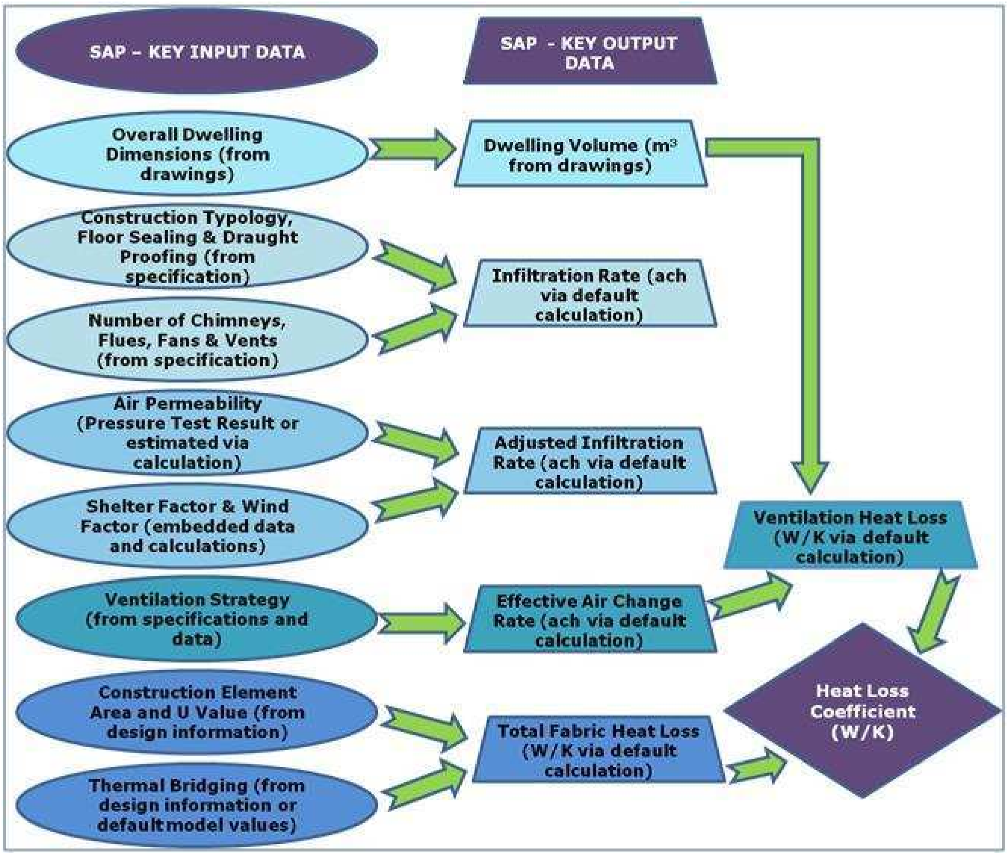


Figure 2-12 - Heat Loss Coefficient Calculation - Key SAP Input and Output Data (Produced by Author)

The HLC is used within SAP methodology to calculate space heating requirements, which account for two thirds of total energy demand in an average UK home (as illustrated previously in Figure 1-6). Therefore, this parameter requires careful calculation in order to accurately predict the energy consumption of a dwelling. As a benchmark for fabric performance of buildings, the HLC has been identified as an appropriate means to evaluate thermal efficiency of housing within this research.

2.3 Post Construction Assessment

As shown in Section 2.2.2, the evaluation of building energy demand at the design stage is standard practice and necessary in order to confirm compliance with minimum building regulations. However, the systematic post construction evaluation of buildings has not been commonplace historically. This situation is changing, as the EU Energy Performance of Buildings Directive (as outlined in Section 1.2.1) now requires demonstration of compliance with minimum performance standards for all new housing and alterations to existing properties, including reviews of public housing stock (Bull *et al.*, 2012). Indeed, the Good Homes Alliance (GHA) is seeking a culture and policy shift in assessment processes so that the energy demand of a building is defined by results from post construction evaluation rather than by outputs from design stage modelling (Good Homes Alliance (GHA), 2012).

Post occupancy evaluation (POE) is a term that is commonly used in relation to the evaluation of constructed building performance. It can be limited to solely qualitative analysis, through the use of questionnaires to gather information from occupants as to their views of the building (Leaman *et al.*, 2010). Alternatively, it is used to refer to a careful and systematic review of physical building and systems performance in addition to occupant feedback (Preiser, 1995). The latter approach provides a comprehensive evaluation tool, which enables a more complete understanding of the strengths and limitations of a particular building design (Preiser *et al.*, 2004; Stevenson *et al.*, 2008). In the wider definition of POE, there are a number of techniques that can be used in order to assess building performance, as illustrated in Figure 2-13.

There is little doubt that to undertake such detailed assessments does require extensive resources, specialist techniques and knowledge, and involves a considerable amount of time. The obtrusive and sometimes destructive nature of some of the testing methodologies is also a barrier to wide-scale use in the context of mainstream housing projects (Energy Saving Trust (EST), 2005). Regardless of this, there has been some progress towards embedding POE into standard assessment practises for housing in the UK (Energy Saving Trust (EST), 2008c). It is recognised that the information that can be obtained from such a study can be invaluable to inform designers, constructors and developers as to the actual as-built performance of a building as compared to design stage aspirations, in order to inform future projects (Zero Carbon Hub, 2013a).

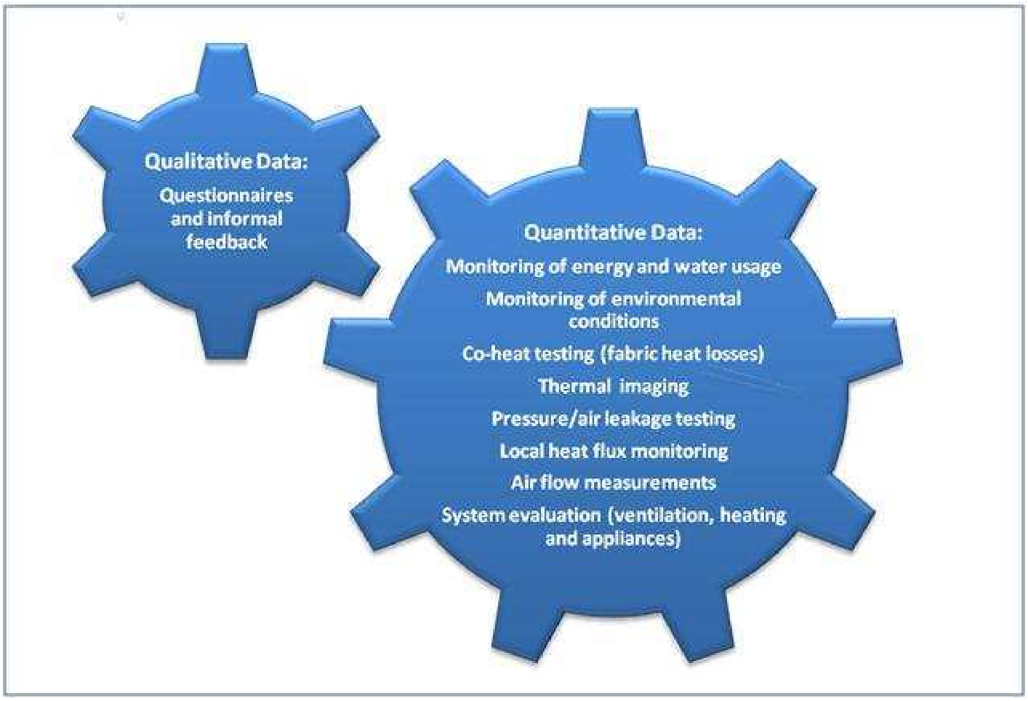


Figure 2-13 - Comprehensive POE - Techniques Used (Produced by Author)

The focus of this research is related to the physical function of UK housing in terms of fabric efficiency, and so assessment will be limited to the evaluation of building fabric through quantitative POE techniques. That is not to say that it is not recognised that occupant behaviour and interaction with a building and embedded systems can have a significant impact upon the energy demand and carbon emissions attributable to a home. Indeed, research suggests that ‘buildings don’t use energy – people do’ (Janda, 2009, p. 1), with the energy demand of a dwelling of the same design varying by as little as 5% to as much as over 50% depending on resident usage of systems and appliances (Ajzen, 1985; Guerra Santin *et al.*, 2009; Sonderegger, 1978).

However, within the confines of the HLC as a benchmark for fabric performance, human intervention is not considered and so is not within the scope of this work. The remainder of this section will discuss the various techniques commonly used to evaluate the various elements of building fabric performance.

2.3.1 Evaluating the Physical Construction

In all new housing developments, Building Regulations Part L 2010 requires an air leakage test to be undertaken on 3 dwellings of each type or 50% of total number of houses, whichever is less (Department for Communities and Local Government (DCLG), 2010b, p. 21). In order to comply with minimum standards, the air permeability must not exceed 10 $m^3/(h.m^2)$ @ 50Pa. As a mandatory requirement, it provides a logical first step in the post-construction performance evaluation process.

The technique most commonly used to evaluate building air-tightness is the fan pressurisation method (‘blower door test’), with procedures prescribed by legislation and best practise (ATTMA, 2010; European Committee for Standardization, 2007b; International Organisation for Standardisation, 2006). The basic principle of the test is to seal all ventilation ducts and vents within a property and then to replace an exterior doorway of the house with a temporary door that incorporates a fan, as shown in Figure 2-14 (Seacoast Inspections LLC, 2013).

Depending on whether the fan is operating in pressurisation or depressurisation mode, it is used to create a slight positive or negative difference between internal and external air pressures, from a baseline state of 50Pa. The air flow through the fan is continuously measured, and the relationship between the pressure difference across the building envelope and rate of air flow required to maintain a specified pressure reflects the air leakage rate of the property. The equipment remains in place and several readings are taken at different pressure levels, with the direction of air flow through the fan being reversed for depressurisation tests (ATTMA, 2010).

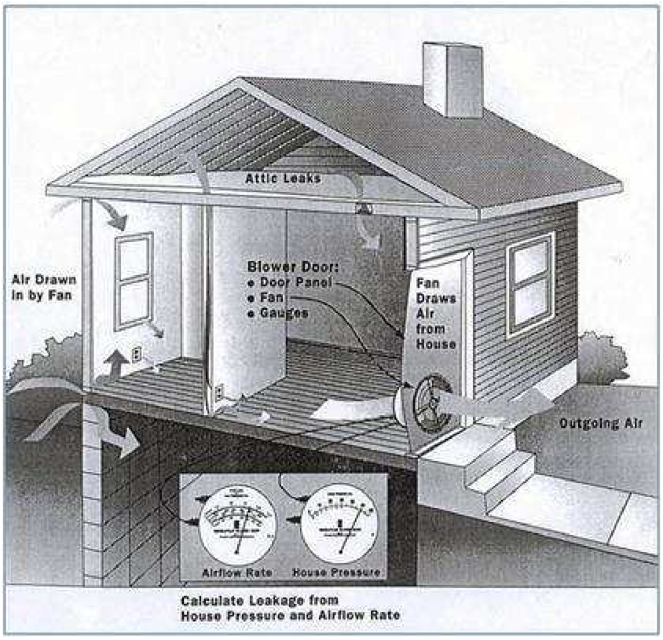


Figure 2-14 - Air Pressure Testing Process
Source: (Seacoast Inspections LLC, 2013, Web)

There are two main terms used to describe the normalised air tightness parameters that can be calculated as outputs from the air pressure test, as defined below (Sinnott, D., Dyer, M., 2012):

> Air Permeability (q50) – the volume of air passing through each m^2 of building envelope, including ground floor area, expressed in m^3/(h.m^2) @ 50Pa
>
> Air Leakage Rate (n50) – airflow at a controlled pressure differential divided by gross internal volume of the dwelling, expressed in air changes per hour (ach)

The air pressure test result can be used to calculate both of the above terms (d'Ambrosio Alfano *et al.*, 2012), but throughout this study evaluation will be limited to relative q50 values as this is the relevant measure included in the SAP methodology. It is standard practise for a pressure and depressurisation test to be undertaken, and an average of the two values taken as the dwelling air permeability value. This enables account to be taken of both additional infiltration due to air being pushed through the fabric, and the sealing effect of depressurisation (Sinnott, D. *et al.*, 2011).

When a building has been pressure tested, the q50 value can be used directly in design stage models and DER calculations in order to ascertain compliance with Building Regulations. However, in the case of a small or repeat developments, the construction team can opt to avoid the necessity of having to undertake such tests, at the penalty of using a q50 result of 15 $m^3/(h.m^2)$ in the calculations and evaluation, as long as the DER is still lower than or equal to the TER declared at the design stage (National House Building Council (NHBC), 2011b, p. 10).

A second technique that can provide a good indication of heat losses from a building is the use of an infra-red thermographic survey. British Standard EN 13187 (British Standards Institution, 1999) implements the standard for thermal imaging in relation to building envelopes. However, the methodology does not extend to include assessment of the amount of insulation or air tightness levels of a building. The Standards therefore govern the procedure used in order to assess the presence of air leakage, but an infrared survey cannot provide information regarding the actual quantitative thermal performance levels of a building.

An infra-red camera can be invaluable in enabling the evaluation of the construction of a property beyond that which is visible to the naked eye in a non-intrusive way with immediate visual results (i.e. details within the external building envelope/building fabric can be viewed without the need for opening up) (Titman, 2001). Used alongside standard air pressure testing methods, it is possible to identify areas of air leakage which can be addressed to improve the air tightness of a property (Balaras *et al.*, 2002).

In order to evaluate individual building elements that may be contributing to unexpected levels of fabric heat transfer, heat flux sensors may be utilised at specific locations to gain a quantitative measure of conductive heat flow through, for example, a wall, floor or building junction. The technique is largely non-intrusive and causes minimal damage, as sensors are simply placed on the surface of the material, and the output of the sensor is a measurement of heat flow in W/m^2K (Doran, 2000).

From this measurement, the in-situ u-value of materials can be calculated when internal and external temperatures are also monitored. Such information can be valuable in terms of assessing actual thermal transmittance performance of materials within the constructed building, whilst taking into account the effects of thermal mass and environmental conditions (Rye *et al.*, 2012).

2.3.2 Quantifying Whole House Heat Losses

As discussed in Section 2.1.2, heat losses through building fabric can be extensive and have a significant effect on space heating demand. However, the evaluation of such losses is not a simple task, and it has been acknowledged that it is almost impossible to undertake repeatable and reliable in-situ thermal performance testing of constructed buildings at a macro-level (Judkoff *et al.*, 2001).

Short term energy monitoring (STEM) tests are the most commonly used technique, and have been utilised for a number of years in order to assess post-construction building performance (Wouters *et al.*, 2005). The majority of such tests that have been undertaken are related to research projects, as the work involved is time and resource intensive and requires long term access to an empty property (Department for Communities and Local Government (DCLG), 2011a).

The primary technique used in the UK for as-built thermal performance testing is the steady state coheating test (Good Homes Alliance (GHA), 2011a). This methodology was first developed in the USA over 20 years ago (Sonderegger et al., 1980), but it is only more recently that a semi-standardised protocol has been developed by Leeds Metropolitan University (Wingfield, J. , 2011).

Techniques of this type involve using electrical heaters to maintain a constant internal temperature in a building (Figure 2-15 (Stamp, 2013)), and measuring the power input of the heaters for a number of consecutive days (Department for Communities and Local Government (DCLG), 2011a). Generally, a time period of seven to ten days per test is recommended (Homes and Communities Agency (HCA), 2010). This minimises the effect of fabric heat storage effects and stabilises the variation between measured air and radiant temperatures (Everett *et al.*, 1985).

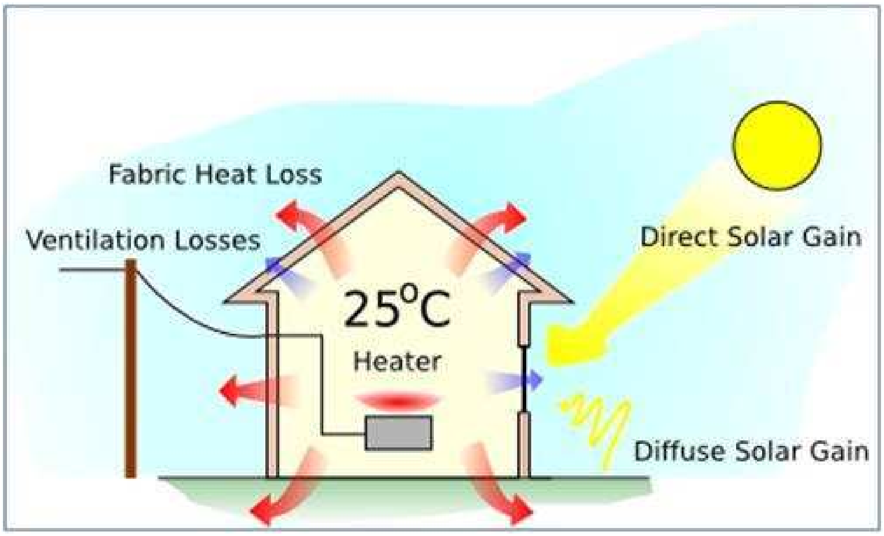


Figure 2-15 - Principles of Coheating Test Procedure
Source: (Stamp, 2013, Web)

The output from a coheating test is a measurement of the as-built HLC of a property. As indicated by Johnston (2013, p. 5), the calculation of the HLC can be undertaken using a rearranged form of the standard heat balance equation (Equations 2-3 and 2.4).

$$Q + R.S = (\Sigma U.A + 1/3nV).\ \Delta T$$

Equation 2-3 – Standard Heat Balance Equation (Johnston, 2013, p. 5)

$$Q/\Delta T \text{ (HLC)} = (\Sigma U.A + 1/3nV) - R.S/\Delta T$$

Equation 2-4 – Rearranged Heat Balance Equation (Calculation of HLC (W/K) (Johnston, 2013, p. 5)

Where:
Q *= Total measured power (W)*
R *= Solar aperture (m^2)*
S *= Total south facing solar radiation (W/m^2)*
$\Sigma U.A$ *= Total fabric heat loss (W/m^2)*
n *= Background ventilation rate (h^{-1})*
V *= Internal volume of the dwelling (m^3)*
ΔT *= Temperature difference between the inside and outside of the dwelling (K)*

The total measured power value is recorded directly by a power meter attached to each heater and fan, whilst internal temperatures and external temperatures are recorded using thermocouples. The circulation fan is employed in order to encourage mixing of hot and cold air, in order to prevent stratification and maintain an even temperature throughout the test dwelling. Individual thermostats are connected to each heater in order to regulate internal temperature. Solar radiation is measured either directly by a site-based pyranometer, or obtained from a local weather station data. The analytical techniques only require input of the south facing solar radiation values, although, depending on the orientation of the building, this could underestimate the overall impact of solar gains to the east and west elevations.

The raw data from the coheating test provides a measurement of the total heat input from the heaters required to maintain a uniform internal temperature. However, the effect of solar gains needs to be accounted for, as less power may be required to heat the dwelling on days with high levels of solar radiation (Jenkins *et al.*, 2013).

There are several techniques that are commonly used to assess the effect of solar gains on the whole house HLC. The Siviour Method is a linear regression method, presented by Siviour over twenty years ago. The parameter $Q/\Delta T$ is plotted against $S/\Delta T$ in order to obtain the solar aperture (R in m^2), which is represented by the slope of the line. The y-intercept is equal to the total solar corrected HLC (W/K) (Siviour, J., 1981).

A modified version of this methodology, referred to as thermal calibration and shown in Equation 2-5 (Johnston, 2013, p. 6) was developed by Everett (1985) in order to isolate floor heat loss values where this building element was considered to have different thermal properties to the rest of the dwelling (such as a solid concrete slab foundation).

$$Q - F/\Delta T - 1/3nV \text{ (HLC)} = \Sigma U.A - R.S/\Delta T$$

Equation 2-5 - Thermal Calibration Equation (Adjusted Calculation of HLC W/K) (Johnston, 2013, p. 6)

Where F = Total Ground Floor Heat Loss (W)

When the data is plotted using this technique, the slope of the line represents solar aperture (R in m^2), while the y intercept equals the total solar corrected HLC (W/K), excluding ground floor heat losses.

When it is not possible to determine the solar aperture through use of either Siviour or thermal calibration analysis, it may be appropriate to obtain this value through either manual or computer-aided calculation. This requires information relating to total glazing area, and values of solar transmittance, solar access factor, frame factor and average incidence factor. The solar aperture value can be used with the mean solar radiation data to calculate mean solar gains in order to adjust the measured raw power input. The corrected data can be used to calculate the solar corrected HLC through linear regression (Johnston et al., 2013).

Multiple regression analysis provides an alternative to simple linear regression techniques, and can be used to obtain solar aperture data. Solar gains and temperature values are regressed against raw power input in order to obtain the solar aperture, represented by the y intercept in the resultant statistical tables. As in the methods described previously, the solar aperture and solar radiation data is used to calculate solar gains, which are then added to the measured raw power input in order to obtain the total HLC through linear regression (Lowe *et al.*, 2007). Other influential independent factors, such as rainfall and wind velocity, can also be included in the multiple regression model in order to evaluate their effect on the HLC value.

In all of the methods described, the calculated solar aperture (R) value is applied to the solar radiation data in order to obtain a value in watts for solar gains to the property. The original value of measured power (Q) is then adjusted to reflect the true amount of electrical power required to heat the property, through addition of the solar gains value. This can be of particular importance when undertaking coheating tests in the autumn and spring months, when levels of solar irradiance could potentially be high and may significantly reduce the amount of energy required by heating to maintain a constant internal temperature (Miles Shenton *et al.*, 2010).

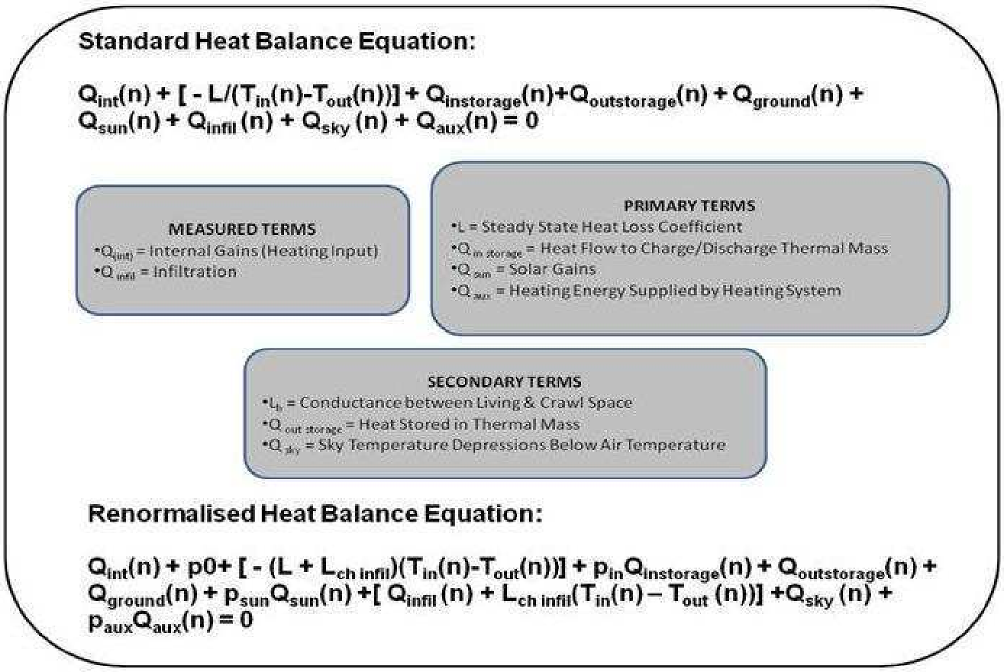
In a study of the reliability of coheating test measurements, Bauwens (2012) found that multiple regression provided the most reliable technique in order determine solar aperture. This was due to the ability of the statistical model to allow for experimental error in all of the variables. The work also provided evidence that the HLC generated as a result of the coheating test and multiple regression analysis was reliable, when it is assumed that S and ΔT are independent variables and a zero x/y intercept is used when plotting the data.

However, when setting the intercept at zero, this reflects a situation where there is no power input and no difference between external and internal temperatures. In reality, this relationship is not strictly linear due to factors such as thermal lag in the building fabric and night time heat dissipation/cooling strategies, which could mean that even when there is no power input, there may be a difference between internal and external temperatures (Bauwens et al., 2012).

An alternative methodology to the coheating test is The Primary and Secondary Terms Analysis and Renormalisation (PSTAR test). This is a slightly different whole house heat loss analytical technique, which utilises the steady state coheating test within its methodology. It was developed by the US National Energy Research Laboratory (formerly the Solar Energy Research Institute) in the 1980's, and detailed explanation of the process is given in publications by the institution (Subbarao, K. , 1998; Subbarao, K. *et al.*, 1989; Subbarao, K. *et al.*, 1998).

In simple terms, a model is constructed using energy simulation software and information collected relating to the building construction and location/position. Data relating to building permeability, heat flows through building elements and thermal bridging is obtained through experimentation, followed by a short term heating test and cooling down period. The data collected is used in linear regression techniques to renormalize the building heat flows within the original model developed for the building. Alongside total HLC and solar aperture values, the method also accounts for thermal mass effects (Carrillo *et al.*, 2009).

There are three types of 'term' defined within the methodology, as shown in Figure 2-16, which are used to realign the standard heat loss equation parameters into a renormalized form that represents the performance of the building under assessment.



Standard Heat Balance Equation:

$$Q_{int}(n) + [- L/(T_{in}(n)-T_{out}(n))] + Q_{instorage}(n)+Q_{outstorage}(n) + Q_{ground}(n) + Q_{sun}(n) + Q_{infil}(n) + Q_{sky}(n) + Q_{aux}(n) = 0$$

MEASURED TERMS

- $Q_{(int)}$ = Internal Gains (Heating Input)
- Q_{infil} = Infiltration

PRIMARY TERMS

- L = Steady State Heat Loss Coefficient
- $Q_{in\ storage}$ = Heat Flow to Charge/Discharge Thermal Mass
- Q_{sun} = Solar Gains
- Q_{aux} = Heating Energy Supplied by Heating System

SECONDARY TERMS

- L_{b} = Conductance between Living & Crawl Space
- $Q_{out\ storage}$ = Heat Stored in Thermal Mass
- Q_{sky} = Sky Temperature Depressions Below Air Temperature

Renormalised Heat Balance Equation:

$$Q_{int}(n) + p0+ [- (L + L_{ch\ infil})(T_{in}(n)-T_{out}(n))] + p_{in}Q_{instorage}(n) + Q_{outstorage}(n) + Q_{ground}(n) + p_{sun}Q_{sun}(n) +[Q_{infil}(n) + L_{ch\ infil}(T_{in}(n) - T_{out}(n))] +Q_{sky}(n) + p_{aux}Q_{aux}(n) = 0$$

Figure 2-16 – Summary of Key Terms and Equations in PSTAR Methodology
(Produced by Author Based on Palmer et al. (2011))

The renormalized parameters (represented by 'p') are those that commonly contribute to the lack of agreement between the building model and test results, and are calculated using statistical linear least squares fit analysis (linear regression) (Chun *et al.*, 1997). The test has been shown to be repeatable and predictable and to give reasonably accurate results (Burch *et al.*, 1989).

In a study undertaken to compare the PSTAR and steady state coheating test methodologies, a 30% difference between the HLC values calculated using each technique was noted (Palmer et al., 2011, p. 61). This was partly explained by differences in the state of the property tested due to a year-long interval between the two tests, but also due to the impact of changing thermal conditions that are taken into account in the PSTAR test and not in the coheating test. The research concluded that the coheating test provided a steady state HLC that has characteristics similar to that derived from models such as SAP, and therefore can be used to evaluate design/construction conformity and compliance. The PSTAR test HLC is more comparable to dynamic thermal modelling outputs, as it accounts for the effect of thermal mass.

Whilst it is acknowledged that the PSTAR testing methodology is rigorous and provides a good indication of whole house heat losses, the coheating test protocol has been selected for use in this research. This is largely because the majority of the studies completed in the field of housing performance in the UK have utilised this technique, and so there is more comparative data and analysis available relating to this method. It also provides a HLC value that can be used for comparison with steady state design stage outputs such as those derived from SAP.

2.3.3 Systems Analysis (MVHR)

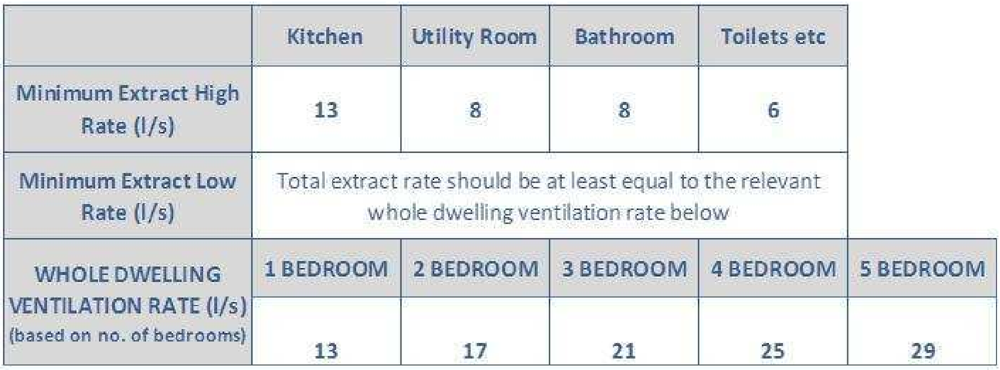
In order to achieve high levels of thermal performance and the upper levels of SAP ratings, many zero carbon homes may rely heavily on the integration of renewable energy systems and technologies (Kelly, S. et al., 2012). These could range from power generating systems, such as photovoltaic arrays and wind turbines, through to heating technologies such as air source or ground source heat pumps and combined heat and power systems. However, such innovations tend to be in addition to good fabric performance, and are considered after the fabric heat losses of a dwelling have been ascertained (Osmani et al., 2009).

A less visible and yet essential technology that is considered within the early stages of building energy modelling is the ventilation system. It is critical that air change rates are evaluated in order to ensure sufficient supply of clean air and adequate removal of stale air. Where background infiltration rates are minimal and a natural ventilation strategy is not feasible, a system such as a mechanically ventilated heat recovery (MVHR) system may be required. Analysis of systems performance within this study is therefore limited to MVHR, as the main scope of the work is to assess the thermal performance parameters within SAP, which is limited to ventilation strategy.

A suitably designed, installed and commissioned MVHR system is able to recover heat from extract air and use this to preheat supply air into a dwelling. It therefore has the capacity to enable energy savings, as offset against the power required to function (Banfill et al., 2011b). Air tightness is a fundamental requirement for efficient operation, as the control unit will be set to maintain a specified air change rate for a property. This is calculated in order to maintain a balanced environment, with no pressurisation or depressurisation effects that may lead to increased air movement through the building fabric (White et al., 2013).

The effectiveness of an MVHR system is directly dependent upon achieving the optimum fan and heat recovery unit efficiencies, balanced flow rates, and building airtightness (Banfill et al., 2011b). Correct installation and commissioning of an MVHR system is essential to ensure that it works efficiently, and provides the correct levels of supply and extract air to maintain a healthy living environment. The extract flow rate for a continuous ventilation system must comply with UK Building Regulations Part F requirements, as detailed in Table 2-2 (Department for Communities and Local Government (DCLG), 2010a, p. 19).

Table 2-2 - Building Regulations 2010 Part F Minimum Extract Ventilation Rates
Source: (Department for Communities and Local Government (DCLG), 2010a, p. 19)



	Kitchen	Utility Room	Bathroom	Toilets etc	
Minimum Extract High Rate (l/s)	13	8	8	6	
Minimum Extract Low Rate (l/s)	Total extract rate should be at least equal to the relevant whole dwelling ventilation rate below				
WHOLE DWELLING VENTILATION RATE (l/s) (based on no. of bedrooms)	1 BEDROOM	2 BEDROOM	3 BEDROOM	4 BEDROOM	5 BEDROOM
	13	17	21	25	29

The commissioning process requires assessment of system flow rates and balancing of the supply and extraction of air in a property. An anemometer is placed over each supply and extract vent, and adjustments made until the total dwelling supply and extract flow rates balance, whilst ensuring minimum acceptable air flows are retained in each individual room (Department for Communities and Local Government (DCLG), 2011c).

In terms of assessing the efficiency of the heat exchanger in the control unit, temperature efficiency is commonly used as a performance indicator (Nicholls, 2008), as defined in Equation 2-6 (Lowe et al., 1997, p. 35).

$$\eta_t = T_2 - T_1 / T_3 - T_1$$

Equation 2-6 - Temperature Efficiency of MVHR System (Lowe et al., 1997, p. 35)

Where:
η_t = *Temperature Efficiency of the MVHR System*
T_1 = *Temperature of Intake Air (°C)*
T_2 = *Temperature of Supply Air (°C)*
T_3 = *Temperature of Extract Air (°C)*

An additional assessment of system function can be obtained through use of the Coefficient of Performance (COP). This is a comparative measure of the heat output as compared to energy input and can be calculated using Equation 2-7 (Lowe et al., 1997, p. 36).

$$COP = (m_s C(T_2 - T_1)) / p$$

Equation 2-7 - Coefficient of Performance of MVHR System (Lowe et al., 1997, p. 36)

Where:
COP – Coefficient of Performance of MVHR Unit
Ms = Supply Mass Flow Rate (kg/s)
C = Specific Heat Capacity of Air (J/kgK)
T_1 = *Temperature of Intake Air (°C)*
T_2 = *Temperature of Supply Air (°C)*
P = total power input to system (W)

Assessment of both temperature efficiency and COP requires additional instrumentation to be installed, namely temperature probes or thermocouples within supply and extract ductwork and a power meter to monitor energy consumption of the MVHR control unit. In terms of evaluation of the resultant data, higher temperature efficiencies should occur as flow rates are reduced, but this can result in a lower COP being achieved (Lowe et al., 1997).

2.4 Conclusions

The area of building energy performance is complex and multidimensional, as demonstrated by the considerable amount of literature contained within this chapter. It can be seen that the materials and systems incorporated into a dwelling can have a significant impact on energy consumption and carbon emissions. In particular, designing and constructing an airtight building envelope should be of primary concern as it is the source of the majority of heat loss pathways in a property. This would appear to justify both the current Government focus on fabric first solutions, and the limitation of this study to evaluation of the thermal performance aspects of housing.

Within both design stage modelling techniques and post-construction coheating fabric testing, the HLC provides the primary measurement of whole house heat losses. Other building evaluation techniques, such as standard air pressurisation testing, thermal imaging and localised heat flow monitoring using heat flux sensors, can be used to isolate areas of poor performance which could impact upon the ability of the design stage prediction to correspond with as-built data.

Analysis of systems within this research project will be limited to the evaluation of MVHR performance. This is primarily due to the focus of this study on thermal performance and the first module of the SAP methodology. As explained in Section 2.2.2, ventilation strategy is the only factor included in initial stages of the assessment protocol that directly considers integrated systems.

Considerations such as sources of space and water heating, lighting, renewable fuel sources (biomass and combined heat and power), photovoltaics and solar thermal collectors are not assessed until after a satisfactory level of building fabric performance and selection of a suitable ventilation strategy has been established. The selected properties within this research both have MVHR systems installed, and so it has been possible to gain information as to their in-situ performance and the effect of mechanical ventilation on the whole house HLC.

The use of design stage models and post-construction testing methods enables the development of a comprehensive picture of the predicted and actual fabric performance of a dwelling. The HLC of a building can be derived as a direct output from analysis at both stages, and so provides a consistent indicator of thermal performance throughout the design and construction processes. This parameter will be central within this study, and will provide the basis for quantifiable interrogation of the accuracy and reliability of theoretical and measured performance data.

3 THE PERFORMANCE GAP

"I want to do everything to cut bills by making homes in this country the most energy efficient possible. From today government and industry will be working hand in hand to ensure new build homes live up to expectations, and drive energy bills down for consumers…I want to work with industry to improve standards and performance in practice."

March 2013 - Rt. Hon Don Foster MP Parliamentary Under-Secretary of State for Department for Communities and Local Government (2012) and Deputy Chief Whip (2013) (Zero Carbon Hub, 2013c, Web)

With the publication of such aspirations by senior ministers, there is little doubt that the UK Government has placed significant importance on the development of legislation, policy and supporting instruments in order to achieve the national targets of an 80% reduction in carbon emissions by 2050 and 20% decrease in energy demands by 2020. Buildings, including homes, have a major part to play in this ambition, as detailed in Chapter 1.

Failure for a home to deliver the expected levels of energy efficiency and carbon emissions could have potential consequences throughout the whole supply chain. It makes it difficult to model future national energy supply requirements with any certainty, may lead to complaints from purchasers of dwellings, decreases confidence in the construction industry, and ultimately undermines efforts being made to improve the performance of UK housing in general (Mhalas et al., 2013).

However, a growing body of research is emerging that suggests that the theoretical designed and modelled levels of energy demand and carbon emissions of buildings are not generally being realised in practise (Baker, 2011; Banfill et al., 2011a; Banfill et al., 2011b; Banfill *et al.*, 2012; Bell, M. et al., 1998; Bell, M. *et al.*, 2010a; Bordass et al., 2004; Bordass et al., 2001; Brown *et al.*, 2011; Building Research Establishment (BRE), 2005; Demanuele et al., 2010; Good Homes Alliance (GHA), 2011a; Johnston et al., 2004; Lowe et al., 1997; Lowe et al., 2007; Rye et al., 2012; Stephen, 1998, 2000; Warren et al., 1980;

Webster, 1987; Wingfield, J. et al., 2006; Wingfield, J. et al., 2010; Wingfield, J. et al., 2011a; Wingfield, J. *et al.*, 2007; Wingfield, J. *et al.*, 2008; Wingfield, J. *et al.*, 2009; Wood, C., 2013; Zero Carbon Hub, 2010, 2013a; Zero Carbon Hub & NHBC Foundation, 2013).

The physical process of building homes is an obvious area where faults may arise, and criticism of the efficiency and structure of the UK construction industry is not a new phenomenon. Indeed, over 15 years ago, Latham (1994) and Egan (1998) identified that the construction sector was characterised by an inherent resistance to change and improvement. Over a decade later, Ryghaug (2009) reported that these issues still exist, with conservative attitudes and lack of innovation, alongside a fixation on capital costs (those borne by the developer rather than the end-user), preventing widespread production of more sustainable buildings.

When buildings do underperform, it would be unfair to place the entire blame on those responsible for constructing the final product. Doran (2000) suggests that there are two key factors that can cause underprediction of energy demands and emissions; firstly, design models may not represent building systems accurately, and secondly that a building may fail to be constructed as specified in the design. This view was supported in responses received from industry to the 2012 Consultation relating to Building Regulations changes, which suggested that procurement issues, inaccuracies in design stage models and overestimation of performance levels in product and system information could also contribute to an apparent failure to meet expected energy and carbon savings (Department for Communities and Local Government (DCLG), 2012b).

In can be seen that the underperformance of a dwelling is a potentially complex matter, and could be attributable to any number of interlinking contributing factors. It is possible to evaluate the divergence between expected and actual energy performance of a property, through comparison of data obtained from design stage assessments and post construction experimentation and monitoring. The remainder of this chapter will outline research that has been undertaken in this area, and reflect upon factors that can lead to the apparent gap that appears to exist between design stage and as-built data, focussing on thermal performance.

3.1 Evidence and Contributing Factors

As energy efficiency in housing has become a matter of greater concern, the amount of research being undertaken in this area has also increased. This relates not only to the design stage assessment, but also to the post-construction monitoring of building performance. Indeed, investment and funding is becoming more widespread in order to investigate the 'significant discrepancy between the predicted energy performance of a building (and hence it's CO_2 emissions) and its performance in practise' (Technology Strategy Board, 2011, Web).

Standardised design stage assessments (through use of SAP 2009) and the emergence of post construction testing techniques are being increasingly utilised in order to assess the performance of dwellings (De Meulenaer *et al.*, 2005). However, such detailed monitoring and evaluation studies are largely confined to houses built specifically for research or demonstration projects (such as the BRE Innovation Park (http://www.bre.co.uk/innovationpark/) and the Creative Energy Homes (CEH) at the University of Nottingham (http://www.nottingham.ac.uk/creative-energy-homes/creative-energy-homes.aspx)). Other projects involve the construction or modernisation of homes in conjunction with developers, house builders and other external parties, which are subsequently inhabited. This leads to a limited amount of information being publicly available for scrutiny, due to issues of confidentiality and sensitivity of the data.

In order to gain a deeper understanding of how buildings perform once built as compared to the design stage, a number of key projects have been undertaken in the UK as shown in Figure 3-1. The interim findings of an on-going 4 year £8 million Technology Strategy Board Building Performance Evaluation project (Technology Strategy Board (TSB), 2013) demonstrate that, of the 13 properties initially examined, nine did not meet their design-stage thermal performance levels, and the mean airtightness level measured in-situ was twice that calculated based on theoretical data (Colmer, 2013). A recent Government-led project to evaluate the contributing factors to the underperformance of homes also revealed that design-stage models and post-construction testing require improvement in order to deliver a sound estimation of housing performance (Zero Carbon Hub, 2013a).

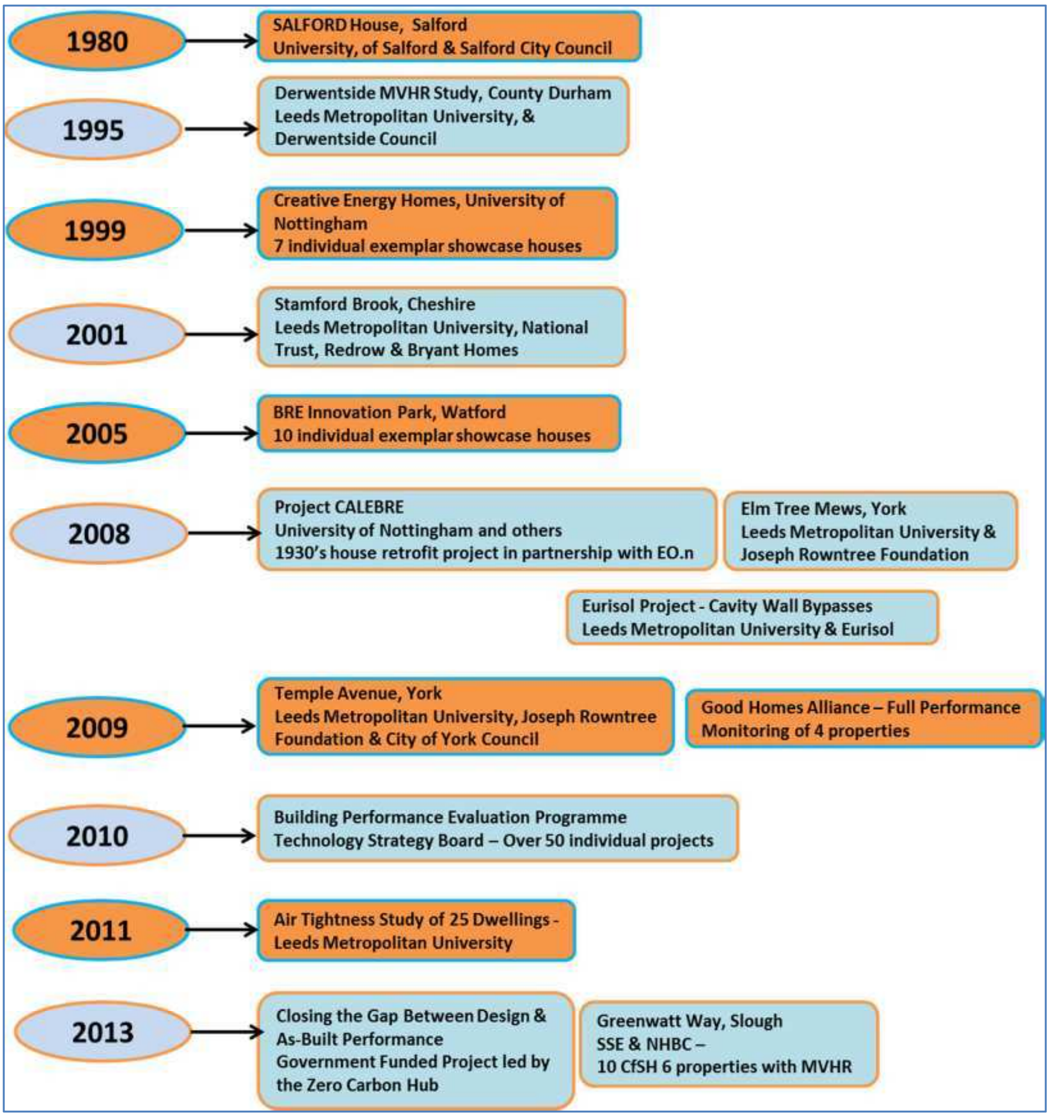


Figure 3-1 - Timeline of Key Research Relating to Building Thermal Performance (Produced by Author)

The National House Building Council (NHBC) and Zero Carbon Hub (National House Building Council (NHBC), 2012; Zero Carbon Hub, 2013d) have suggested several key areas that could be contributing to the discrepancy between designed and as-built performance, namely:

- Modelling – is SAP and the underlying calculation methodology sufficiently accurate?
- Input Procedures – could human error, inaccurate data or incorrect data entry protocols have an impact?
- Building Design – is design information complete and is the design simple and not challenging in terms of construction?
- The Construction Process – is a suitably skilled workforce available? Are substituted products of the same standard as the original specification?
- Performance of Individual Materials and Systems– are laboratory test results for materials and systems being realised in practice?
- Post-construction Evaluation Techniques – are the methods used to test various aspects of dwellings after construction robust and reliable?

The following sections will provide an overview of the evidence to support the contribution of many of these aspects to the underperformance of dwellings. This will be limited to matters relating to fabric performance and will not consider occupant behaviour, due to the focus of this study being concerned with building thermal efficiency.

As Bell (2013) suggests, it is commonplace to criticise end-users when dwellings use more energy than expected, but this blame may be misplaced if the building envelope and integrated technology is not performing to base-line design-stage assessments or standards prescribed by the manufacturer.

3.1.1 Building Air Tightness

As described in Section 2.3.1, currently an air pressurisation test provides the sole mandatory quantitative measure of compliance of new-build housing with minimum Building Regulations Part L standards. The value measured on-site is inputted into the SAP model to obtain a true value of the DER. As such, whilst public datasets relating to the results of the test are not widely available, this still forms the most comprehensive basis upon which to compare predicted and as-built performance of housing. The minimum acceptable standard for background infiltration is currently 10 $m^3/(h.m^2)$ @ 50Pa, which is often achieved in practise by new build housing. Figure 3-2 (Zero Carbon Hub, 2010, p. 14) demonstrates the shift in compliance with this target, with data from post 2002 (Grigg), 2005 (Stamford Brook) and post-2006 (NHBC).

There is a definite improvement in building airtightness levels after introduction of mandatory air pressure testing in 2006, from 33% to 3% of houses tested not meeting the minimum acceptable value. However, whilst compliance with this standard is now being widely achieved, dwellings will need to perform beyond this minimum (CfSH Level 3) in order to achieve the high levels of thermal efficiency required to meet zero carbon performance.

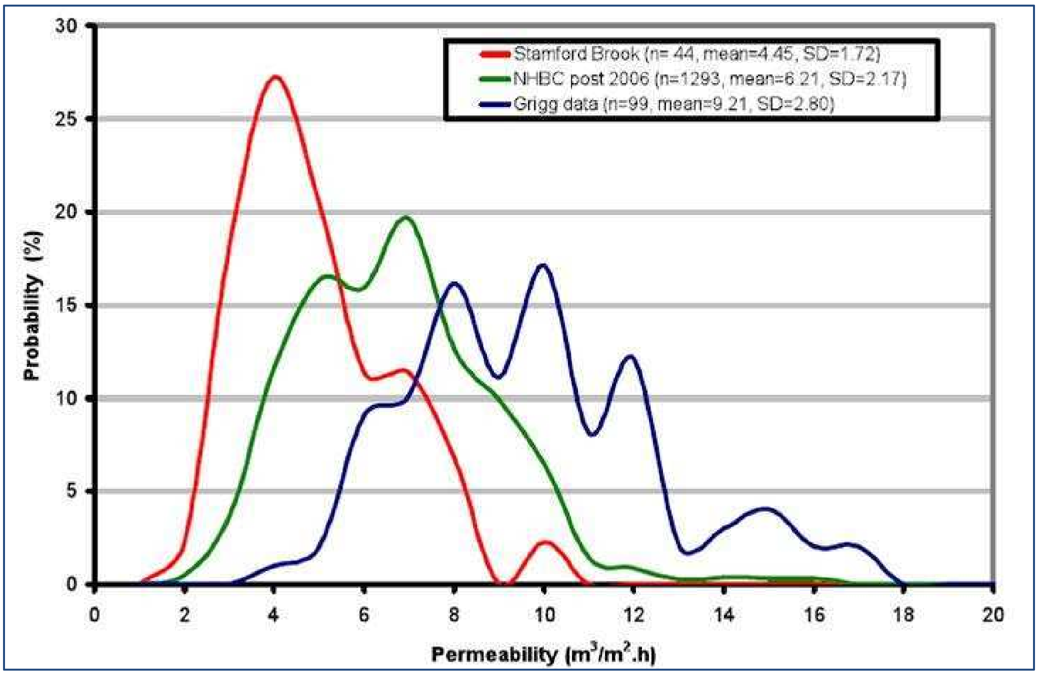


Figure 3-2 – Mean Air Permeability Distributions
Source: (Zero Carbon Hub, 2010, p. 14)

As such, while a property may achieve compliance with Building Regulations standards, it could still underperform when comparison is made between the design-stage and as-built background infiltration rates. Initial results from 13 properties included in the TSB research programme show a measured mean air pressure test result of 4.1 $m^3/(h.m^2)$. When compared to the design stage predicted mean of $2.1m^3/(h.m^2)$, it can be seen that there is significant underperformance, largely due to optimistic data being inputted during the modelling process (Colmer, 2013, p. 9).

In a detailed investigation of 44 houses during the Stamford Brook Project at Altrincham, Cheshire, the mean air tightness value was calculated to be 4.5 $m^3/(h.m^2)$ @ 50Pa (Wingfield, J. et al., 2011b, p. x). This is clearly well within the limits of Building Regulations compliance, and also compares favourably with several other studies which recorded mean values of between 6.43 and 11.1 $m^3/(h.m^2)$ @ 50Pa (ARUP, 2003; Grigg, 2004; Johnston *et al.*, 2006).

However, the mean value of airtightness conceals the true performance of the dwellings under evaluation. Figure 3-3 (Wingfield, J. et al., 2011b, p. 41) shows the distribution of air tightness results across the 44 dwellings at Stamford Brook. It can be seen that the data varies from approximately 1.5 to 10 $m^3/(h.m^2)$. The design airtightness was set at 5 $m^3/(h.m^2)$, and, whilst the mean value showed an improvement upon this, almost one third of the 44 properties did not meet this level of airtightness (Wingfield, J. et al., 2011b, p. 41).

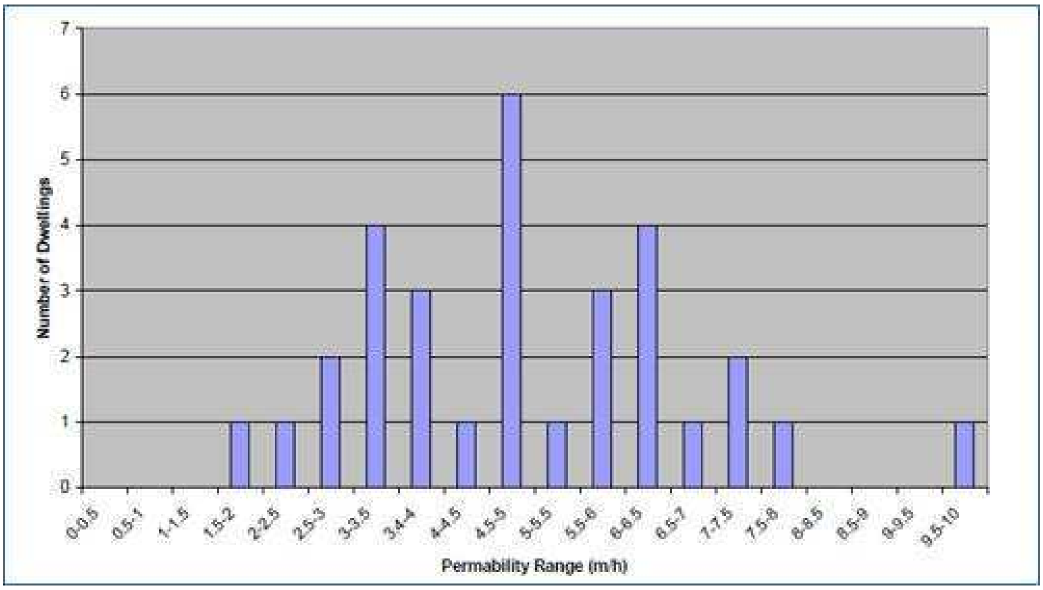


Figure 3-3 - Distribution of Air Tightness Values at Stamford Brook
Source: (Wingfield, J. et al., 2006, p. 41)

This situation is not uncommon, as demonstrated in results reported by other studies. The BedZed development of 82 mixed type dwelling, located in Hackbridge, London and designed to perform to net zero carbon levels, had airtightness results three times greater than the design air permeability target of 2 $m^3/(h.m^2)$ (ARUP, 2003, p. 5 & 11). At Elm Tree Mews, a project situated in York involving 6 dwellings built to meet CfSH Level 4 standards, the mean airtightness value achieved was 7 $m^3/(h.m^2)$, over twice the design stage calculation of 3 $m^3/(h.m^2)$ (Wingfield, J. et al., 2011a, pp. 13, 27 & 28).

All of these examples demonstrate that a minimum airtightness compliance target of 10 $m^3/(h.m^2)$ is achievable, and is improved upon in many cases. However, this could be disguising a greater issue, concerning the failure of constructed dwellings to meet design stage air tightness values. Where research has allowed, investigation using thermal imagery has highlighted a number of key areas that could contribute to the divergence in performance. These include (Johnston et al., 2006; Wingfield, J. et al., 2011b):

- Complexity of design details and the continuity of the air barrier;
- Lack of attention to junctions between walls and ceilings;
- Poor seal to service penetrations;
- Poor seal around windows and doors; and
- Integration of trickle vents.

The observed defects outlined above correspond largely with those identified as key air leakage pathways in Building Regulations guidance and best practise documents. The general advice given is that the design should incorporate a continuous barrier to air movement that maintains constant contact with the insulative layer (Department for Communities and Local Government (DCLG), 2010d). Government departments and the BRE provide further guidance for achieving air tightness, as follows (Department for Environment Food and Rural Affairs (DEFRA), 2001; Stephen, 2000; Stevenson et al., 2008):

- Avoid complex detailing to achieve an airtight envelope;
- Avoid designs that may be difficult to construct;
- Pay attention to joints between building components;
- Carefully integrate components and openings in elements;
- Seal all service penetrations through the building envelope and elements;
- Close off all ducts at all open ends;

- Apply draught proofing measures to loft hatches, windows and doors; and
- Ensure attention is paid to less obvious sources of air leakage, such as behind fixings and cupboards.

Whilst the construction of a building may generate areas of unaccounted air leakage, the design stage model could also contribute to the apparent lack of as-built performance. Within the SAP methodology, there are two ways in which the background infiltration rate of a building can be calculated. The first is based upon a series of inputs relating to:

- Number of chimneys, open flues, intermittent fans, passive vents and flueless gas fires;
- Number of storeys in the dwelling;
- Type of construction (steel frame, timber frame or masonry);
- Presence of sealed or unsealed wooden floors;
- Presence of a draught lobby; and
- Percentage of windows and doors draught stripped.

If this approach is used, standardised inputs are used to calculate infiltration rate based upon the data entered for each parameter. This provides a rough indication of the infiltration rate, before a factor is applied to reflect the number of sheltered sides to the property and ventilation strategy is taken into account.

Alternatively, an air pressure test result (assumed or measured) can be used to calculate infiltration. The value from the test certificate can be entered directly into the model, but has to be converted from infiltration at 50pa to an operational infiltration value. Sherman (1987), developed a rule-of thumb equation in order to make this conversion, as shown in Equation 3-1 (Jones et al., 2012, p. 1):

$V_1 = V_{50} / N$

Equation 3-1 – Simplified Sherman Leakage -Infiltration Ratio (Jones et al., 2012, p. 1)

Where:
V_1 *= Operational Infiltration Rate* (m^3/s)
V_{50} *=Air Leakage Value from Air Pressure Test* (m^3/s)
N = a nominal value

In practise, a value of 20 is most often used for *N*, assuming a linear relationship between the q50 test result and annual infiltration rates (Jones 2013). This converts the q50 data into units of ACH relevant in ambient environmental conditions. However, Sherman also developed a series of adjustments in order to account for dwelling height, shelter/exposure, type and size of air leakage pathways, and environmental factors (Berge, 2011), as detailed in Equation 3.2 (Minch, 2011, p. 7).

$$V_1 = \frac{V_{50}}{(C x H x S x L)}$$

Equation 3-2 – Detailed Sherman Leakage -Infiltration Ratio (Minch, 2011, p. 7)

Where:

V_1 *= Operational Infiltration Rate* (m^3/s)
V_{50} *=Air Leakage Value from Air Pressure Test* (m^3/s)
C = Leakage Infiltration Ratio (Climate Dependent)
H = Height Correction Factor
S = Wind Shielding Correction Factor
L = Leakiness Correction Factor

The SAP methodology does not expressly employ the latter stages of Sherman's calculation technique. Within the SAP methodology, the 'divide by 20 rule' is used to obtain a baseline measure of infiltration, which is then modified via data inputs to reflect the factors outlined previously (chimneys through to ventilation strategy) before application of an adjustment is made for level of exposure/shelter (BRE 2013, DECC 2011).

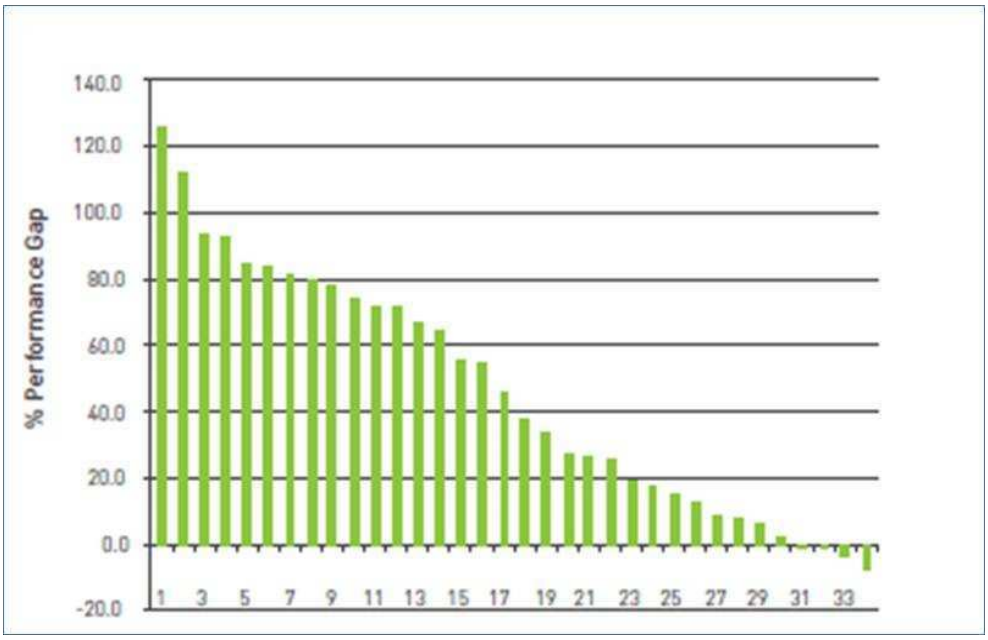
Therefore, there is some concern as to the ability of the simplified equation to accurately reflect background infiltration rates in energy models, although research in this area is currently limited (Jones et al., 2012). Whilst such an approach could be criticised for being imprecise, it does avoid the requirement for detailed dynamic modelling each time a building design is altered (Sherman, M., 1998). Further investigation into the sensitivity of HLC values to this parameter will form part of this research.

3.1.2 Fabric Heat Losses

As discussed in Section 2.3.2, the coheating test methodology is currently the most commonly used technique in the UK to assess the as-built HLC in order to calculate whole house fabric heat losses. Much of the work undertaken in this field has been limited to specific research projects, due to length of time needed to obtain reliable data from the tests, and the requirement for access to unoccupied dwellings whilst the experiment is in progress (Department for Communities and Local Government (DCLG), 2011a).

The extent of publicly available coheating data is not extensive, but the number of tests that are being undertaken is increasing due to the recognised need to investigate post-construction performance. The data shown in Figure 3-4 (Stafford, A. et al., 2012, p. 8 & 9) is some of the most comprehensive published to date, and relates to tests undertaken by Leeds Metropolitan University.

It can be seen that the majority of the test properties showed failure to meet the design stage calculated HLC, with the discrepancy against measured HLC values ranging from approximately 5% to 125% over predicted data. Bell (2013) later reported on the work completed by Leeds Metropolitan University, indicating that the number of coheating tests completed had exceeded 50 in number, and the full sample showed a similar range of design stage/post-construction HLC disparities as that displayed in Figure 3-4.



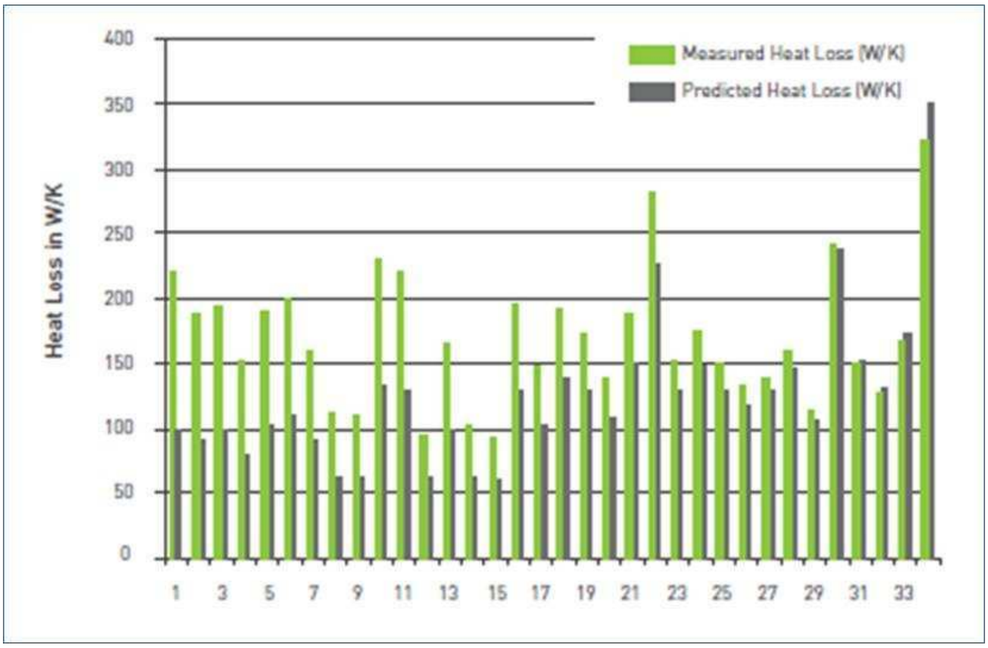


Figure 3-4 - Measured and Predicted Whole House Heat Loss (Difference in % Terms & Absolute W/K Values)
Source: (Stafford, A. et al., 2012, p. 8 & 9)

With regard to the four dwellings that showed an improvement in measured HLC when compared with expected values, Stafford (2012) does include a word of caution. Two of the tests were undertaken on existing dwellings, and so confidence in the predicted HLC is not high due to a large amount of assumed data being included in the SAP model. The other two highly performing houses achieved these results after intervention to rectify observed heat loss pathways, and so are not truly representative of the level of performance gap originally observed.

Thirteen properties included in the initial analysis of the TSB Building Performance Evaluation Project displayed measured HLC values ranging from 41 W/K to 221 W/K, with the lowest values observed in PassivHaus projects. Whilst four of the dwellings had HLC values that were lower than the design stage calculation, the mean measured HLC value was 98.8 W/K as compared to a predicted mean of 83.6 W/K. Even this value disguises the true performance gap of some of the properties, with a difference of up to 60% being recorded in one case (Colmer, 2013, p. 8).

Other work exists that strengthens the evidence of a gap between designed and as-built fabric performance. A study of four homes (Good Homes Alliance (GHA), 2011a, p. 17), all designed to achieve CfSH Level 4, or higher, showed a gap of between -1% (for a CfSH Level 5 home) up to +29% (for a timber framed CfSH level 4 property). Johnston (2013, p. 1) presents evidence based on three separate PassivHaus compliant dwellings, where the measured HLC is greater than the predicted HLC in all cases, but the difference is only a matter of 8 W/K. Guerra-Santin (2013, p. 36) observed an increase in measured HLC above design-stage HLC values for two PassivHaus compliant properties, with predicted and actual values being 53.3 W/K vs 62 W/K and 34.1 W/K vs 45 W/K for each dwelling respectively.

It should be noted that the measured heat losses in both of these studies were actually still very low, so in absolute terms the maximum difference between the modelled and coheating test data was not as large as for some of the properties with lower percentage gap results reported in the study by Stafford (2012). To enable fairer comparison between properties, it is possible to use a value of heat loss parameter (HLP). This essentially takes the HLC value divided by dwelling floor area in order to calculate a normalised effective whole house u-value measured in W/m^{2}K (Sutton *et al.*, 2012). However, few studies to date have presented their results based upon this indicator of performance.

In some cases, the findings from the coheating test have prompted further investigation as to the lack of agreement between the design stage and post construction HLC values. At Elm Tree Mews, the design stage HLC was calculated to be 127.5 W/K, yet the measured value was over 50% higher than this at 196.4 W/K, and when ventilation losses were discounted, the fabric heat loss only divergence was almost 70% (Wingfield, J. et al., 2011a, p. 33). An analysis of factors contributing to the performance gap revealed that there were several factors influencing either the predicted or measured HLC, namely (Bell, M. *et al.*, 2010b, p. 2):

- 23% contribution: underestimation at design stage of extent of timber used in roof and wall construction;
- 25% contribution: inaccurate calculation of thermal bridge effects;
- 30% contribution: lack of awareness of party wall thermal bypass mechanism;
- 21% contribution: change of window supplier and no account taken of change in specification.

A similar investigation was also undertaken relating to the data from the Stamford Brook project. Six dwellings were tested, and the difference between calculated and measured HLC ranged from 75% - 103% (Wingfield, J. et al., 2008, p. 40). Two of the properties were analysed closely, revealing a 46 W/K absolute disparity between the two values. Approximately 43% of this unexpected heat loss was attributed to the presence of a party wall thermal bypass mechanism (identified through use of thermal imaging), whilst one third was considered to be due to complex joints in the building construction and consequent increases in thermal bridging calculations. The remaining additional heat loss could not be accounted for, but could be due to background ventilation losses and air movement in the building fabric (Wingfield, J. et al., 2011b, p. 45).

The research undertaken in both of these studies has been invaluable in isolating the effects of a party wall bypass as a key heat loss pathway. The mechanism was observed to be attributable to air movement in the cavity, caused by stack effects and conduction, and external wind effects around the building. Conduction occurs as air moves through the party wall into the cavity from heated living areas, and the warm air then moves upwards in the cavity and disperses into the roof space (Lowe et al., 2007). Figure 3-5 illustrates this concept (Wingfield, J. et al., 2007, p. 6).

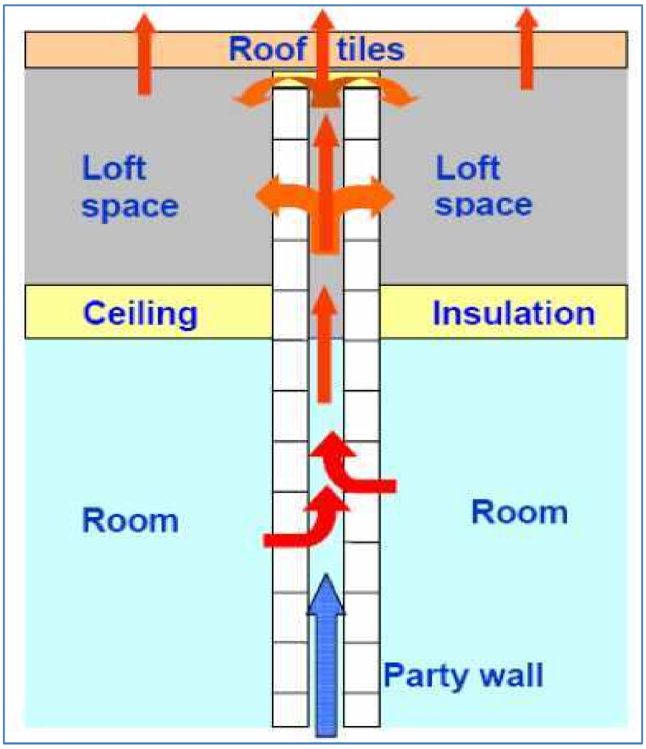


Figure 3-5 - Schematic Showing Cavity Wall Thermal Bypass Mechanism
Source Data: (Wingfield, J. et al., 2007, p. 6)

Whilst the possible presence of this mechanism had been acknowledged previously (Harrje *et al.*, 1985; Siviour, J. B., 1994), the Stamford Brook project provided an opportunity to gain full quantitative data in order to understand it further. In masonry dwellings, the effect of the bypass resulted in a measured fabric HLC that was almost twice the magnitude of the design stage value, although this was mitigated through use of an insulated sock placed at the top of the party wall cavity (Wingfield, J. et al., 2009). The timber framed dwellings showed a difference of up to 12% between predicted and actual HLC data, which was largely eliminated when the party wall was filled (Wingfield, J. et al., 2010, p. 17).

The findings were of significance, as at the time the conventions in the effective versions of SAP and Building Regulations Part L (SAP 2005 and Part L 2001) did not recognise heat losses through the party wall. However, the evidence was presented and amendments were subsequently made to SAP 2009 and Building Regulations Part L 2006 to allow input and calculation of a party wall u-value rather than a blanket assumed value of zero, alongside enforced additional requirements for party wall design and construction standards (Stafford, A. et al., 2012).

In addition to party wall u-value inaccuracies, the performance of building elements such as envelope materials, windows and doors can also impact upon the level of heat losses through the building fabric. Investigation relating to in-situ u-value measurements has been on-going for a number of years, with deviations in construction u-values ranging from 30% to over 160% as compared to that stated by the manufacturer and therefore used in design models (Siviour, J. B., 1994; Wingfield, J. et al., 2011a; Wingfield, J. et al., 2008; Zero Carbon Hub, 2013a).

Baker (2011) undertook in-situ u-value measurements on 57 different wall constructions, utilising heat flux sensors to measure heat flow through the material under consideration and temperature sensors to monitor internal and external temperatures. The study found that 44% were lower, 42% were approximately equal to, and 14% were higher than, the calculated value (Baker, 2011, p. 24). Doran (2000) examined 29 separate building elements in order to assess the standard protocols for calculating u-values (Building Standards Institute (BSI), 2008a) and reasons for divergence between calculated and measured performance. It was observed that the calculation methodology underestimated heat losses by up to approximately 30% (Doran, 2000, p. 25). Error sources in the testing equipment and process included:

- 5% - Heat flow meter calibration issues;
- 5% - Thermal storage effects;
- 2% - Physical in-situ use;
- 3% - Accuracy of temperature difference related to data logging resolution;
- 10% - Repeatability and reliability of achieving good thermal contact between sensor and element under investigation.

The study concluded that a total random error of 13% could be affecting each individual u-value measurement, which is not an insignificant level of uncertainty (Doran, 2000, p. 82). In addition, concern has been raised that the lack of agreement between the two values could be compounded by poor workmanship, as the design u-value is based on tests undertaken in laboratory conditions rather than following installation in a dwelling, and so no account is made for gaps in insulation layers or thermal bridge effects (Zero Carbon Hub, 2013b).

Substitution of products in the final building construction with no later adjustment of details made in the model has also been identified as a point of concern (Dowson et al., 2012). Construction type can also affect the reliability of data, with timber framed buildings showing closer agreement between the designed and construction u-values than more traditional types of construction (Doran, 2000; Hens *et al.*, 2007). Whilst Guerra-Santin (2013) observed agreement between design and measured u-values, the question was raised as to how useful post construction testing of u-values would be if the fault does lie in design stage calculations, as this would be difficult to remedy once the dwelling is constructed.

Whilst post-construction testing techniques such as elemental u-value analysis and coheating tests can be invaluable in terms of evaluating key indicators of thermal performance, there are also limitations to their widespread use. As outlined in Section 2.3.2, the coheating test requires there to be a relatively large temperature difference between the inside and outside of a dwelling, which currently limits the testing period in the UK to the winter months (National Physical Laboratory (NPL), 2012). The effects of solar radiation on test results also needs to be considered, which again could mean that tests undertaken in the summertime may not provide reliable data.

This raises questions over the suitability of the procedure for wide-scale testing as standard, as the completion of developments is not limited to the same time periods as the coheating test methodology. Therefore, it would potentially not be feasible to use the process as it currently stands due to the impact it would have on the supply chain and workflow (Zero Carbon Hub, 2010).

Concerns have also been raised over the ability of existing whole house and elemental thermal performance tests to deliver consistently reliable data (Wingfield, J. et al., 2011b; Zero Carbon Hub, 2013a). The BRE undertook an extensive programme of research, in which coheating tests were undertaken consecutively by seven different project partners on a single property, whilst an adjacent identical dwelling was coheated continuously using a consistent technique and equipment set-up. The aim of the study was to investigate the impact of variations in coheating test methodology on the outcomes of the experiment.

The main conclusion from the work was that, while results did differ due to slightly different practical approaches, the analysis and interpretation of output data presented a more significant area of divergence (National House Building Council (NHBC) Foundation, 2013) This finding agreed with previous work, which observed that a lack of standardisation in approaches to coheating test data analysis, mainly in relation to methods employed to make adjustments for solar gains and the treatment of background infiltration rates, could lead to high variances in HLC data (Sutton et al., 2012).

3.1.3 Installed Systems – MVHR

With an increased design focus on air tightness to achieve energy efficiency and carbon reductions, it is probable that the use of MVHR systems will begin to replace more traditional background infiltration and natural ventilation strategies. It is essential to obtain a minimum whole house background ventilation rate of between 0.5 and 1.0 ACH in order to maintain a healthy indoor environment (Department for Environment Transport & the Regions (DETR), 2005, p. 4).

Concern has been raised regarding an apparent underperformance and the limited research that has been undertaken into the correct application of this type of technology and the factors that can prevent it from functioning efficiently (Zero Carbon Hub, 2012c). It has been recognised that MVHR systems need to be designed and installed correctly (National House Building Council (NHBC), 2013), yet the limited number of studies that have been undertaken in this area show that this is not always the case (Good Homes Alliance (GHA), 2011b).

In a study of two PassivHaus compliant dwellings, several issues were identified relating to the MVHR installation, such as incorrect positioning of the control unit and ductwork (Guerra-Santin et al., 2013). A study of five CfSH Level 4 homes also found similar issues. Evaluation showed that the MVHR air extract rate did not meet Building Regulations Part F minimum standards in any of the cases, and only one of the systems was correctly balanced at all fan speeds. In addition, the heat recovery temperature efficiency was measured to be half that stated by the manufacturer (maximum value of 47% compared to manufacturer literature which indicated 89% efficiency) (Haynes, 2013, p. 46).

Recent work involving the installation of MVHR system in 10 CfSH Level 6 properties at Greenwatt Way, Chalvey, Slough, revealed a number of areas where installation and commissioning was not of a satisfactory standard. The system throughput rate was specified by the designer and manufacturer as being 29 l/s in all cases, but measured data showed values ranging from 13 l/s to 33 l/s, depending on dwelling type (Dengel *et al.*, 2013, p. 19). Power consumption of the units was found to be high, due to incorrect humidity and temperature settings within the system causing them to operate almost constantly at boost levels. Low insulation levels, poor siting of ductwork and outlets, and inexperience/lack of communication between the design and installation teams, all led to low levels of measured efficiency and performance (Dengel et al., 2013).

A detailed evaluation of MVHR systems retro-fitted into 12 Local Authority dwellings at Derwentside, County Durham, discovered a number of deviations from the intentions of the designer and manufacturer as compared to the fitted systems. The systems were found to be unbalanced, with measured data showing examples of both oversupply of fresh air and excessive extract rates. All of the units were found to have a whole house air throughput rate below the 0.5 ACH stated by the manufacturer (Lowe et al., 1997, p. 33). One of the properties was found to have a temperature efficiency of only 41%, less than half of that included in manufacturer literature, and Coefficient of Performance values ranged between 2.5 and 11 (Lowe et al., 1997).

The limited case study examples clearly illustrate the impact that poor installation and commissioning can have on MVHR system performance. In order to attempt to rectify the issues relating to the design, installation and commissioning of MVHR systems, the NHBC has developed a best practise guide that will be effective from 2014 (National House Building Council (NHBC), 2013).

However, whilst the publication of minimum standards may result in an increase in MVHR performance, the design stage SAP methodology could still undermine this initiative. Values relating to system performance, such as specific fan power and efficiency in-use factors, and details held in the supporting database of information relating to different systems, are based on specifications and data provided by manufacturers that is obtained in optimum laboratory conditions (Todd, 2001). As found in a study by the BRE, in the system under consideration the fan power was given by the manufacturer as 25%, but measured values after installation were found to be up to 66% greater than this (Zero Carbon Hub & NHBC Foundation, 2013, p. 40).

Another assumption within the SAP methodology that could be questioned relates to ventilation calculation, where a default value of 0.5 ACH is used with respect to air throughput through the mechanical system, in addition to background ventilation. The AECB (2009) studied the use of SAP methodology as applied to different theoretical ventilation strategies in a model constructed for a PassivHaus compliant dwelling. The data showed that the assumption of 0.5 ACH appears to penalise the use of MVHR, as the model uses the same baseline ventilation rate for MVHR and natural ventilation simulations. In a true situation this would not generally be the case (Crilly *et al.*, 2012). In addition, air throughput values can vary once systems are installed and commissioned, and so the assumption of a fixed rate in the model could result in an apparent performance gap that is actually being caused by incorrect input data (Lowe et al., 1997).

3.2 The Role of Design Stage Assessments

Concerns regarding the appropriateness and ability of the SAP methodology to produce an accurate indication of building energy demand and carbon emissions have been expressed for a number of years. Bordass (2001, p. 115) recognises that often there is “very little connection between the values that tend to be found in completed buildings and the assumptions made in design estimation and computer models”.

In an interim publication resulting from an on-going study into the performance gap, it was recognised that, whilst the building physics base within SAP is valid, there is still a need to investigate the inputs and assumptions within the model in order to improve the accuracy of output data (Zero Carbon Hub, 2013a). Consistency and quality control in use of modelling software and full integration into the design process are also areas which could be targeted in order to improve the reliability of results (Raslan *et al.*, 2009).

Several studies have highlighted that quality of input data, alongside equations, calculations and assumptions embedded within the SAP methodology, can have a significant effect on the outputs of the model. Indeed, it is becoming more accepted that inaccurate assessment of ventilation and thermal mass could be key contributing factors in the discrepancy between designed and as built performance, which is then compounded by further technological issues (MacDonald, 2002; Menezes et al., 2012; Quigley, 2010; Zero Carbon Hub, 2013a). The remainder of this section will evaluate the main areas where error and underlying assumptions and calculations could have a large impact on the calculated HLC value.

3.2.1 Data Inputs

"You can get worse answers if you collect more data than if you just make reasonable default assumptions. These detailed models are precise but not accurate — so they miss the target. The simplified models are accurate but not precise. It is better to be approximately right than precisely wrong" (Holladay, 2012, p. Web). Whether this stance is universally accepted or not, it does offer an alternative viewpoint to the more commonplace contention that assumptions within energy models are not useful in predicting energy consumption.

The SAP methodology consists of the front-end worksheet where data is inputted, supported by a series of Appendices and Tables containing further information to aid in the population of the required fields. These are comprehensive and enable estimations to be made in the absence of actual design-stage data, and are included in the assessment manual (Department of Energy & Climate Change (DECC), 2011).

The manual also enables verification of input parameters, which is useful when using Government approved computer programs, such as SAPPER (developed by RUSFA – www.rusfa.com) or Plan Assessor National Home Energy Rating Software (NHER by National Energy Services (NES) – http://www.nesltd.co.uk/), in which some values are automatically selected (i.e. not visible) depending on options and details inserted into the software interface. Figure 3-6 identifies those that are most relevant to building thermal performance.

SAP – Relevant Tables & Appendices

- Table 1e – Heat Capacities for Common Constructions
- Table 1f - Thermal Mass Parameter
- Table 4g – Default Specific Heat Capacity for MVHR system
- Table 4h – In-Use Factors for MVHR Systems
- Table 6b – Transmittance Factors for Glazing
- Table 6c – Frame Factors for Windows & Doors
- Table 6d – Solar & Light Access Factors
- Table 6e - Default U-Values for Windows & Doors
- Table 7 – Wind Speed (m/s)
- Table 8 – Mean External Temperature (°C)
- Appendix K – Thermal Bridging

Figure 3-6 – SAP Methodology - Relevant Supporting Tables and Appendices (Produced by Author)

At the design stage of a project, a number of assumptions may be made relating to the values that are inputted, based on the experience of the designer in terms of materials and systems that they are familiar with using. The fragmented nature of the process may mean that full consideration is not given to the interaction between fabric efficiency and building services and technology. This could result in poor overall integration of these aspects at the design stage, and later in works programmes, leading to a subsequent adverse effect on performance (Carbon Trust, 2012).

The use of assumptions also relies heavily on the competency and knowledge of the person undertaking the assessment, as what may seem a simple variable in, for example, orientation or number of sheltered sides of a dwelling, could impact significantly on later calculations embedded within the model (Kavgic et al., 2010). Such factors could lead to inadequate predictions of energy demands and carbon emissions, which remain untested at regular intervals throughout the design/construction process and are finally manifested in apparent post-completion underperformance (Carbon Trust, 2012; Menezes et al., 2012; Zero Carbon Hub, 2010, 2013a).

It would seem that assumptions are useful in terms of making an initial assessment of probable energy demands and carbon emissions, but the model should be amended and updated as design details become more robust. Whilst much of the data contained in the SAP tables and appendices is helpful in determining an estimate of the performance of a building, sometimes the original input values may not represent the properties of the materials and systems included in the final design stage information (Iorwerth *et al.*, 2013).

Bell (2013, p. 8) summarises a number of examples where input data has affected the outputs of the SAP model, including a review of 82 SAP assessments where 52 of the final report sheets were found to contain errors. In this case, when the inputs were replaced with amended details, one fifth of the properties under examination failed to comply with emissions targets (Trinick *et al.*, 2009). At Elm Tree Mews, the u-value of a timber frame was misjudged by over 65% due to use of outline rather than final design stage details, accounting, in conjunction with similar issues observed within the roof structure, for almost 25% of the misalignment between design stage and measured HLC (Bell, M. et al., 2010a, p. 31 & 33). Similar issues can be observed in relation to installed systems and technologies (White et al., 2013; Zero Carbon Hub & NHBC Foundation, 2013).

It would seem logical to ensure that the SAP model for a particular dwelling is reviewed regularly during the design and construction period, in order to take account of changes in materials used and specifications of building elements and systems (Carbon Trust, 2012). However, such a process is not in place, although it has been recognised that that the introduction of a compulsory quality assurance procedure would be beneficial in terms of ensuring reliability of modelled data outputs (Department for Communities and Local Government (DCLG), 2012b). The communication of design information to the construction team, and feedback of changes to the design during the construction process so that details can be adjusted in the SAP model, is necessary in order to obtain a true representation of the situation (Carbon Trust, 2012).

Menezes (2012, p. 13) observed that when monitored data was used in conjunction with predictive energy modelling, the actual electrical consumption of the property under consideration was accurate to within 3% of the calculated values. At Elm Tree Mews, making changes to design stage parameters by replacing them with construction stage data resulted in an almost complete alignment between design stage and as built performance, as shown in Figure 3-7. (Stafford, A. et al., 2012, p. 22).

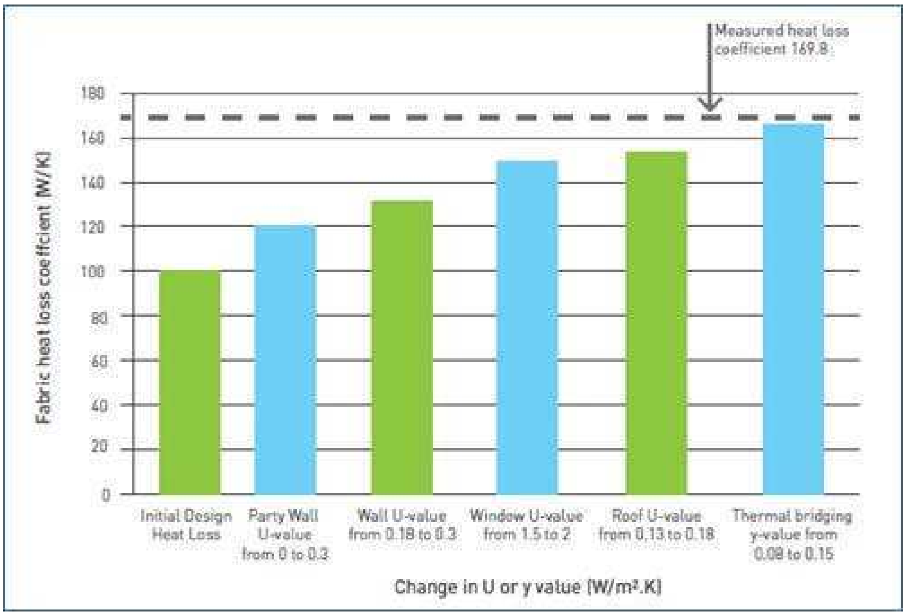


Figure 3-7 - Elm Tree Mews - Changes Made to Design Stage Data
Source: (Stafford, A. et al., 2012, p. 22)

During the course of this research project, all of the SAP worksheets examined have been found to contain input errors, relating to both basic parameters (measurement of dwelling floor areas and building element areas), and more complex issues such as incorrect u-values and glazing types. These matters, in conjunction with potential over-estimation of MVHR system performance through use of default tabulated values regarding specific fan power and heat recovery efficiency, will have an effect on the HLC calculated for a dwelling, and so will be investigated further within this work.

3.2.2 Assumptions

The most frequently challenged assumption within the SAP methodology relates to weather data. As outlined in Section 2.1, due to the basic laws of building physics, the temperature difference between the internal and external environments of a dwelling will have a significant effect on the heating demand of the property. Solar radiation/hours of sunlight and wind direction/speed will also impact upon the performance of the building.

However, whilst SAP 2009 has been updated to account for monthly average external temperatures rather than the yearly average values contained in SAP 2005, the data used for a significant proportion of the calculations is still based on a single UK monthly average value. The location of this data source is the East Pennines, as dictated by the underlying BREDEM base model.

A study undertaken by the Zero Carbon Hub (Zero Carbon Hub, 2011b) attempted to evaluate the implications of using regional rather than national weather data in calculations. Using the Fabric Energy Efficiency Standards (FEES) as a benchmark, the same property in the East Pennines, South West, and Scottish Borders would achieve a FEES result of 46, 38 and 51 respectively (Zero Carbon Hub, 2011b, p. 37). Murphy (2013a, p. 2) observed that, when modelling the same building in 14 different locations with correct local weather data, the calculated energy consumption could vary by +/-15%.

This demonstrates the sensitivity of the model to environmental parameters, and the weakness of SAP 2009 in terms of not being able account for the actual localised weather effects that a dwelling may experience once constructed. However, the benefits of using a simple single weather data-set approach need to be weighed against a more localised approach.

Using solely climatic conditions from the East Pennines does enable direct comparison of projects through normalisation of temperature and solar effects (Murphy *et al.*, 2013b). However, the impact on large-scale house builders could be that a single specification of dwelling is no longer appropriate – for example, a single thickness of wall insulation may produce lower efficiencies in Northern areas as compared to the South-West, due to temperature and wind variations and subsequent effects on thermal performance. This introduces the issue of economic implications for developers (Bergin, 2011).

The changes made to SAP 2012, introduced on the 6th April 2014, have included the use of 21 regional weather datasets, based on postcode, for the calculation of the Renewable Heat Incentive, dwelling running costs and savings in-use for display on EPC's. It will retain a single climate data set to calculate final FEES, SAP and EI ratings, and hence the building fabric elements of the model will remain largely unchanged in this respect (National Energy Services (NES), 2012).

Appendix U of the SAP methodology, relating to Climate Data, will be incorporated into the methodology documentation, to provide monthly regional values for wind speed, solar radiation and declination, latitude, and a standard national value of 50m height above sea level. Wind speed will be incorporated into the infiltration calculations in order to account for regional variations, but there will be no adjustment for wind direction (Department of Energy and Climate Change (DECC), 2011d). The rudimentary technique of merely taking wind speed and dividing it by a value of 4 in order to calculate wind factor will still be applied, regardless of dwelling orientation.

It can be seen that there are weaknesses within the SAP 2009 methodology, and whilst the amendments that have been introduced in SAP 2012 will rectify some of the known issues, other aspects will still remain that could affect the HLC calculation. This study will include an analysis of the potential impact that areas such as environmental factors, infiltration and ventilation default calculations/values and accuracy of element u-values may have on the final HLC value.

3.3 Conclusions

Whilst there is an increasing amount of evidence to support the existence of a gap between predicted and measured performance of UK housing, it is still an area where more work is required to fully understand the causal links between the design and construction processes and final physical performance of buildings (Stafford, A. , 2012). Indeed, the construction industry is starting to acknowledge that such a problem may exist, but are demanding more evidence is presented to illustrate that underperformance is not localised to individual projects, but is apparent throughout mainstream housing developments (Department for Communities and Local Government (DCLG), 2012b).

As outlined in the available literature, the ability of the current SAP methodology to provide an accurate indication of as-built performance has been questioned. This is largely due to the limitations of single point weather data, standardised values in calculations, and the use of manufacturer data for parameters such as u-values and system properties, which introduce an element of optimism bias into the model.

At present, there are limited requirements and provisions for mandatory post-construction evaluation within UK legislation and Building Regulations documentation (National House Building Council (NHBC), 2012). Changes to Building Regulations Part L have led to an increase in the number of properties required to be subjected to mandatory air-tightness testing on large scale developments (National House Building Council (NHBC), 2011b). This move will contribute in some part to ensure increased standards of building practises and early identification of issues that may be present due to problems with design and construction matters.

It would appear that two main courses of action are required in order to fully understand and subsequently address the factors that contribute to the performance gap. Firstly, a simplified and standardised regulatory approach for monitoring needs to be developed which can be implemented with limited impact upon developers, construction teams and residents (Zero Carbon Hub, 2013b). This should be supported by a centralised portfolio resource, uniting and containing research and case studies relating to housing developments throughout the UK, in order to learn from the experience and observations of other projects (Lowe et al., 2008).

It is probable that compliance with regulations and standards will move towards being based upon as-built rather than designed performance, so it is essential to understand the factors contributing to the discrepancy (Zero Carbon Hub, 2011a). This research aims to complement general studies that are associated with the assessment of building design and construction, whilst also providing an original contribution in the form of quantification of the magnitude of the impact of individual factors on thermal performance.

4 INVESTIGATIVE METHODS

Through detailed review of theory and practise relating to the area of building performance evaluation, a number of experimental techniques have been identified for use within this research study. Air pressurisation tests allow measurement of the airtightness of a building, providing an indicator of potential thermal performance. The output data is a key input parameter within the calculation of a design stage HLC in the approved SAP energy assessment methodology. The SAP 2009 theoretical platform is used throughout this work to construct models and subsequently assess predicted thermal performance, and airtightness information is necessary in order to complete the design-state assessments.

The coheating test forms a critical investigative technique that is central to the core methodology of the experimental work undertaken, as it provides a direct indication of as-built whole house heat losses and the output data can be used to calculate a measured in-situ HLC value. Therefore, conducting such tests is an essential step in the evaluation of the apparent gap that exists between design-stage and as-built performance of dwellings.

Heat flows through building elements can provide an indication of potential heat loss pathways within the building envelope. Infra-red surveys using a thermal imaging camera can help to identify such defects through visual inspection, providing a qualitative form of assessment. Heat flux sensors measure the amount of heat passing through a material, in conjunction with temperature measurements, can be used to calculate an in-situ u-value of an individual building element. This can provide a quantitative indication of as-built performance, which can be compared to manufacturer design and specifications.

Adequate levels of ventilation are central to the design and delivery of desirable houses, and this is essential to provide a healthy and pleasant internal environment. MVHR systems may be installed in more airtight houses in order to ensure an adequate supply of fresh air and removal of stale air and odours.

Balanced levels of supply and extract air flows are necessary in order to ensure that such a system works effectively, and flow rates can be measured at outlets within a dwelling in order to verify that this is the case. In addition, the efficiency of the integrated heat exchanger in recovering heat from extracted air (temperature efficiency) can be assessed through measurement of temperatures in the ductwork located close to the MVHR control unit.

The experimental methods summarised here form the foundation of the investigative work undertaken between October 2010 and November 2013, as shown in Figure 4-1.

Figure 4-1 - Timeline of Experimental Work

The remainder of this section will present the rationale and general methodology associated with the techniques that have been used in the assessment of both design-stage and post-construction thermal performance. The associated experimental data analysis and building performance modelling using SAP methodology was on-going throughout the duration of the research period. More detailed consideration of specific experimental design, alongside analysis of the resultant data from the practical and desk-based evaluations, is provided in Chapters 5 and 6.

4.1 The Creative Energy Homes (CEH) Project

The Creative Energy Homes (CEH) is an innovative project that enables research into sustainable design, construction, retro-fitting and operation of homes in the United Kingdom It is located at the University of Nottingham, on the University Park campus at Green Close. The development of seven houses provides a facility for the in-situ testing of housing design, materials and technologies, through collaboration of the Department of Architecture and Built Environment (DABE) and a number of industrial sponsors.

Each dwelling in Green Close has a specific design remit and objective in terms of research focus and outcome. All of the houses are fitted with integral monitoring systems in order to assess performance, which record data relating to parameters such as internal temperature, carbon dioxide levels, humidity/environmental quality, power and gas consumption, and water usage.

In 2001, the David Wilson Millennium EcoHouse was the first house to be completed. It is of standard brick and block construction, and currently provides staff office space. The house is primarily used as a testing facility for domestic scale renewable energy systems. Areas of research include combined heat and power systems, solar thermal energy production, smart grid and hydrogen fuel cell applications, and effectiveness of wind catcher and solar chimney ventilation and cooling strategies.

The BASF house was designed by Derek Trowell Architects and completed in June 2008. The main target of the design brief was to minimise energy demands and carbon emissions whilst providing an affordable house that would appeal to potential occupants (Gillott *et al.*, 2010). A second key aim was to achieve a cost effective build with a short construction period that would be attractive to housing developers. Modern methods of construction were essential to achieve these aims. The walls at ground floor level were formed using polystyrene form-work filled with concrete (insulated concrete formwork -ICF), whilst prefabricated timber insulated sandwich (SIPS) panels were utilised in the first floor and roof construction.

The most recent addition to the development is the Mark Group House, completed in October 2013. It is designed to appeal to those at the upper end of the property ladder, and is a four bedroom, three storey home. It is built using lightweight construction, ICF and a steel frame, finished with polystyrene formboard with cladding and rendering.

The Nottingham H.O.U.S.E. (Home Optimising the Use of Solar Energy) is a modular timber framed house that was designed and constructed by University students as the UK entry for the Solar Decathlon competition held in Madrid in 2010. The design aim was to create a home that was self-sufficient using energy from the sun, whilst achieving high levels of performance in terms of fabric and systems efficiency.

The primary aim of the Tarmac Masonry Homes Research Houses project was to design and construct energy efficient traditional masonry homes that are straightforward to construct and mass produce, whilst being visually appealing and affordable for potential home owners to purchase, maintain and operate. They comprise of a pair of semi-detached houses, constructed on University Park Campus and completed in March 2010, to meet the minimum requirements of the CfSH Level 4 and Level 6.

The E.On Retrofit Research House comprises of a newly constructed property, completed in 2008 on the University Park campus, initially built to the equivalent standard of a typical 1930’s house in the style of a traditional semi-detached dwelling. It forms the basis of a staged retrofit programme, with fabric and systems upgrades undertaken utilising materials, technology and methods that would be available to an average homeowner. Each intervention has been evaluated and the impact of the work on various parameters, such as thermal performance and energy efficiency, systematically assessed and attributed to individual stages of the programme. No renewable energy technologies were installed in the E.On Retrofit Research House, as the main aim of the project was to investigate a ‘fabric first’ approach to the retrofitting of existing housing stock.

The Tarmac Research House Code Level 6 (Tarmac House) and E.On Retrofit Research House (E.On House) have formed the basis of detailed research and investigation within this project. Both of the houses are fully monitored using comprehensive monitoring systems, with data being collected in relation to temperature, energy consumption, water usage and other aspects of the integrated systems.

The two properties were selected for several reasons, including:

- The research presented the opportunity to investigate the thermal performance of two dwellings, each designed and constructed to meet a different level of the CfSH;
- The E.On House is representative of the characteristics of a large number of existing UK homes, and so a sound understanding of the performance of the house and areas for improvement could have an impact through identifying ways to reduce the energy and carbon load of the wider UK housing stock;

- The Tarmac House is an example of early efforts made by a mainstream housing developer to design and construct a zero carbon home, and evaluating the actual performance will help to inform future design of highly efficient new-build housing; and
- Access could be gained to undertake a range of tests, sometimes for long periods, and was particularly straightforward in the case of the E.On House as this property was uninhabited for the duration of the research timeframe.

It is recognised that the number of example dwellings assessed during this research could be a limitation to the extensive application of the findings, due to the small sample size. However, detailed investigative studies require a large amount of time and resources, and so it is not possible to undertake such work on a wider scale within the confines of a doctorate project. It should be noted that, within existing literature, there are few examples of comprehensive design and post-construction stage evaluations. Therefore, the work undertaken here is of value in contributing to and extending the current knowledge-base, and providing novel assessment of the impact of various factors to underperformance of housing.

4.2 SAP Modelling

Initially, the design-stage SAP assessments prepared for the E.On and Tarmac dwellings were obtained. In the case of both properties, SAP 2005 methodology had been used to undertake the work, utilising Plan Assessor NHER (NES) software. A review of approved software programs revealed that SAPPER (RUSFA) software was a more cost effective option, and so the worksheet information for each property was transferred onto this platform. The results replicated using the original input data are slightly different to the original SAP 2005 worksheets, as this study utilises SAPPER 9, which is based upon SAP 2009 conventions. The original SAP worksheets for the retrofit and new-build dwellings are included in Appendix 2.

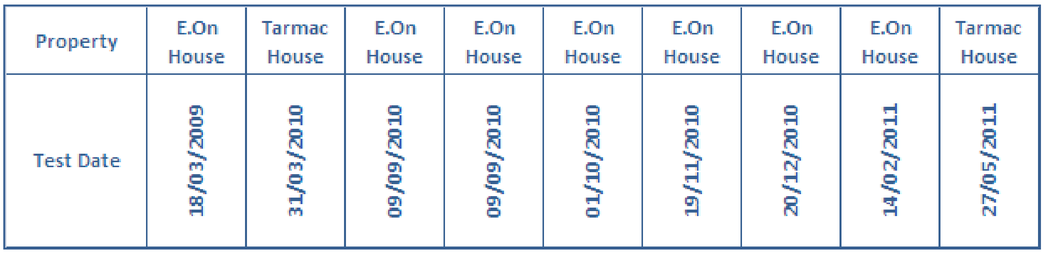
In addition to the SAPPER software, a spreadsheet was developed to allow differential sensitivity analysis to be undertaken for parameters that could affect design stage HLC calculations. A second worksheet was developed in order to be able to change default input values in the section of the model relating to ventilation strategy, including local environmental information. This enabled a more comprehensive analysis of the effect of ventilation on the HLC value to be obtained. Both worksheets are located in Appendix 3.

4.3 Air Tightness

Air pressure testing was undertaken on both the E.On House and Tarmac House at significant points during the overall period of experimentation. The tests were carried out by a third party, utilising the standard blower door test methodology (ATTMA, 2010) as required by UK Building Regulations (Department for Communities and Local Government (DCLG), 2010b). This technique has been previously outlined in Section 2.3.1.

The relevant dates of each test are shown in Table 4-1.

Table 4-1 - Relevant Dates of Airtightness Tests



Property	E.On House	Tarmac House	E.On House	E.On House	E.On House	E.On House	E.On House	E.On House	Tarmac House
Test Date	18/03/2009	31/03/2010	09/09/2010	09/09/2010	01/10/2010	19/11/2010	20/12/2010	14/02/2011	27/05/2011

The tests were scheduled to correspond with project milestones, including the completion of the Tarmac House and the end of each stage of the E.On House retrofit improvement programme. On each occasion, a pressurisation and depressurisation test was completed and the average value of the q50 result taken as an indication of building air tightness performance. This ensures that consideration is given to additional infiltration imposed due to air being pushed through the building fabric during pressurisation, and also the sealing effect when the fan is operating in depressurisation mode.

4.4 Thermal Performance

Infra-red thermography surveys, through use of a FLIR T400 thermal imaging camera (FLIR Systems Co. Ltd., 2008), were utilised in order to identify building defects and areas where there could be potential to improve the thermal performance and air tightness of the test houses. The use of this assessment technique also extended to the investigation of the MVHR system installed in the E.On House.

The timing of the surveys generally coincided with the dates of the air pressurisation tests, as the increased movement of heated air through the building fabric enabled clearer identification of thermal bridges and air leakage pathways. On other occasions, the test property would be heated to an unusually high temperature in order to achieve a large temperature difference between the internal and external environments. This allowed both major and minor defects within the building fabric to be detected. With regards to the MVHR system, surveys were undertaken when the system was in operation in order to identify heat losses from the control unit and ductwork in the loftspace, and at supply/extract duct outlets installed in each room.

Whilst thermal images do not provide a quantitative measure of heat losses, they are useful in order to isolate areas within a building or system that can be targeted for improvement. They are also relatively simple and non-invasive to undertake, and provide immediate indicative qualitative data.

4.5 Whole House Heat Losses

As discussed previously in Section 2.3.2, short term energy tests provide a key analysis technique in order to quantify whole house heat losses through the building fabric. In terms of this study, the coheating test has been identified as a key method to assess fabric performance. The use of this method can be justified as follows:

- It is the technique in the UK most widely used to assess whole house heat losses;
- Standard protocols have been developed for the testing procedure;
- The test is simple to undertake and does not require extensive specialist equipment; and
- The final data output can be used to calculate a measured HLC for a property, which can be adjusted so that it is comparable with design-stage predicted HLC values.

In terms of limitations, data derived from such tests is quite scarce due to the restricted number of detailed studies undertaken, meaning that it may be difficult to draw comparisons with other studies. Whilst efforts are being made to standardise the methodology, the coheating test is not fully understood or developed. As more field trials are completed, the procedure for conducting the test is under continuous review and refinement (National House Building Council (NHBC) Foundation, 2013). Analysis of the resulting data is also an area that is evolving in terms of consideration of the influence of environmental effects on the calculated HLC.

Whilst the lack of a truly standardised coheating test methodology leads to variation within the execution of the test and the techniques used to derive a HLC value, it also presents an opportunity to investigate uncertainties within the methodology in order to inform future developments in the field of whole house heat loss assessment.

4.5.1 Methodology

A version of the co-heat test methodology developed by Wingfield (2011) has been used to measure the total heat loss arising from fabric and background ventilation pathways, in order to obtain a measure of the in-situ whole house HLC. The general concept of the test works on the basis that by heating a dwelling to a constant temperature (approximately 25°C) with electrical heaters, and then measuring the amount of energy required to maintain that temperature, the daily heat input into the house can be measured (watts). When this value is plotted against the daily difference between internal and external temperatures (ΔT), it produces a HLC value. The HLC can then be used to estimate the amount of electrical energy required to heat a dwelling per 1K difference between internal and external temperatures.

Prior to commencement of the procedure, it is important to ensure that:

- all heating and electrical systems that are not required during the test are turned off, either at the fuse box or at individual power sockets.
- all external doors, windows, trickle vents, mechanical supply/extract vents, flues and fireplaces are closed and sealed and all water traps and U-bends in toilets, sinks, baths and showers are filled with water.
- all internal doors, wardrobe/cupboard doors and furniture drawers are propped open in order to promote unobstructed circulation of air.

Following the initial preparations, the equipment for the test can be set up, which includes electric fan heaters, circulation fans, in-line thermostats and power meters. At least one group of apparatus is required in each test zone, and such zones are generally defined as a single floor of a house (i.e. there would be two zones in a standard two storey dwelling). It is often necessary to use several groups of equipment in each zone (such as one set in each habitable room) in order to ensure that a consistent and uniform internal temperature is maintained throughout the property for the duration of the test. In addition, in a semi-detached or terraced house, the adjoining properties should ideally maintain the same internal temperature as the test dwelling in order to prevent heat flow through party walls.

When the equipment has been placed in the required locations, each thermostat is adjusted to maintain a temperature of 25°C. The electric fan heaters are set to work at their maximum heat and fan setting, whilst circulation fans are adjusted to their maximum fan speed setting. In the initial stages of the test, the temperature data throughout the house is assessed to ensure that it is uniform, and the positions of the equipment may be altered until uniformity is achieved.

Each heater and circulation fan is connected to a power meter in order to measure energy consumption of all of the equipment used within the test. A datalogger is used to collect all of the data generated from the experiment, with recordings taken at 5 minute intervals. In addition, environmental conditions, such as internal and external temperatures, wind speed and solar radiation levels are measured.

The specification of the instruments used in the coheating tests in this experimental work is detailed in Table 4-2, whilst Figure 4-2 shows a typical experimental set-up. Appendix 4 contains data sheets for the equipment used. External environmental data was obtained from a University weather station situated 150m from the CEH Project location.

Table 4-2 - Coheating Test Equipment Specification

Component	Equipment Used	Measurement Error Range
Datalogger 1	Datataker DT500	+/- 0.15% at 25°C operating temperature
Datalogger 2	Datataker DT85	+/- 0.1% between 5°C and 40°C operating temperature
Internal Temperature	Microwatt Installed System	+/- 2°C
kWh Meter	Elster A100C, 1 Wh pulse output	+/- 0.4 % (maximum)
Thermostat	Timeguard ET05 Plug In Thermostat Heating Control	Differential cut in of +/- 1°C
Fan Heater	Dimplex 3kW and 2kW Convection Heater	n/a
Circulation Fan	Various Desk-Type Fans	n/a

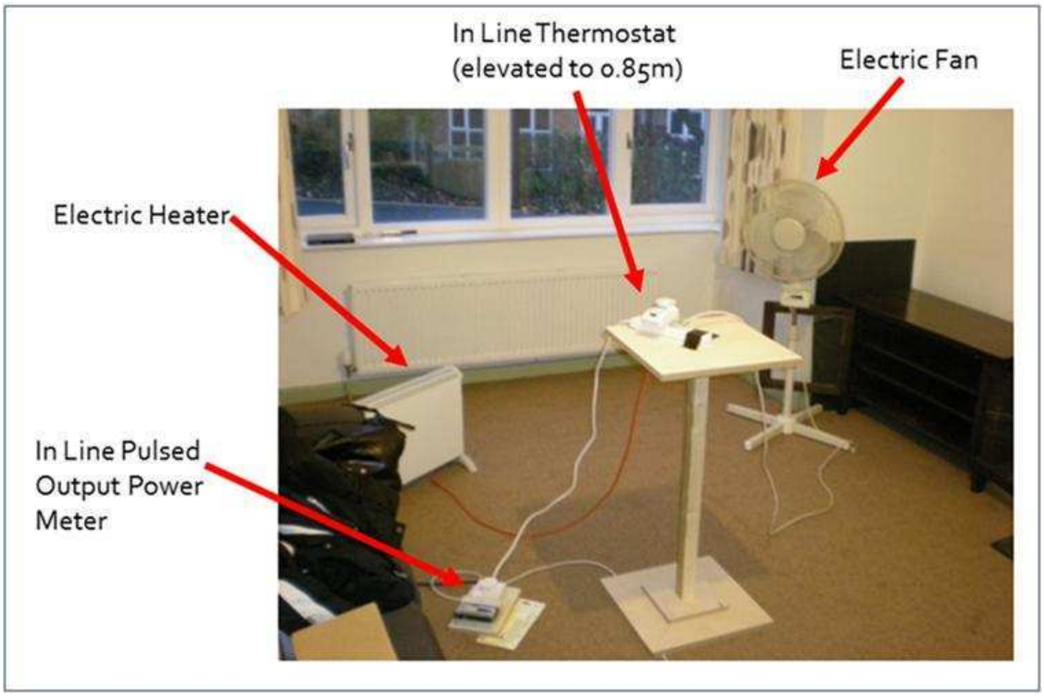


Figure 4-2 - Coheating Test Equipment

The testing schedule was as follows:

- E.On House No MVHR System Operating – 20th -28th November 2010
- E.On House With MVHR System Operating – 30th November – 2nd December 2010
- Tarmac House No MVHR System Operating – 9th – 15th December 2010
- Tarmac House - MVHR System Operating – 18th – 22nd December 2010
- E.On House 25°C ΔT – 26th – 21st February 2011
- E.On House 35°C ΔT – 24th – 27th February 2011
- E.On House No MVHR System Operating – 25th- 28th March 2011
- E.On House With MVHR System Operating – 29th- 31st March 2011
- E.On House With MVHR System Operating – 2nd – 5th April 2011

The research work extended to include consideration of the impact of MVHR systems on the HLC of each dwelling. Little or no work associated with this area was discovered during the literature review and wider reading, highlighting an opportunity for novel investigation.

4.5.2 Analysis of Data

A large volume of data is generated during a coheating test, as a single experiment may last anywhere between 3 and 14 days. The theory behind the analysis of the data is based on the application of the standard heat balance equation, previously outlined in Section 2.3.2 (Equations 2.3 and 2.4).

The coheating test outputs allow calculation of total measured power and ΔT for each day of the relevant timeframe. A simple measure of HLC can be derived from these two parameters using linear regression analysis, where ΔT is plotted on the x axis and power is plotted on the y axis. A linear trendline is fitted to the dataset, forced through the zero point, as shown in Figure 4-3.

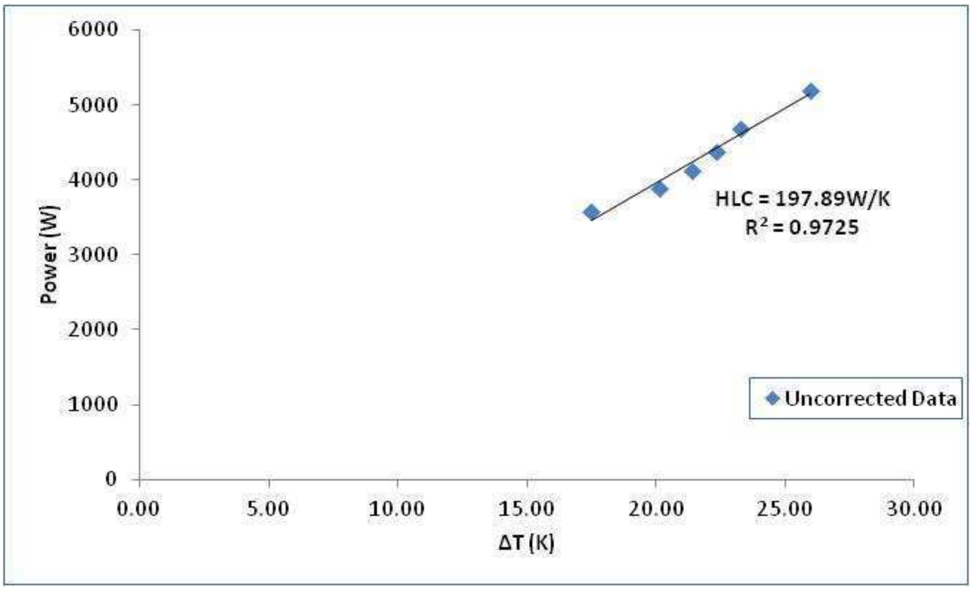


Figure 4-3 - Example of Linear Regression of Raw Coheating Test Data

The HLC value is given as the Y value output – in this case it is 197.89 W/K. The R^2 value is the coefficient of determination, and represents the degree of correlation between variables (in this case ΔT and power) and how closely the experimental data fits with a statistical model. It ranges between 0 and 1 (0 being no relationship and 1 being strong correlation). In this example, the R^2 value is 0.9725, which indicates a close fit with the theoretical linear relationship.

However, the HLC value (Y) obtained from this process does not account for the effects of solar radiation, which could influence the HLC value. During periods of high solar radiation levels, the power input to a dwelling, particularly in south facing rooms, may be reduced due to the heat associated with passive solar gains.

Therefore, it is common practise to correct the raw power data obtained from the experiment to account for such impacts. There are two main techniques employed in order to do this, namely multiple regression and Siviour analysis, as described in Section 3.3.2. Both methods require local data relating to south facing solar radiation for use in the correction calculations.

Multiple regression analysis utilises the power data, and evaluates the combined relationship between *ΔT* and solar radiation values in order to generate an effective value that can be used to correct for solar effects. The following equation is used in this technique (Equation 4-1, (Bauwens et al., 2012, p. 352):

$$Q = constant + (A \times \Delta T) - (B \times S)$$

Equation 4-1 - Multiple Regression Equation (Bauwens et al., 2012, p. 352)

Where:
Q = Total measured power (W)
A = Constant derived from multiple regression analysis
B = Constant derived from multiple regression analysis
S = Mean solar radiation
ΔT = Mean temperature difference between the inside and outside of the building

The values of the constant, A and B are provided through the regression analysis, while the mean solar radiation (S), mean temperature difference (ΔT) and mean power input (Q) are taken from the coheating test data. When the regression process is completed, a value for A is produced, which can be applied to the solar radiation data in order to provide a correction for solar gains, as shown in Equation 4-2 (Bauwens et al., 2012, p. 352).

$$Q_S = Q+(A \times S)$$

Equation 4-2 - Multiple Regression - Correction for Solar Gains (Bauwens et al., 2012, p.

Where:
Q_s = Solar corrected total measured power (W)
Q = Total measured power (W)
S = Total south facing solar radiation (W/m^2)
A = Constant derived from multiple regression analysis

Following the use of multiple regression analysis to derive a value of A, the recalculated Q_s power data is plotted against the temperature difference data through means of linear regression and the use of a linear trendline. Figure 4-4 shows a linear regression plot of the original data displayed in Figure 4-3, which has now been corrected for solar gains using the value of A obtained through multiple regression analysis. The HLC (y) value has now increased to 209.2 W/K, due to the adjustment of the power data to reflect under-estimation resulting from solar gains. The correlation between the variables is still strong, with an R^2 value of 0.9638.

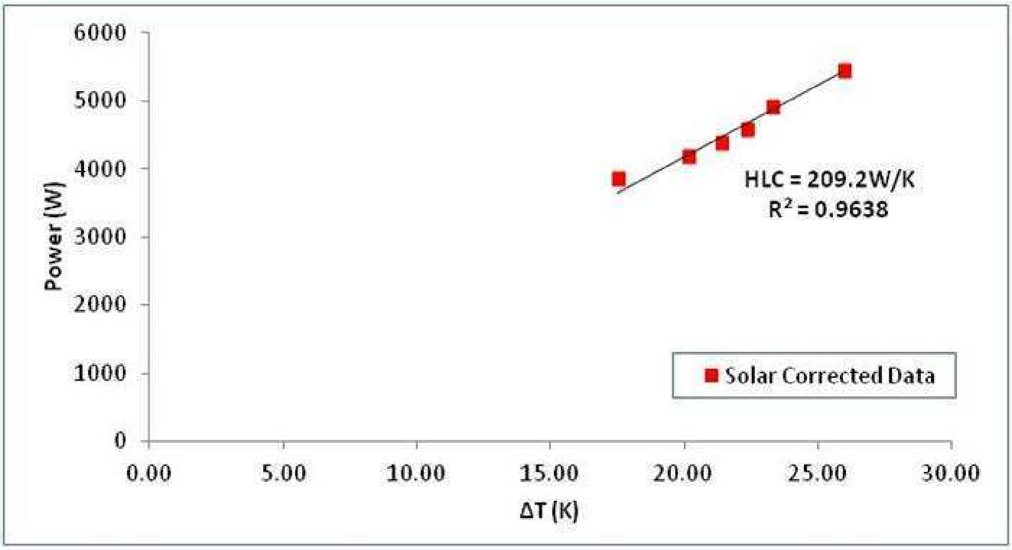


Figure 4-4 - Example of Solar Corrected Data Derived from Multiple Regression Analysis

Alternatively, the Siviour analysis linear regression technique can be employed to correct for solar effects. When considering the rearranged form of the heat balance equation stated previously in this section, it can be determined that a graph constructed with an x axis of S/ΔT and y axis of Q/ΔT would produce a line where the solar aperture (R) is represented by the slope and $\sum U.A$ + $1/3nV$ is the intercept of the y axis. Therefore, the value of the y intercept on such a plot would be equivalent to the total measured HLC, inclusive of correction of power input to account for the effects of solar gains. Figure 4-5 shows the same data set as displayed in Figure 4-3 and Figure 4-4, with a HLC calculated using

Siviour technique. The solar aperture (R) has a value of -19.328, while the HLC would be 210.02 W/K (the point at which the trendline crosses the y axis).

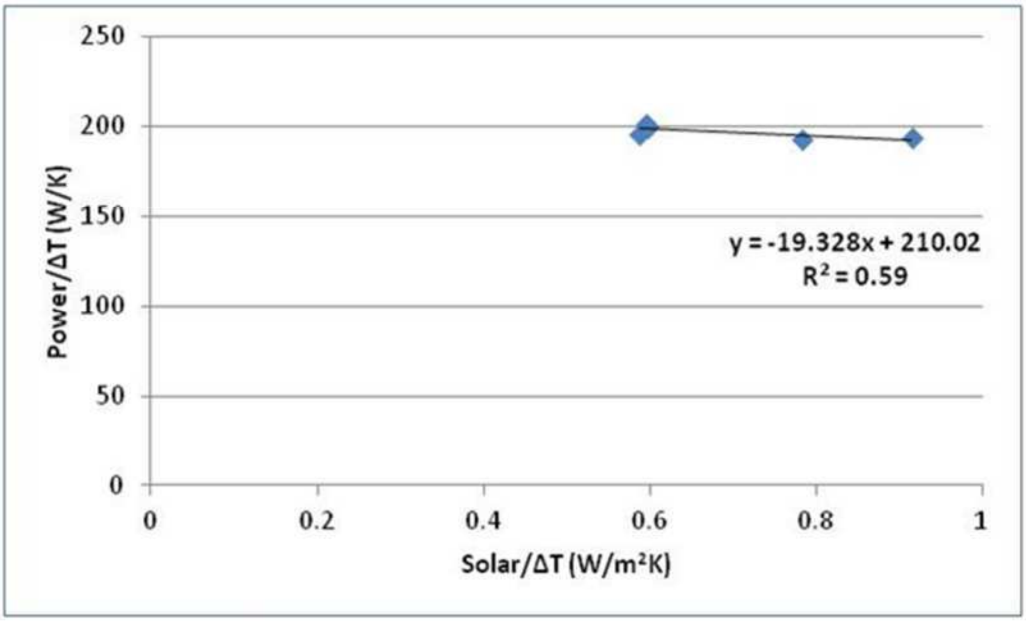


Figure 4-5 - Example of Solar Corrected Data Using Siviour Analysis

In the context of this study, the multiple regression technique has been employed in order to correct for solar gains. Work undertaken by Bauwens (2012) provided guidance that this method has the advantage, over linear regression, of considering the gains to opaque surfaces, and the solar correction factor is derived from detailed analysis of the relevant datasets rather than by calculation. Linear regression methods can be restricted due to limited consideration of total errors within the methodology, as power input is defined as the sole independent variable.

The data obtained from a coheating test experiment can be sensitive to changes in external temperature, wind speeds, wind direction and precipitation levels. Whilst such parameters are not routinely accounted for in the analysis of the output data, it is important to be aware of the weather conditions present at the time of a test so that any extreme conditions can be considered. The summary data relating to all of the coheating tests undertaken is included in Appendix 5.

4.6 Heat Transfer

Heat flux monitoring of materials allows the thermal performance of building elements such as walls, floors and ceilings to be measured and assessed. Sensors can be used to monitor heat flow, which in conjunction with internal and external temperature data, can be used to calculate in-situ thermal resistance (R value) and thermal transmittance (u-value) properties (Hukseflux, 2008). The measured results can then be used to evaluate in-situ performance as compared to design/manufacturer expectations.

4.6.1 Methodology

In-situ monitoring of heat flows were measured using Hukseflux HPF01 Heat Flux Plates (specification included in Appendix 4), fixed using thermal paste to ensure good connectivity with the surface of the material under investigation and secured with non-conductive tape. The sensors produce an output voltage reading, measured in millivolts, which is then divided by the individual sensor unique sensitivity constant provided by the manufacturer, in order to gain a value of heat flux in watts.

The manufacturer states a nominal sensitivity of 50 μV/ Wm^2, a measurement range of +2000/-2000 Wm^2, and an expected typical accuracy of +5/ -5% when installed to monitor heat flow through walls (Hukseflux, 2008). This could present a potential source of error within the experimental data.

In addition, k-type thermocouples were installed in order to measure temperatures in the cavity wall construction. Such temperature probes have an intrinsic maximum permissible measurement error of +1.5/-1.5 °C when operating in temperatures ranging from 0 – 200 °C (National Instruments Corporation, 2010). This will be considered when assessing the measured temperature data.

A DT85 datalogger or DT500 datalogger was used to collect data from the heat flow analysis experimental work. When a voltage output is utilised, the DT85 datalogger has a maximum operating error of +/-0.1% when situated in a temperature range of between 5°C and 40°C (Thermo Fisher Scientific Inc., 2011). The error associated with the DT500 datalogger is +/-0.15% at a given temperature of 25°C (Datataker Inc., 2010). It is noted that the slight difference in the accuracy of the data recording equipment could account for some divergence in measured data.

4.6.2 Analysis

The calculation of in-situ u-values can be undertaken using measurements of heat flux, and internal and external air temperatures, using Equation 4-3 (Baker, 2011, p. 37):

$$U = \frac{1}{\frac{Ti-Te}{Q}}$$

***Equation 4-3 - U-value Calculation - Air Temperature Method (Baker, 2011, p. 37*)**

Where:
U = In-situ u-value
T_i *= Internal air temperature*
T_e *= External air temperature*
Q = Heat flux

Internal and external surface temperatures can also be used in the calculation instead of air temperatures, in which case factors need to be considered to account for surface resistance of materials and the heat flux sensor. Standard theoretical resistances are generally in the order of 0.04 Km^2/W and 0.13 Km^2/W for external and internal walls respectively (Anderson, 2006). A resistance adjustment of 6.25 x 10^{-3} Km^2/W is required to account for presence of the heat flux sensor (Hukseflux, 2008). The following equation for calculating heat flux can then be applied (Equation 4-4 (Baker, 2011, p. 37)):

$$U = \left(\frac{1}{\frac{Ti-Te}{Q}}\right) + rint + rext - rhf$$

Equation 4-4 - U-value Calculation - Surface Temperature Method) (Baker, 2011, p. 37)

Where:
U = In-situ u-value
Ti = Internal surface temperature
Te = External surface temperature
Q = Heat flux
ri_{nt} *= Interior wall surface resistance*
r_{ext} *= External wall surface resistance*
r_{hf} *= Heat flux sensor surface resistance*

Both techniques provide a valid measure of in-situ u-value, but the analysis will be limited to those calculated using air temperature data due to the lack of surface temperature data in some of the experiments undertaken.

4.7 MVHR System Function

Whilst the effect of the MVHR system operation on the fabric performance and whole house HLC value was assessed through use of the coheating test procedure, the evaluation work extended to the assessment of the function and installation of the MVHR systems installed in the E.On and Tarmac Houses.

4.7.1 Methodology

An assessment of the flow rates at each of the supply and extract ducts within the two dwellings houses was undertaken. A Testo 417 vane anemometer was used to obtain readings of the air flow at each outlet (specification included in Appendix 4). This device has an integral air flow and temperature vane, and has the capability to provide timed and multi-point mean calculations. It is accurate to +/- 0.1 m/s and +/- 0.5°C (Testo Inc, 2011).

On each occasion, the houses were heated to 21°C and the anemometer was held over each supply and extract vent within the dwelling living spaces in turn. Mean values of flow rate (m/s) and temperature (°C) measured over a 30 second time period were recorded. The flow rate values were later converted to l/s and air changes per hour (ACH) units.

A FLIR T400 thermal imaging camera was used to investigate areas of potential heat loss from both the MVHR system control unit and heat exchanger, and the ducting work in the loft space. A power meter was installed in order to measure the electrical consumption of the system. Thermocouples were placed in the supply and extract ductwork to a depth of 70mm at a distance of 500mm from the main control box, as shown in Figure 4-6.

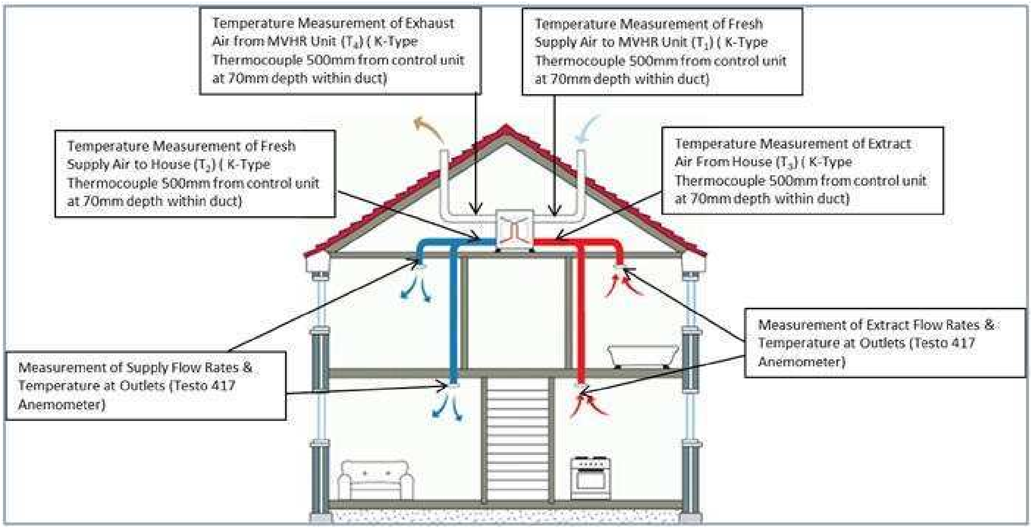


Figure 4-6 - MVHR System Measurement Locations
Source: (Efficiency Meets Sustainability, 2011) (Altered by Author)

4.7.2 Analysis

The measured outputs enabled calculation of the Temperature Efficiency through the methodology outlined in Equation 4-5 (Lowe et al., 1997, p. 35):

$\eta_t = T_2 - T_1 / T_3 - T_1$

Equation 4-5 - Temperature Efficiency of MVHR System (Lowe et al., 1997, p. 35)

Where:
η_t *= Temperature Efficiency of the MVHR System*
T_1 *= Temperature of Intake Air (°C)*
T_2 *= Temperature of Supply Air (°C)*
T_3 *= Temperature of Extract Air (°C)*

This parameter provides an indication of the performance of an MVHR system, and the experimental calculated values can be compared to manufacturer design-stage data and utilised in SAP 2009 assessments in order to evaluate post-installation function.

4.8 Conclusions

The primary purpose of this section has been to provide an overview of the core methods as utilised throughout the experimental and analytical work undertaken during the course of this research programme. The main areas of investigation are the performance of the building fabric and installed ventilation systems, at both the design and post-construction stages. SAP 2009 methodology is employed as the primary means of evaluating predicted levels of dwelling performance. Throughout the evaluation of the two selected case-study properties, coheating testing and heat flow monitoring provide essential tools for assessing the as-built thermal performance of the building fabric. Measurement of system temperatures, power inputs and air throughput rates can enable assessment of MVHR system performance.

Whilst the general concepts pertinent to each evaluation method have now been described, the specific details relating to the actual experiments performed will be outlined subsequently in the context of the remaining chapters as required.

5 THE RETRO-FIT CONTEXT

As identified in Section 1.1, whilst much progress is being made towards the improvement of the fabric of new build dwellings in order to enhance thermal performance, the existing building stock presents a potentially more complex problem. The UK has over 8.5 million houses that are in excess of 60 years old (Energy Saving Trust (EST), 2007b, p. 4), resulting in slow progress towards lower domestic carbon emissions through replacement with more efficient properties alone. This poses a dilemma for policy makers, developers and local authorities at the strategic level and home owners at a more localised level – is the best solution to abandon older houses (relocation of occupants and major demolition/rebuild projects) or to refurbish and retro-fit existing properties? (Power, A, 2008).

Housing demolition rates are relatively low in the UK, and several studies have been undertaken to assess the impact of increased demolition rates within different scenarios to achieve Government energy targets. It has been observed that higher demolition levels may not present a significant contribution in reducing energy demands and carbon emissions, when compared to the impact of wide-scale renovation schemes (Johnston *et al.*, 2005; Lowe, 2007; Natarajan *et al.*, 2007).

With this in mind, the role that the improvement of the existing housing stock could have in providing more efficient properties cannot be ignored, although the mechanisms by which this is implemented at Government level could impact upon uptake and effectiveness of improvement measures (Dowson et al., 2012; Killip, 2011). It is largely dependent upon the ability of the wider community to understand the concept of sustainable retro-fit, which may include improvements to the fabric or systems integrated into a dwelling that result in a reduced energy demand, or inclusion of localised power generation from renewable sources (Swan, W. *et al.*, 2013).

Research into effective retrofitting practises and techniques is essential in order to inform and aid those undertaking such work at an individual dwelling or whole development scale. As such, Project CALEBRE (Consumer-Appealing Low Energy Technologies for Building Retrofitting) (www.calebre.org.uk/) has been undertaken as a partnership between several leading universities, with £2 million of funding provided by E.On and the Research Councils UK (RCUK) Energy Programme. Central to this project was the construction of the E.On 2016 Research House, completed in 2008 as a three bedroom new-build property but built to 1930's equivalent building standards (Banfill et al., 2011b). Over a four year period, the house has been upgraded to exceed 2010 Building Regulations standards through a staged programme of retrofit measures (Loveday *et al.*, 2011).

This property is representative of the large number of hard to treat dwellings in the UK, and so has been investigated in order to evaluate the performance of a retro-fit dwelling. The remainder of this chapter will present an overview of the design and construction of the building, and report on the findings relating to the design stage and post construction fabric and systems evaluations undertaken.

5.1 Scope and Methods of Investigation

As outlined previously in Chapter 4, the main techniques that will be utilised throughout the performance gap evaluation work will be the interrogation of the design stage SAP assessment, in conjunction with whole house coheating tests and MVHR system evaluation. The experimental work was largely reliant upon the opportunity to access the E.On House at opportune times throughout the staged retrofit work. This led to the work programme evolving rather than being pre-planned, as delays and unscheduled works meant that a strict plan could not be adhered to. In some cases, the length of time available for experimental work was very limited.

In terms of the coheating test, the standard protocol described in Section 4.5.1, with regard to equipment and procedure, was followed. The location of the electric fan heaters, circulation fans, power meters, thermostats and dataloggers throughout the house was noted and remained consistent throughout all of the tests, and the position of each group is shown in Figure 5-1. The property was divided into two zones (the upper and lower floors), with data collected from a datalogger located centrally in each zone.

A number of tests were undertaken at different stages throughout the retrofit project. Several analyses were used to calculate the measured HLC, including linear regression of the data prior to solar correction, linear regression of the data using a solar adjustment derived from multiple regression, and linear regression accounting for solar gains using Siviour analysis. The theory behind each method has been detailed in Section 4.5.2, with results presented in this chapter as each test is considered. The impacts of external environmental effects of the HLC data are considered in relation to individual tests.

Air pressurisation testing, infra-red thermography and MVHR system evaluation work have also been used for evaluation purposes, following the approaches described in Chapter 4.

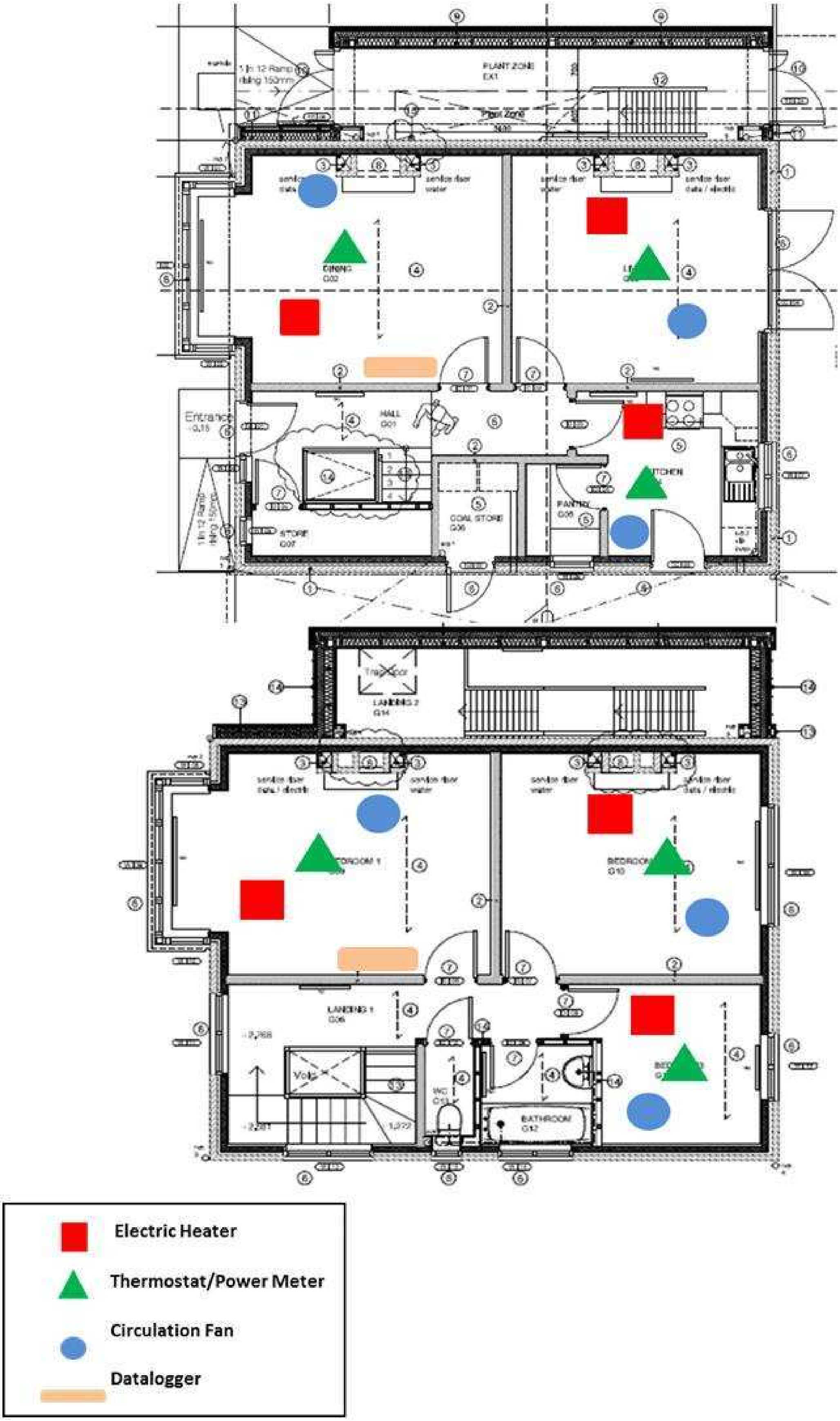


Figure 5-1 - E.On House - Position of Coheating Test Equipment

5.2 *The Retro-Fit House*

The design of the E.On House follows that of a traditional 1930's semi-detached property of 108m^2 floor area, with two reception rooms, kitchen and pantry on the ground floor and three bedrooms, a bathroom and a separate toilet on the first floor. Due to limited land availability, the property was designed and constructed as one half of a pair of semi-detached dwellings, with a party wall dividing the house from a service zone that is intended to simulate the presence of an attached property (Figure 5-2). The service zone also provides access to the loft space, where monitoring equipment is located.

Figure 5-2 - The E.On 2016 Research House

Retrofit improvements were undertaken in five main stages between 2010 and 2012, and included upgrades to both the building fabric and integrated systems. Table 5-1 summarises the key properties of the dwelling and work undertaken at each stage.

	Baseline	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Experimental Work	SAP HLC: 484.58 W/K Coheat HLC: N/A Q50 Result: 15.57	SAP HLC: 252.60 W/K Coheat HLC: N/A Q50 Result: 14.31	SAP HLC: 233.92 W/K Coheat HLC: N/A Q50 Result: 9.84	SAP HLC: 229.00 W/K Coheat HLC: 209.20 W/K Q50 Result: 8.6	SAP HLC: 213.26 W/K Coheat HLC: N/A Q50 Result: 5.0	SAP HLC: 212.28 W/K Coheat HLC: 205.46 W/K Q50 Result: 4.74
External Wall	u-value: 1.29 W/m^2k External brick skin, 50mm uninsulated cavity, 100mm Tarmac Hemelite solid block with lath and plaster finish	u-value: 0.55 W/m^2k Cavity insulated with Knauf Supafil 40 mineral wool	No change	No change	No change	No change
Party Wall	As external wall	As external wall	No change	No change	No change	No change
Roof	u-value: 1.63 W/m^2k Uninsulated pitched rafter & purlin roof with breathable membrane	u-value: 0.15W/m^2k Insulated with 300m Isover Spacesaver glass mineral wool	No change	No change	No change	No change
Ground Floor	u-value: 0.720 W/m^2k Uninsulated suspended timber floor with 920mm undercroft beneath Exception – kitchen floor comprised uninsulated concrete slab- u-value: 0.99 W/m^2k	Carpets & underlay fitted	No change	No change	Isover VARIO membrane fitted under carpets sealed with Isover KB1/Isoflex tape. Ovecladding of existing skirting boards	No change
Upper Floor	Uninsulated suspended timber floor	No change	No change	No change	Carpets fitted with Isover VARIO membrane beneath sealed with Isover KB1/Isoflex tape. Overcladding of existing skirting boards	No change
Windows	u-value: 4.8 W/m^2k Timber framed single glazed	u-value: 1.2-1.7 W/m^2k Timber framed double glazing. Obscure glass – Pilkington Stipolyte. Clear glass Saint Gobain Planitherm	No change	No change	No change	No change
Doors	u-value: 3.6-4.0 W/m^2k Timber framed single glazed	u-value: 1.7 W/m^2k Timber framed double glazed Pilkington Stipolyte glass	No change	Covers fixed to external door locks	No change	No change
Draught Proofing & Air Tightness Work	N/A	GTI PAL Systems installed to clear glass windows & doors	GTI PAL Systems installed to obscure glass windows & doors. Silicone sealant to frames	Service risers and penetrations sealed with expanding foam. Kitchen extract fan removed and hole sealed	Floor sealing work (detailed above)	Isover Powerflex tape and coving fixed to wall/ ceiling junction. Silicone ceiling to light fittings & power sockets
Heating System	Open fires to two ground floor and two upper floors rooms. Electric heating	Radiators & A-rated Worcester Bosch 24Ri Greenstar Gas Condensing Boiler with fully programmable thermostat	No change	No change	No change	No change
Ventilation Strategy	Background infiltration & natural ventilation	Titon HRV2 Q Plus MVHR System	No change	No change	No change	No change

Table 5-1 - Summary of Fabric and Ventilation Characteristics of the E.On 2016 Research House

Following completion of the improvement works included within the scope of the CALEBRE Project, further upgrades to the insulation levels of the ground floor were undertaken. This involved the installation of 200mm thick Thermafleece insulation fitted between the floor joists from underneath (via undercroft access), overlaid with a breathable membrane and 100mm thick Edenbloc 35 insulation board fixed to the underside of the joists. This build-up achieved a calculated ground floor u-value of 0.12 W/m^2K, and is referred to within this work as Phase 6.

A number of evaluation techniques were used to assess the performance of the dwelling, ranging from design stage modelling through to air pressurisation testing, coheating testing and infrared thermography. The following sections report the findings of the comprehensive programme of assessment undertaken over several months as the fabric of the property was improved.

5.3 Design Stage Assessment

Initially, copies of the original design stage SAP assessments, as included in Appendix 2, were obtained for the E.On House. Two assessments were completed in August 2009 by an independent assessor using NHER (NES) software based on SAP 2005 methodology, one relating to the property in its original post-construction state, and the second to reflect work undertaken in the first phase of upgrade works (Phase 1). Due to the use of different software in this study, the original information from the relevant worksheets was inputted into SAPPER 8 (RUSFA SAP 2005 version) software in order to establish a design-stage baseline assessment. This provided information relating to the original state of the E.On House prior to any retro-fit interventions, and also a revised assessment following the first stage of retrofit.

The same original details were inputted into both SAPPER 8 and SAPPER 9 software (SAP 2005 and 2009 versions), with each model assuming a natural ventilation strategy for the house. The resulting data is shown in Table 5-2.

Table 5-2 - Design-Stage SAP Data – Original Assessment Modelled in SAP 2005 and 2009

	Original House (Prior to retrofit work)					Phase 1 (as described in Table 6 1)				
	Fabric Heat Losses (W/K)	Ventilation Heat Losses (W/K)	Heat Loss Coefficient (W/K)	SAP Rating	EI Rating	Fabric Heat Losses (W/K)	Ventilation Heat Losses (W/K)	Heat Loss Coefficient (W/K)	SAP Rating	EI Rating
SAPPER 8 (SAP 2005)	653.2	125.7	778.9	9(G)	7(G)	343.0	67.1	410.2	31(F)	26(F)
SAPPER 9 (SAP 2009)	653.2	141.6	794.9	6(G)	8(G)	343.5	73.8	417.4	27(F)	27(F)
Difference	+0.0	+16.0	+16.0	+3	+1	+0.5	+6.7	+7.1	+4	+1

It can be seen that there are slight differences between the values generated for each parameter in the two versions of SAPPER. Due to the input data being exactly the same, the variance is most probably attributable to improvements in the SAP methodology made within the more recent version. Several of the main differences between SAP 2005 and 2009 are included in Table 5-3.

In addition, significant changes were made to the carbon emissions factors associated with different fuel types, with increases applied to those relevant to carbon intensive fuels such as electricity and gas, and reductions made to those related to more renewable energy sources (e.g. waste products and biomass). More detailed consideration was also given to the calculation of incidental gains from people, lighting, appliances and cooking, and updates made to Appendix Q in order to allow for the inclusion of an increased number of acceptable new technologies (Hughes, 2009).

In terms of the SAP assessments under consideration in relation to the E.On House, the main changes within the methodology that would affect the magnitude of heat losses calculated in the initial stages of the model are those related to party wall u-values and thermal bridging. The fabric heat loss value is virtually identical in both the SAP 2005 and 2009 versions, as the same element areas, elemental u-values and thermal bridging values were used in each model.

Table 5-3 - Main Differences Between SAP 2005 and SAP 2009
Source Data: (Hughes, 2009)

	Position in SAP 2005	**Position in SAP 2009**
Party Wall u-value	Assumed to be 0 W/m^{2}K	Allows input of value ranging from 0-0.5 W/m^{2}K to account for specification details
Thermal Bridging	Allows assumed Y values to be used to calculate non-repeating thermal bridges	Default Y value of 0.15 used in the absence of details calculation of individual thermal bridges
Air Conditioning and Cooling	Considers the risk of summer overheating but does not quantify the impact of use of cooling systems	Assesses the need for cooling and calculates the additional energy requirements and carbon emissions resulting from associated system operation
Thermal Mass	Thermal mass considered for summer overheating calculation	Thermal mass considered when calculating heating and cooling requirements
Hot Water	No automatic reduction in hot water usage levels associated with low use properties	Assumed hot water usage is reduced by 5% in properties designed to require under 125 l of total water per person per day
Multiple Heating or Ventilation Systems	Limited to one main and one secondary heating/ventilation source	Ability to split heating/ventilation demand between two main heating systems that utilise different fuels and/or two ventilation systems
Heat Pumps	Coefficient of Performance (COP) is a fixed value	COP is provided by the heat pump manufacturer via an integrated product database

As indicated in Table 5-3, SAP 2005 does not take account of the thermal properties of the party wall, as at this point in time it was assumed that the u-value would be zero. However, due to the research described in Section 3.1.2, it has since been found that this is not strictly the case and the party wall cavity can, in fact, act as a heat loss pathway in a dwelling.

SAP 2009 subsequently introduced the functionality to input data relating to the party wall, but in the data presented in Table 5-2, a u-value of 0 has been assumed to replicate the analysis undertaken during the original SAP 2005 assessment. However, if a party wall u-value of 0.5 (standard value for unfilled cavity) is inputted into the model for the original house unmodified, it would result in an increase in fabric HLC of 23.38 W/K. This is not insignificant, and is of a similar level to that observed at Elm Tree Mews and Stamford Brook (Bell, M. et al., 2010a; Wingfield, J. et al., 2011a; Wingfield, J. et al., 2008), confirming the validity of those investigations and findings with regard to the thermal bypass mechanism described in Section 3.1.2.

In relation to the level of ventilation heat losses, there is an increase of 15.97 W/K (Original House) and 6.66 W/K (Phase 1) when the data from SAP 2005 is inputted into the SAP 2009 software. The SAP 2005 value for the Original House model is 126.66 W/K, which is greater in the SAP 2009 model at 141.63 W/K. In the case of the Phase 1 house, the relevant values are 67.17 W/K and 73.63 W/K for the SAP 2005 and SAP 2009 data respectively. Ventilation effects are more visible in the house prior to any improvement work, which would be expected due to the presence of additional inherent background infiltration due to the lower airtightness levels.

Identical air permeability data has been used to calculate the infiltration rate in both cases (the assessor inserted equivalent values of 19 $m^3/(h.m^2)$ @ 50Pa for the original house and 15.8 $m^3/(h.m^2)$ @ 50Pa for the Phase 1 house). Therefore, the increase in ventilation heat losses is most likely due to the monthly average wind speed data embedded in SAP 2009 to calculate the adjusted air infiltration rate. The value of background infiltration rate is adjusted for monthly wind effects and then the adjusted infiltration rate is used to calculate monthly effective air change rate, which is then applied to provide a monthly ventilation heat loss value. In SAP 2005, the calculation was less detailed and was based upon a yearly average effective air change rate.

In SAP 2009, the adjusted air infiltration rate data is combined with the fabric heat loss value on a monthly basis, before an average value of the summed data provides a total HLC value. It would explain why the differences between the two total HLC values are virtually identical to the ventilation losses, as the increase in the total HLC in each case is directly attributable to this parameter.

The SAP Rating determined for both cases appears to be more sensitive to the changes introduced in SAP 2009 calculation techniques than the Environmental Impact (EI) Rating. In both cases, the EI Rating only increased by a factor of 1, while the SAP Rating increased by 3 or 4. However, this does not affect the actual band for either rating assigned to the property in any of the examples.

Whilst it is strictly outside the scope of this research project, it is interesting to note that Primary Energy, the approximation of the total energy demand of a property per m^2 per year, decreases in both of the SAP 2009 models as compared to the SAP 2005 calculations. Changes to the way in which the space heating requirement is calculated can probably be attributed as the main reason for this reduction.

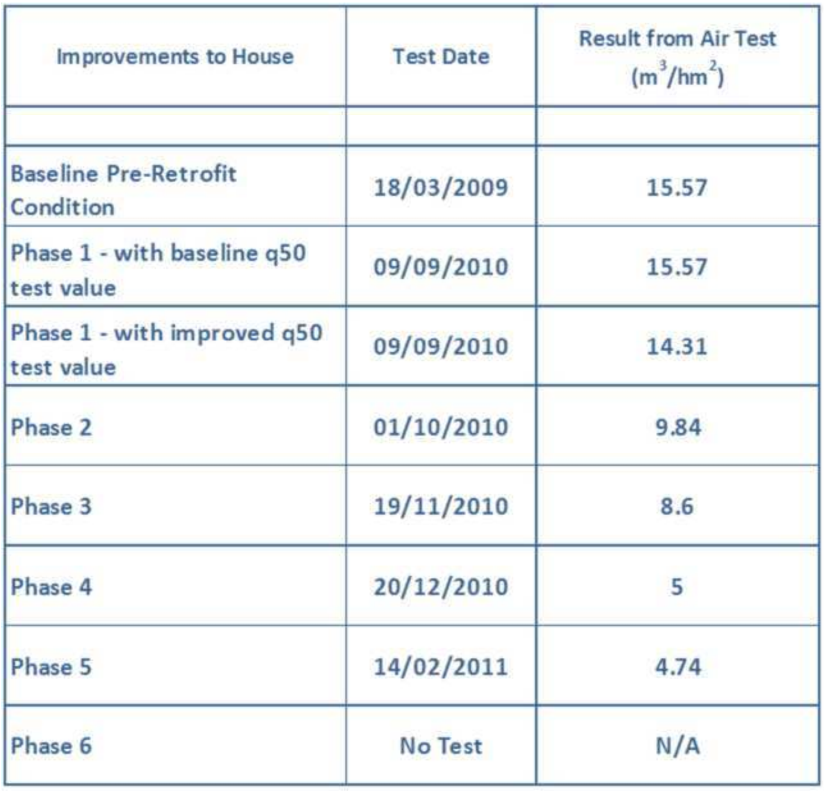
As explained by Ingram et al. (2011), the space heating requirement in SAP 2005 is based upon total internal gains and HLC data, whilst in SAP 2009 the average internal and external temperatures are also used in the calculation. SAP 2009 is also based on monthly data, while SAP 2005 utilised annual data. The use of more detailed data within the updated model allows greater consideration of the sensitivity of heating requirements to environmental effects, such as external temperature and level of solar gains, leading to more accurate, and often lower, final calculations.

5.4 Air Pressure Testing

Having established a base-case design stage HLC for the dwelling, investigation into fabric performance commenced, concentrating on post-construction analysis of the completed dwelling. An air pressurisation test was completed at several key points during the staged retrofit project, by a third party certified assessor utilising the blower door methodology described in Section 2.3.1. The results of the various tests completed are included in Table 5-4.

As would be expected, the air pressure test results reduce considerably as fabric and airtightness improvements are made to the dwelling. The decrease in air leakage values observed between Phases 1 and 2 was much smaller than expected, as it was anticipated that the integration of wall and roof insulation and replacement of single glazing with double glazed units would significantly improve air tightness (Gillott *et al.*, 2013a).

Table 5-4 - E.On House - Air Pressure Test Values



Improvements to House	Test Date	Result from Air Test (m^3/hm^2)
Baseline Pre-Retrofit Condition	18/03/2009	15.57
Phase 1 - with baseline q50 test value	09/09/2010	15.57
Phase 1 - with improved q50 test value	09/09/2010	14.31
Phase 2	01/10/2010	9.84
Phase 3	19/11/2010	8.6
Phase 4	20/12/2010	5
Phase 5	14/02/2011	4.74
Phase 6	No Test	N/A

As shown in Figure 5-3, thermal imaging revealed that the Phase 1 draught proofing measures and sealing to the windows and doors had not been completed to a satisfactory level.

Figure 5-3 - E.On House - Air Leakage Thermal Imaging

The images clearly indicate heat losses through these elements, and so Phase 2 works included the application of further draught-proofing measures. The improvement in airtightness recorded at this point then aligned more readily with expectations.

The most significant area of work in terms of reduction of the air pressure test result can be attributed to the sealing of the ground and upper floors during Phase 4. This resulted in a value of 5 $m^3/(h.m^2)$ @ 50Pa, against an original figure of 15.57 $m^3/(h.m^2)$ @ 50Pa) and Phase 1/2 value of 9.84 $m^3/(h.m^2)$ @ 50Pa. When it is considered that the wall/roof insulation and glazing improvements combined achieved a reduction of 5.73 $m^3/(h.m^2)$ @ 50Pa, the further 4.84 $m^3/(h.m^2)$ @ 50Pa accredited to the floor sealing works alone is quite considerable. This demonstrates that it is extremely important to ensure that an air tight seal is present at the junction between the floor and wall elements in order to restrict heat losses via this pathway (Gillott *et al.*, 2013b).

5.5 Initial Coheating Test – November 2010

A coheating test was undertaken in relation to the E.On House in November 2010, following the completion of the Phase 3 improvements (air tightness of 8.6 $m^3/(h.m^2)$ @ 50Pa). The methodology outlined in Sections 2.3.2 and 4.5.2 was utilised, and the data is included in Appendix 5. Linear regression was first used to calculate a HLC for property using the measured temperature and raw power data, as shown in Figure 5-4.

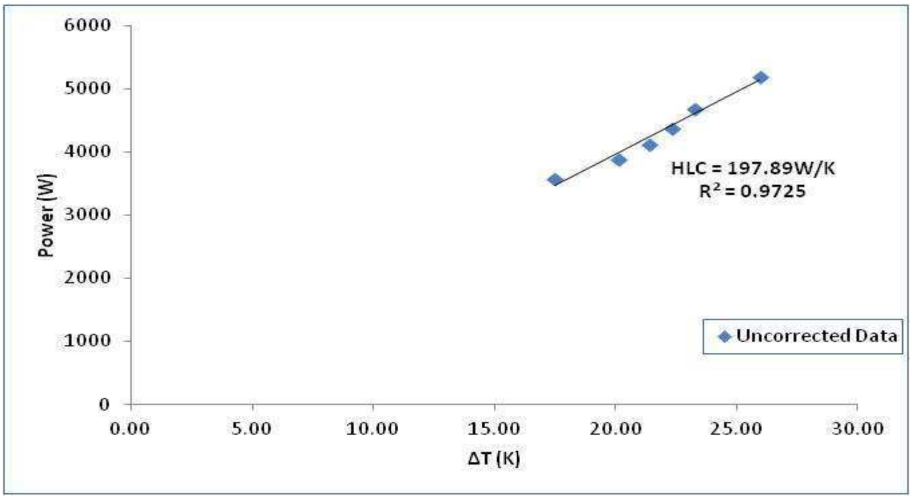


Figure 5-4 - E.On House November 2010 Coheating Test – Uncorrected Data

The calculated HLC is given as 197.89 W/K, and the R^2 value indicates a strong linear relationship between the variables. However, the heat input into the property during the test may not truly represent the level of energy required to maintain a constant internal temperature due to the impact of solar gains. Therefore, solar data was obtained from a local weather station situated approximately 150m from the dwelling, in order to correct the raw power data for solar contribution. Multiple regression was used to obtain a factor in order to correct for solar gains, which was then applied to the original power data. Figure 5-5 shows the resulting linear regression analysis, derived from the adjusted power data.

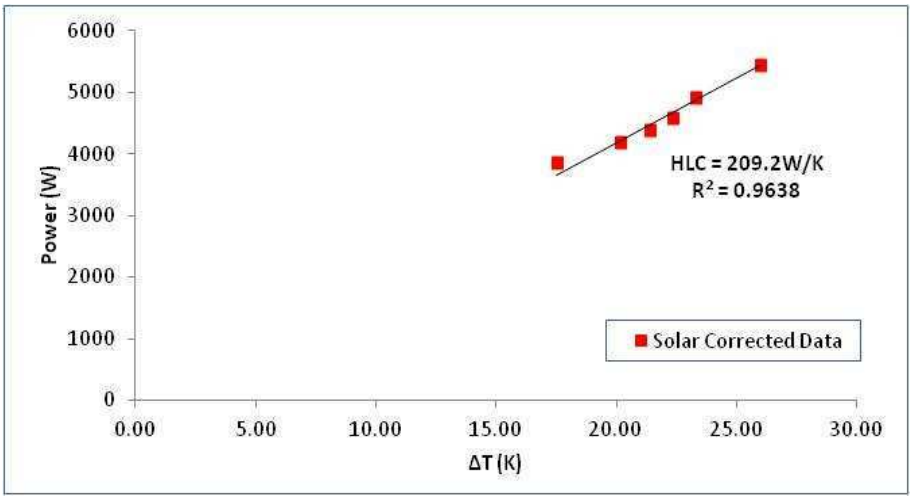


Figure 5-5 - E.On House November 2010 Coheating Test - Solar Corrected Data

It is evident that there is some influence from solar gains during the test, with the solar corrected HLC being 209.20 W/K as compared to the uncorrected value of 197.89 W/K. The high R^2 value leads to a good level of confidence in the data. The corrected HLC is 11.31 W/K higher than that calculated from the raw power data. This reflects the environmental conditions at the time, as the test was conducted on a number of clear days with moderate levels of solar irradiance.

The more concerning aspect of this test result is that it is considerably lower than the baseline SAP 2009 results generated using SAPPER 9 (Case 7). Whilst the condition of the house had changed in the time elapsed between the assessments, this was not considered to account for the 208.15 W/K difference between the Phase 1 SAP value obtained from the data supplied by the original assessor (417.35 W/K) and the measured coheating test value of 209.2 W/K. The possible cause of this divergence was further explored in the next stage of evaluation work.

5.6 Modified SAP 2009 Assessment

Whilst the initial predicted HLC cannot be directly compared to the first coheating test measured value due to improvements made to the building fabric, the exceptionally high level of divergence did present a cause for concern. A review of the design-stage and post-construction information was undertaken, which included re-measurement of floor and element areas, and research into final specified u-values for materials used. The key cases examined in the theoretical modelling work are summarised in Table 5-5.

A revised SAP model was constructed in SAPPER 9 (Case 3 and 6), in order to obtain an indication of thermal performance that was more representative of the completed dwelling in the original and Phase 1 states. This work is summarised in Table 5-6.

Table 5-5 - E.On House Key SAP Analyses

Reference Name	Description
Case 1	SAP 2005 Original House Assessment (No MVHR)
Case 2	SAP 2009 Assessment based on Case 1 data input (No MVHR)
Case 3	SAP 2009 Original House Assessment with as-built data (No MVHR)
Case 4	SAP 2005 Phase 1 Assessment (No MVHR)
Case 5	SAP 2009 Assessment based on Case 4 data input (No MVHR)
Case 6	SAP 2009 Phase 1 Assessment with as-built data (No MVHR)
Case 7	SAP 2009 Phase 3 Assessment (No MVHR)
Case 8	SAP 2009 Phase 3 Assessment (With MVHR)
Case 9	SAP 2009 Phase 4 Assessment (No MVHR)
Case 10	SAP 2009 Phase 4 Assessment (With MVHR)
Case 11	SAP 2009 Phase 6 Assessment (No MVHR)

Table 5-6 - SAP 2009 Adjusted Values

	Fabric Heat Losses (W/K)	*Ventilation Heat Losses (W/K)*	*Heat Loss Coefficient (W/K)*	*SAP Rating*	*EI Rating*	*Primary Energy (kWh/m^2/ year)*	*Space Heating(kWh/ m^2/year*
Unadjusted Original House (no retrofit work)	653.24	141.63	794.87	6(G)	8(G)	770.9	293.14
Adjusted Original House (no retrofit work)	419.67	68.26	487.93	36(F)	33(F)	420.8	182.86
Difference	-233.57	-73.37	-306.94	+30	+25	-350.1	-112.96
Unadjusted Phase 1 House	343.52	73.83	417.35	28(F)	28(F)	481.93	150.84
Adjusted Phase 1 House	192.61	64.43	257.04	74(C)	73(C)	146.84	89.91
Difference	-150.91	-9.4	-160.31	+46	+45	-335.59	-60.93

It became clear that the information inputted into the original 2005 model, then transposed into SAP 2009, did not accurately reflect the final state of the dwelling. In respect of the Original House data, the HLC value derived from the SAP 2005 using unadjusted data was 794.87 W/K, whilst the model created using known data gave a reduced value of 487.93 W/K.

The amended data was inputted into the SAPPER 9 software, and an attempt was made to quantify the contribution of each aspect of divergence of 306.94 W/K between the two versions. Each parameter was altered independently using a one at a time approach, in order to estimate the W/K difference attributable to each factor. Table 5-7 shows the information obtained from this exercise.

It can be seen that the total W/K value obtained slightly exceeds the difference noticed between the two models. This is possibly because of the difficulties of isolating the effect of adjusting the floor area within the SAP software, as changing this value would have influenced the resultant data throughout the analysis. It could also be due to the need to change area and u-value data for each element simultaneously, in order to gain an estimate of the true impact of u-value variance within the model. Another area of ambiguity could relate to the treatment of party walls, as the unadjusted model appears to take account of this within the external wall measurement.

It is interesting to note that minor alterations to the window, door and floor areas and u-values have very little influence on the overall calculations, and collectively balance to almost a nil effect. The subjective assessment of the level of sheltering to the property does have a small effect on the data, and the use of measured air pressure test data also affects the HLC to a notable extent.

Table 5-7 - Original E.On House - HLC W/K Variances for Key Input Data

Parameter	Original House – Unadjusted Model	Original House - Adjusted Model	HLC Contribution (W/K)
Floor Area	108.08m^2	107.82m^2	Accounted for in alterations
Air Permeability	19	15.57	+13.45
Sheltered Sides	1	2	+4.54
Door Details – Solid (area and u-value)	6.65m^2 3.00W/m^{2}K	1.91m^2 4.08W/m^{2}K	+6.85
Door Details – Glazed (area and u-value)	Included	1.91m^2 3.00W/m^{2}K	Included
Window Details (area and u-value)	24.47m^2 4.03W/m^{2}K	28.52m^2 4.03W/m^{2}K	-4.47
Floor 1 Details (main house) (area and u-value)	43.34m^2 0.68W/m^{2}K	42.43m^2 0.72W/m^{2}K	-0.95
Floor 2 Details (kitchen) (area and u-value)	9.46m^2 1.00W/m^{2}K	10.27m^2 0.99W/m^{2}K	-0.83
Floor 3 Details (bay window) (area and u-value)	2.48m^2 0.81W/m^{2}K	2.42m^2 0.81W/m^{2}K	+0.05
Wall 1 Details (masonry external) (area and u-value)	129.53m^2 1.39W/m^{2}K	63.57m^2 1.29W/m^{2}K	+109.37
Wall 2 Details (bay window) (area and u-value)	8.56m^2 1.69W/m^{2}K	6.72m^2 1.39W/m^{2}K	+21.34
Wall 3 Details (coal house) (area and u-value)	Included	10.61m^2 1.19W/m^{2}K	Included
Wall 4 Details (cladded external) (area and u-value)	Included	5.76m^2 0.25W/m^{2}K	Included
Roof 1 Details (main roof) (area and u-value)	71.55m^2 2.10W/m^{2}K	53.18m^2 1.63W/m^{2}K	+66.23
Roof 2 Details (over hang) (area and u-value)	2.49m^2 3.15W/m^{2}K	1.93m^2 3.15W/m^{2}K	+17.79
Thermal Bridging	Assumed (y value 0.5)	Assumed (y value 0.15)	+80.23
Total			**313.60**

The main areas contributing to the large difference observed between the models are the roof and wall details. In the case of the roof, it appears that the original assessor used a different technique to measure the roof area, taking it to relate to the pitched roof rather than to the flat area over the ceiling plan. The latter approach results in a smaller area being used to determine heat losses. This measurement technique has been selected due to the intention to insulate at this level in future retro-fit phases. The difference in methodology is responsible for almost 30% of the divergence in data, which is essentially due to a data input error rather than the calculation methods included in the SAP methodology.

Measurement of the external wall areas is another aspect that contributes greatly, and is responsible for over 40% of the difference in HLC value. The assumptions made by the original assessor are not known with regard to this, so it is difficult to make detailed observation on this matter. However there is an obvious difference in the method used to determine external wall areas, which may be in part due to the treatment of the party wall.

Thermal bridging calculations are also a key influence, where the use of calculated data reduces the HLC in the unadjusted model by 25%. Whilst the default Y value within SAP 2005 was 0.15, the level of thermal bridging included by the original assessor indicates that larger allowances (0.5) were made within their model. It is possible to input this data manually within the SAP based software packages.

A similar exercise was undertaken with respect to the E.On House Phase 1 data, as shown in Table 5-8. An unadjusted HLC of 417.35 W/K was provided in the initial assessment, which is 160.31 W/K higher than the version constructed using updated details (257.04 W/K). After adjustment, there is still a heat loss difference of 10.81 W/K unaccounted for. This could be largely due to the factors outlined previously in respect of the Original House analysis.

The main areas of discrepancy are similar to those observed in relation to the Original House assessments. The contribution from the roof details has reduced significantly, as has that from the external wall to some extent, due to the lower u-values now achieved in the property through installation of insulation. Thermal bridging has the same absolute value as no change has been made to this aspect of the structure, but has a more pronounced effect in the more airtight and thermally efficient property as heat losses through other means are reduced.

All of the factors highlighted in this analysis demonstrate the importance of accurate data entry and the need to realign initial models with updated data in order to obtain a more fair representation of the thermal performance of a dwelling.

Table 5-8 - Phase 1 E.On House - HLC W/K Variances for Key Input Data

Parameter	Phase 1 House – Unadjusted Model	Phase 1 House - Adjusted Model	HLC Contribution (W/K)
Floor Area	108.08m^2	107.82m^2	Accounted for in alterations
Air Permeability	15.80	14.31	+4.57
Sheltered Sides	1	2	+3.84
Door Details – Solid (area and u-value)	6.65m^2 3.00W/m^{2}K	1.91m^2 2.82W/m^{2}K	+11.73
Door Details – Glazed (area and u-value)	Included	1.91m^2 1.7/m^{2}K	Included
Window Details (area and u-value)	24.47m^2 1.59W/m^{2}K	28.52m^2 1.5 & 1.7W/m^{2}K	+2.73
Floor 1 Details (main house) (area and u-value)	43.34m^2 0.68W/m^{2}K	42.43m^2 0.72W/m^{2}K	+2.9
Floor 2 Details (kitchen) (area and u-value)	9.46m^2 1.00W/m^{2}K	10.27m^2 0.99W/m^{2}K	+3.01
Floor 3 Details (bay window) (area and u-value)	2.48m^2 0.81W/m^{2}K	2.42m^2 0.81W/m^{2}K	+3.9
Wall 1 Details (masonry external) (area and u-value)	129.53m^2 0.54W/m^{2}K	63.57m^2 0.554W/m^{2}K	+33.15
Wall 2 Details (bay window) (area and u-value)	8.56m^2 0.69W/m^{2}K	6.72m^2 1.39W/m^{2}K	-3.16
Wall 3 Details (coal house) (area and u-value)	Included	10.61m^2 1.19W/m^{2}K	Included
Wall 4 Details (cladded external) (area and u-value)	Included	5.76m^2 0.19W/m^{2}K	Included
Roof 1 Details (main roof) (area and u-value)	71.55m^2 0.15W/m^{2}K	53.18m^2 0.164W/m^{2}K	+4.77
Roof 2 Details (over hang) (area and u-value)	2.49m^2 3.15W/m^{2}K	1.93m^2 3.15W/m^{2}K	+1.84
Thermal Bridging	Assumed (y value 0.5)	Assumed (y value 0.15)	+80.23
Total			**149.50**

5.6.1 SAP 2009 Assessments for Each Phase of Retrofit

The work undertaken in Section 5.6 enabled a greater degree of confidence to be placed in the data used to construct the SAP 2009 model. Therefore, the design-stage HLC for each phase of the retrofit project, as described in Section 5.1, was calculated through use of SAPPER 9. Measured air permeability values were used, as obtained through the air pressurisation method and presented in Section 5.4. No pressurisation test was undertaken following Phase 6, and so the data from the most recent test (Phase 5) was used in the calculations. It is assumed that this value would have remained relatively constant, as the retrofit measures during Phase 6 were related to fabric upgrades rather than draught proofing or improvements to air tightness.

Table 5-9 and 5-10 show the relevant information for the property in a naturally ventilated and mechanically ventilated (MVHR) state. When a natural ventilation strategy is applied to the model, the largest impact on the HLC values is related to fabric upgrades, with most of this work occurring between Phases 1 and 2 and Phases 5 and 6. The reduction in HLC attributable to these two areas comprises 255.94 W/K (almost 90%) of the total decrease in this parameter. The air tightness works between Phases 2 and 5 account for the remaining 10% improvement. A similar trend is apparent in the Primary Energy and Space Heating demand data. This demonstrates that ensuring that the building envelope is thermally effective is of key importance, with additional air tightness measures providing some, but not as extensive, benefits.

It is interesting to observe the different trend in the data contained in Table 5-10 as compared to the naturally ventilated case presented in Table 5-9. In Table 5-10, a ventilation strategy utilising an MVHR system is applied to the data from Phase 2 onwards (the point at which the MVHR system was installed in the E.On House).

Table 5-9 - SAP 2009 Assessment Data for Each Phase of Retrofit (Natural Ventilation)

	Fabric Heat Losses (W/K)	Ventilation Heat Losses (W/K)	Heat Loss Coefficient (W/K)	SAP Rating	EI Rating	Primary Energy (kWh/m^2/year)	Space Heating (kWh/m^2/ year
Original House	419.67	68.26	487.93	36(F)	33(F)	420.8	182.66
Phase 1	192.61	64.43	257.04	74(C)	73(C)	146.84	89.91
Phase 2	192.61	53.46	246.07	75(C)	74(C)	140.87	84.73
Phase 3	192.61	51.13	243.74	75(C)	75(C)	139.59	83.62
Phase 4	192.61	46.16	238.77	76(C)	75(C)	136.83	81.22
Phase 5	192.61	45.90	238.51	76(C)	75(C)	136.69	81.1
Phase 6	167.15	45.90	213.05	77(C)	77(C)	124.41	70.42

Table 5-10 - SAP 2009 Assessment Data for Each Phase of Retrofit (MVHR in Operation from Phase 2 Onwards)

	Fabric Heat Losses (W/K)	Ventilation Heat Losses (W/K)	Heat Loss Coefficient (W/K)	SAP Rating	EI Rating	Primary Energy (kWh/m^2 /year)	Space Heating (kWh/m^2/ year
Original House	419.67	68.26	487.93	36(F)	33(F)	420.8	182.66
Phase 1	192.61	64.43	257.04	72(C)	71(D)	159.53	89.91
Phase 2	192.61	51.37	243.98	73(C)	73(C)	150.17	84.67
Phase 3	192.61	46.18	238.79	74(C)	73(C)	147.52	82.37
Phase 4	192.61	31.14	223.75	75(C)	75(C)	139.7	75.58
Phase 5	192.61	30.06	222.67	75(C)	75(C)	139.13	75.09
Phase 6	167.15	30.05	197.20	77(C)	77(C)	126.57	64.17

Figure 5-6 displays this more clearly, with the original house HLC value omitted as this was the same in both cases.

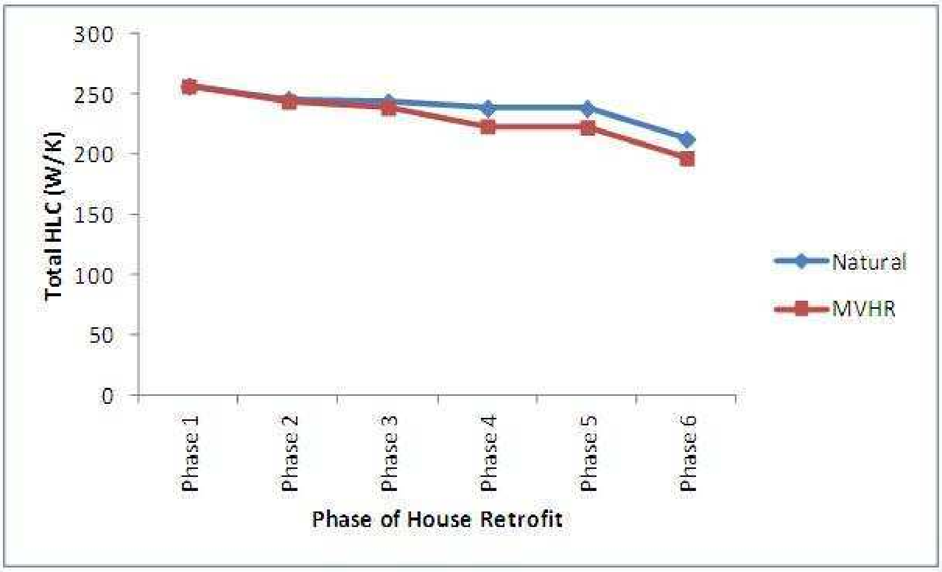


Figure 5-6 - Impact of Ventilation Strategy on HLC

The integration of the MVHR system into the model results in a consistent decrease in HLC value, suggesting that it presents a more efficient ventilation strategy as compared to natural ventilation. This conflicts with conclusions drawn from earlier research into the E.On House, which observed that an MVHR system would not become an effective ventilation option until airtightness levels of approximately 3 to 5 $m^3/(h.m^2)$ @ 50Pa were achieved (Banfill et al., 2011a; Banfill et al., 2011b). In the data presented here, a saving against natural ventilation is realised at 8.6 $m^3/(h.m^2)$ @ 50Pa.

Investigation into possible causes for this discrepancy revealed that part of the issue may be related to the treatment of natural ventilation in the SAP methodology. An additional uplift of 0.5 ACH rate is applied to the effective air change rate associated with background infiltration levels during the calculation, and so increases the overall ventilation rate for this strategy. This may apply in a non-airtight dwelling, where it is anticipated that occupants will open windows and trickle vents in order to maintain a good level of air quality. However, when the building envelope is increasingly sealed, and an MVHR unit is installed as the means of ventilation, this is no longer the case.

It was therefore concluded that background infiltration rate, with no allowance for natural ventilation, would be a more appropriate value for comparison against both the MVHR modelled data and the measured coheating test HLC results. This contention is further supported when the condition of the property during the coheating test is considered, with all windows and vents closed to prevent all but background fabric infiltration losses.

5.6.2 Design-Stage HLC Values for Comparison to Measured Data

In order to calculate the background infiltration design-stage HLC values, the SAP methodology for this component of the calculation was exported into a specifically constructed Excel spreadsheet. This was necessary as, within the software and SAP worksheet, this value cannot be treated separately prior to application of an additional ventilation strategy. Table 5-11 shows the theoretical background infiltration only values derived using this approach, applying SAP embedded generic monthly wind speed data, for both the unventilated and mechanically ventilated conditions.

The data is now more comparable to the situation observed in previous work associated with MVHR systems, where operational effectiveness is not apparent until a highly air tight building envelope is attained. The point at which the MVHR system becomes the more efficient ventilation is clearly at Phase 6, where a pressure test result of 4.74 $m^3/(h.m^2)$ @ 50Pa, in conjunction with additional fabric improvements, results in a lower HLC for this modelled state as compared to background only infiltration.

Table 5-11 - E.On House Background Infiltration Only and MVHR in Operation HLC Values

	No Additional Ventilation (Background Infiltration only)			MVHR Ventilation		
	Fabric Heat Losses (W/K)	Ventilation Heat Losses (W/K)	Heat Loss Coefficient (W/K)	Fabric Heat Losses (W/K)	Ventilation Heat Losses (W/K)	Heat Loss Coefficient (W/K)
Original House	419.67	64.91	484.58	419.67	75.10	494.77
Phase 1	192.61	59.99	252.60	192.61	70.18	262.79
Phase 2	192.61	41.31	233.92	192.61	51.49	244.10
Phase 3	192.61	36.39	229.00	192.61	46.57	239.18
Phase 4	192.61	20.65	213.26	192.61	30.84	223.45
Phase 5	192.61	19.67	212.28	192.61	29.85	222.46
Phase 6	167.15	40.49	207.64	167.15	29.85	197.00

The relationship between the two sets of HLC values is shown in Figure 5-7.

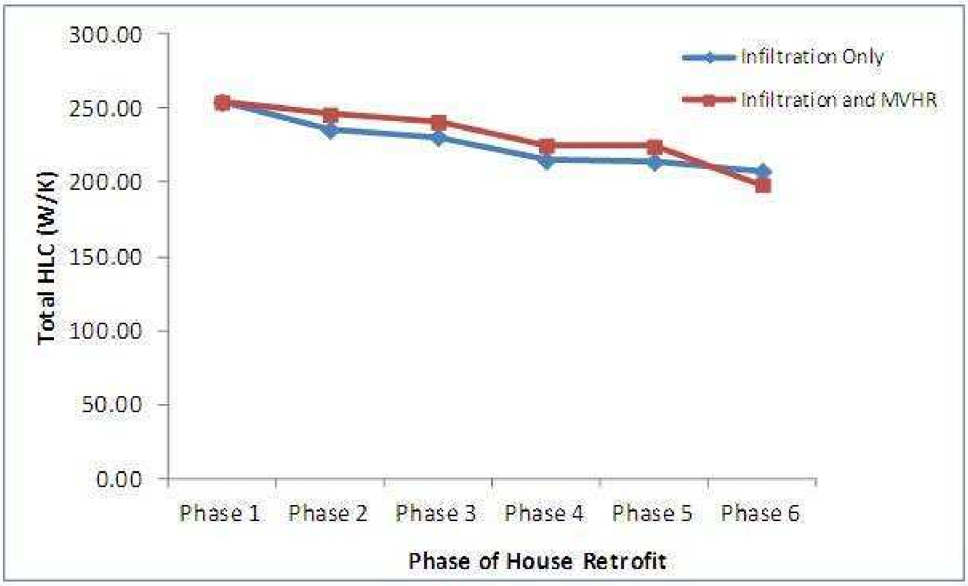


Figure 5-7 - E.On House - Background Infiltration Only and MVHR in Operation HLC Relationship

The interrogation of the integrity of natural ventilation HLC data for use as a design-stage benchmark has suggested that it perhaps does not provide an equivalent value for comparison with measured coheating test results. Background infiltration values may be more appropriate, due to the fact that the coheating test is undertaken in sealed conditions with no natural ventilation. Comparison of the data with previous research undertaken regarding ventilation strategy on the property appears to support this assertion, and so the values of HLC utilising background infiltration only data will be used throughout this analysis. In addition, local daily wind data will be introduced into the bespoke spreadsheet for evaluation of the coheating test HLC, in order to include empirical data and adjust for wind conditions relevant to the site at the time of each test.

5.7 Coheating Test – Ventilation Strategy – November 2010

The data from the initial coheating test detailed in Section 5.5 was reassessed following the adjustment of the SAP model parameters, and the data is included in Appendix 5. A design-stage HLC (Case 6) was calculated utilising background only infiltration rates, an air pressure test result of 8.6 $m^3/(h.m^2)$ @ 50Pa, and relevant daily wind speed data. This produced a predicted HLC value of 205.26 W/K, which can be compared against the measured coheating test result of 209.2 W/K, corrected for solar gains using multiple regression analysis. The two values are very close, and the difference of 3.94 W/K (less that 2% disparity) is within the scope of error attributable to the methodology used to derive either HLC value. This indicates that the post-construction fabric performance of the property is aligning with design-stage prediction.

Due to the apparent agreement between the two HLC values, and the availability of the E.On House for further testing at this time, the opportunity was presented to undertake a second coheating test but with altered ventilation conditions. Immediately following the completion of the initial test, the MVHR outlet vents were unsealed and the system was activated. The HLC calculated from the uncorrected data amounted to 239.84 W/K, and increased minimally to 241.57 W/K when corrected for solar radiation effects. The background infiltration only HLC calculated for the property with an airtightness of 8.6 $m^3/(h.m^2)$ @ 50Pa and MVHR ventilation strategy operating at the manufacturer stated 90% level of efficiency was 222.68 W/K.

It can be seen that there is now a larger divergence between the predicted and measured HLC data. This is displayed more clearly in Table 5-12.

Table 5-12 - Impact of Ventilation Strategy on HLC

	SAP Heat Loss Coefficient (HLC) W/K	Regression Analysis Heat Loss Coefficient (HLC) W/K	Difference (W/K)	Difference (%)
EOn House - Background Infiltration Only	205.26	209.20	3.94	1.92%
EOn House - MVHR in Operation	222.68	241.57	18.89	8.48%
Difference (W/K)	17.42	32.37		
Difference (%)	8.49%	15.47%		

The W/K difference between the design stage and solar corrected measured data values has increased by almost five times (in absolute terms) when the MVHR system is in operation, with approximately 8.5% discrepancy now apparent between the two values. This is still relatively low when considered in the context of the analysis as a whole, although the magnitude of difference between the design and measured HLC attributable to the difference in ventilation strategy remains quite considerable.

It is also interesting to note that the MVHR system increased the energy demand of the dwelling by about 15% as compared to the infiltration only base-case coheating test result. This is over 50% more than the increase observed in the equivalent predicted HLC values calculated using SAP principles. In order to determine whether the actual function of the MVHR system, rather than the methodology used to derive the theoretical and post-construction HLC data, was affecting the results, further analysis of the MVHR system was undertaken.

Temperature probes were placed into the supply and extract ductwork 500mm from the MVHR control unit in the loft space to depth of 70mm in each duct (one third of total diameter to ensure unrestricted air flow), and a power meter was installed in order to collect data relating to system energy consumption. Using internal dwelling temperature data, it was possible to assess the overall temperature efficiency of the system, using the methodology outlined in Sections 2.3.3 and 4.7. Several tests were undertaken, and the measured post-installation efficiency was found to be 81%. This was not surprising, given the difficulties that can be encountered when retro-fitting an MVHR system into an existing property. However, the SAP-based design-stage HLC was calculated based on an assumed manufacturer specified efficiency of 90%, and so this could be erroneously reducing the predicted HLC value.

In addition, system flow rates were measured at each supply and extract duct within the living space of the house using a Testo 417 vane anemometer, in order to evaluate air throughout through the MVHR system. The supply ducts were located in the living and dining rooms and each of three bedrooms, while the extract ducts were situated in the kitchen, bathroom and toilet.

The SAP methodology assumes that the supply and extract flow rates within the system are balanced, and both supply and extract flow rates are fixed at 0.5 ACH per hour. In practise, this may not always be the case, which may impact upon the performance of the heat recovery potential of the ventilation system. When the supply and extract rates are not equal, the dwelling may be placed in a pressurised or depressurised state, which could result in the absolute loss of warm air that cannot be heat recovered. It may also influence natural infiltration levels within the property.

Table 5-13 contains the data obtained during the testing process.

Table 5-13 - E.On House MVHR System Flow Rate Data

	Supply Flow Rate (l/s)	Supply Flow Rate (ACH)	Extract Flow Rate (l/s)	Extract Flow Rate (ACH)	Balance
E.On House - MVHR System Evaluation	40.68	0.55	32.35	0.44	+0.11ACH

In terms of actual air throughput in l/s, a comparison can be made with the optimum levels specified in literature for a Titon HRV2 QPlus system, where the system specified flow rate is 33 l/s (Titon, 2009). This is slightly lower than that measured on site (an average supply/extract flow rate of 36.515 l/s). The finding of the most concern within the data is that the system is placing the dwelling in an artificially pressurised state, with an over-supply of fresh air as compared to extract levels, which could ultimately lead to increased heat losses due to additional air movement through the building fabric.

The measured extract rate of 0.44 ACH is lower than the 0.5 ACH rate that is assumed in calculations embedded within the SAP methodology, whilst the supply rate is higher at 0.55 ACH. However, both are close to the theoretical values used within the model. The difference of 0.11 ACH between the two values represents the imbalance within the system.

The results obtained from the tests associated with the MVHR function show that the assumed values of 90% efficiency and 0.5 ACH rate are not providing a fair design-stage HLC value, as this level of performance was not being achieved by the system at the time of the coheating test. Therefore, further analysis was undertaken in order to align the SAP predicted data with the conditions relevant during the post-construction evaluation, as detailed in Table 5-14.

Table 5-14 - Adjusted HLC Data Following MVHR System Assessment

	SAP Heat Loss Coefficient (HLC) W/K	Regression Analysis Heat Loss Coefficient (HLC) W/K	Difference (W/K)	Difference (%)
EOn House - Background Infiltration Only	**205.26**	**209.20**	**3.94**	**1.92%**
EOn House - MVHR in Operation (81% Efficiency)	**226.08**	**241.57**	**15.49**	**6.85%**
Difference (W/K)	**20.82**	**32.37**		
Difference (%)	**10.14%**	**15.47%**		

The use of the adjusted SAP HLC derived for the MVHR system functioning at 81% rather than 90% efficiency affects the difference in HLC value attributable to the function of the MVHR system, reducing the discrepancy between the predicted and measured values by 3 W/K. An additional energy requirement was calculated to account for the pressurised operation of the system, as follows:

0.11 x 264.33 x 0.33 = 9.60 W/K

In this instance, 0.11 represents the additional ACH associated with the system imbalance, whilst 264.33m^3 relates to the dwelling volume and 0.33 is a factor applied to account for the specific heat capacity and density of air. The calculated increase in theoretical heat loss due to the pressurisation effects of the MVHR system amounts to approximately 10 W/K.

The additional heat losses observed in designed and measured HLC attributable to the function of the MVHR system at 81% is 11.55 W/K (32.37 W/K (81%) minus 20.82 W/K (90%)). This is comparable to the 10 W/K calculated in relation to the impact of the system pressurisation effects. An estimate of potential experimental error due to variances within equipment measurements showed that an inaccuracy could exist of approximately +/- 8% in the data.

It can clearly be seen that careful installation and commissioning of the system could have enabled agreement to be achieved between the predicted and observed HLC values, as both poor system efficiency and incorrect flow rates have contributed to the apparent disparity between the original SAP HLC and the coheating test data. The work also emphasises the need to ensure that MVHR systems are designed and fitted correctly, in order to prevent unnecessary heat losses arising from, and reduced effectiveness of, this type of ventilation strategy.

5.8 Coheating Test – MVHR Upgrade Work – March 2011

The investigations undertaken as part of the initial coheating test detailed in Section 5.7 raised concerns as to the performance of the MVHR system installed in the E.On House. The manufacturer expressed an interest in being involved with further investigation work to attempt to resolve the issues of the less than optimum efficiency levels (81%) and the imbalance (+0.11 ACH) associated with the system.

As such, in March 2011, a coheating test was undertaken, with and without the MVHR system in operation, in order to verify and establish the baseline performance levels of the dwelling at this point in time. The data is included in Appendix 5. Since the previous coheating test performed to evaluate the performance of the MVHR system in November 2010, the property had been subjected to a number of fabric upgrades. These correspond to Phase 4 (SAP Case 9 and 10) of the retro-fit programme outlined in Section 5.1, and the property now achieved an air pressure test result of 4.74 $m^3/(h.m^2)$ @ 50Pa. Baseline predicted HLC data was derived using the methodology previously employed, resulting in a value of 173.04 W/K and 184.00 W/K for the dwelling with background infiltration only and MVHR in operation (assuming 90% efficiency) respectively. Table 5-15 contains the coheating test data obtained.

Table 5-15 - Baseline MVHR Coheating Test Data

	SAP Heat Loss Coefficient (HLC) W/K	Raw Coheating Test Heat Loss Coefficient (HLC) W/K	Regression Analysis Heat Loss Coefficient (HLC) W/K
EOn House - Background Infiltration Only	173.07	162.68	171.62
EOn House - MVHR in Operation (Assumed 90% Efficiency)	184.00	165.12	209.80
Difference (W/K)	10.93	2.44	38.18

The impact of solar radiation and the importance of adequate correction for solar effects is clearly apparent within the data. Prior to the application of multiple regression analysis, the uncorrected (raw) measured HLC derived from linear regression misleadingly implies that the dwelling is out-performing the design stage W/K value by a considerable amount. However, when adjustments are made for solar gains using multiple regression, the coheating test HLC increases significantly and exceeds the modelled data. This situation is not surprising, as this series of tests were undertaken in the early spring, during a period when clear skies and sunshine were the prevailing weather conditions.

In terms of the performance of the dwelling, the baseline case with background infiltration included shows that the fabric of the building is performing largely in line with expectations. The MVHR system adds an additional load of 24 W/K, but it is already known that it is not performing to the optimum 90% efficiency levels specified by the manufacturer, and the air throughput is not correctly balanced. The error inherent in the measuring equipment could also be accounting for approximately +/- 14 W/K or 17 W/K for the background infiltration only and MVHR in operation ventilation strategies respectively, thus explaining the apparent over-performance against design expectations observed in the former case.

In order to assess performance of the system at this point in time, measurements of power consumption, duct temperatures, room temperatures and supply/extract flow rates were obtained using the methods already outlined. This resulted in the data displayed in Table 5-16.

Table 5-16 - Experimental Data - E.On House MVHR System

	Supply Flow Rate (l/s)	Supply Flow Rate (ACH)	Extract Flow Rate (l/s)	Extract Flow Rate (ACH)	Balance	Efficiency
E.On House - MVHR System (before work)	51.19	0.85	37.36	0.62	+0.23ACH	76%

The efficiency of the system appears to have reduced further, possibly due to the impact of the fabric improvements undertaken and changes to the airtightness properties of the dwelling. The system supply and extract flow rates have both increased significantly compared to previous tests, by a factor of around 15-20%.

Thermal imaging was used to determine the possible location of heat losses within the MVHR system unit and ductwork situated in the loft. Figure 5-8 illustrates that both the system control unit and heat exchanger, and the ducting in the loft space, were not adequately insulated. It was concluded that increased insulation of all system elements could enable higher temperature efficiencies to be achieved.

Figure 5-8 - Thermal Images of MVHR Control Unit & Duct Work

Modifications were made to the MVHR control box unit, whereby an insulated jacket was fitted in order to reduce heat losses from the heat exchanger at source. Further work was also undertaken to improve the seal at junctions between insulation lengths around the ducting in the loft space. In addition, a variable speed independent fan control was installed, which enabled more refined regulation of air flow rates, due to the ability to adjust the supply and extract fan speeds independently.

Following completion of the improvement works, the MVHR system was recommissioned through adjustment of the supply and extract rates using the control unit and fine-tuning at individual supply and extract vents. The design flow rate of 33 l/s was attained. Subsequently, as a direct result from this research, the manufacturer now utilises independent fan control units as standard on all of their MVHR units, due to the ease with which it enables balanced system air throughput levels to be achieved.

Further investigation of the MVHR system performance enabled evaluation of the effect of the new controller and enhanced insulation. This involved a coheating test, and re-measurement of system efficiencies and flow rates, with the latter data shown in Table 5-17.

Table 5-17 - E.On House MVHR System Data (Improved)

	Supply Flow Rate (l/s)	Supply Flow Rate (ACH)	Extract Flow Rate (l/s)	Extract Flow Rate (ACH)	Balance	Efficiency
E.On House - MVHR System (before work)	51.19	0.85	37.36	0.62	+0.23ACH	76%
E.On House - MVHR System (after work)	33.74	0.56	28.89	0.48	+0.08ACH	90%

The measured flow rates following the installation of the new controller are significantly lower than those present prior to the works, and are more comparable to the optimum air throughput values suggested by the manufacturer (33 l/s) but remain in excess of minimum required extract flow rates of 21 l/s, as stipulated for a three bedroom dwelling by Building

Regulations 2010 Part F (Department for Communities and Local Government (DCLG), 2010a). The MVHR system is still placing the house in a pressurized state, although the level of air over-supply has reduced considerably. The calculated system efficiency is now 90%, indicating that the heat recovery performance has improved due to the insulation of the control unit and ductwork in order to achieve optimum operational conditions.

A second comparative analysis of the predicted and measured HLC values was undertaken, in order to assess the effect of the improvement works to the overall energy demand of the E.On House. The initial assessment was based on a comparison between the SAP and coheating data, which has now been shown to be inappropriate as the predicted and measured heat loss values were not based on consistent operating conditions due to inefficiencies later measured within the MVHR system. The HLC calculated using SAP assumed a system efficiency of 90%, whilst at the time of the coheating test, the MVHR system was found to be operating at 76% efficiency. The original HLC data did, however, highlight the inefficient working of the system, resulting in further research and system improvements.

It can be seen in Table 5-18 that the increase associated with each ventilation scenario is twice as much for the measured data as it is for the modelled data, with the increased W/K value associated with the lower efficiency accounting for approximately a 23-30% uplift in HLC value against the background infiltration only base case.

This is more clearly demonstrated in Table 5-19 where a direct comparison is made between the three sets of data. As noted previously, the difference between the measured and predicted HLC for the infiltration only baseline case is minimal, which suggests that the fabric of the E.On House is functioning to design levels of thermal performance. However, even when the MVHR system is functioning at 90% optimum efficiency, there is a discrepancy between the two HLC values of 14.50 W/K. This is greater when the system is functioning at 76% efficiency (22.58 W/K).

Table 5-18 - HLC Values for Ventilation Strategies

	SAP Heat Loss Coefficient (HLC) W/K	Increase (W/K)	Regression Analysis Heat Loss Coefficient (HLC) W/K	Increase (W/K)
EOn House - Background Infiltration Only	173.07	14.15	171.62	38.18
EOn House - MVHR in Operation (Measured 76% Efficiency)	187.22		209.80	
EOn House - Background Infiltration Only	173.07	10.93	171.62	26.88
EOn House - MVHR in Operation (Measured 90% Efficiency)	184.00		198.50	

Table 5-19 - Comparison of Predicted and Measured HLC Values

	SAP Heat Loss Coefficient (HLC) W/K	Regression Analysis Heat Loss Coefficient (HLC) W/K	Difference W/K
EOn House - Background Infiltration Only	173.07	171.62	-1.45
EOn House - MVHR in Operation (Measured 90% Efficiency)	184.00	198.50	14.50
EOn House - MVHR in Operation (Measured 76% Efficiency)	187.22	209.80	22.58

The measured supply and extract flow rates appear to remain unbalanced following the system modifications and recommissioning of the system, amounting to the house being pressurised by +0.08 ACH. The equivalent air leakage rate, when calculated as in Section 5.7, suggests that this imbalance could account for increase in the theoretical heat loss of approximately 6.98 W/K (0.08 x 264.33 x 0.33 = 6.98 W/K).

The imbalance is greater prior to the improvement works, where the MVHR system is pressurizing the house with an over-supply of air of +0.23 ACH, which is the equivalent to heat losses of approximately 20.06 W/K (0.23 x 264.33 x 0.33). The impact of the system imbalance is shown in Table 5-20.

Table 5-20 - MVHR Improvement Work - HLC Data

	SAP Heat Loss Coefficient (HLC) W/K	Regression Analysis Heat Loss Coefficient (HLC) W/K	Difference W/K	Heat Loss Due to System Imbalance W/K	Unaccounted Heat Loss W/K
EOn House - Background Infiltration Only	173.07	171.62	-1.45	n/a	n/a
EOn House - MVHR in Operation (Measured 90% Efficiency)	184.00	198.50	14.50	6.98	7.52
EOn House - MVHR in Operation (Measured 76% Efficiency)	187.22	209.80	22.58	20.06	2.52

The data now aligns more closely with the design stage expectations. This demonstrates clearly that it is necessary to ensure that the predicted and measured HLC values are comparable and that the same assumptions are applied to each case. Without adjustments to account for heat recovery inefficiencies and the increased heat losses associated with unbalanced system function, a misleading comparison would have been made using data based on different ventilation scenarios.

Whilst, in this case, that was not exceptionally significant, it does highlight that careful consideration should be given to the installation and commissioning of systems, and to the interpretation of data obtained from design stage and post construction evaluations. The unaccounted for heat loss could be accounted for, in part, by the level of measurement error inherent in the monitoring and recording equipment (approximately +/-8% - equivalent to up to 16 W/K).

If a comparison is drawn between the predicted and measured data for each of the investigations where the house was in a background only infiltration and MVHR ventilated condition, trends can be observed within the data. As shown in Table 5-21, in both cases where there is a reduced efficiency noted in the MVHR system (81% and 76%), the additional measured heat losses associated with the reduced efficiency of the MVHR system are greater than those predicted in the SAP model.

Table 5-21 - HLC Data Comparison - Predicted and Measured Values (Ventilation Strategy)

	SAP Heat Loss Coefficient (HLC) W/K	Difference (W/K)	Regression Analysis Heat Loss Coefficient (HLC) W/K	Difference (W/K)
EOn House - Background Infiltration Only (November 2010)	205.26	+20.82	210.02	+31.55
EOn House - MVHR in Operation (Measured 81% Efficiency)	226.08		241.57	
EOn House - Background Infiltration Only (March 2011)	173.07	+14.15	189.43	+20.37
EOn House - MVHR in Operation (Measured 76% Efficiency)	187.22		209.80	
EOn House - Background Infiltration Only (March 2011)	173.07	+10.93	189.43	+9.07
EOn House - MVHR in Operation (Measured 90% Efficiency)	184.00		198.50	

However, when the MVHR system is operating at optimum efficiency (90%), the values align, and both modelled and measured data indicates an additional uplift for MVHR of approximately 10 W/K. Whilst the actual HLC values still vary between theoretical and observed values, it is interesting to see that the penalty imposed by the SAP methodology for an MVHR ventilation strategy is relevant in practise.

5.9 Coheating Test – Impact of ΔT – February 2011

The standard coheating test methodology developed by Leeds Metropolitan University suggests that, for the duration of a test, a dwelling should be heated to approximately 25°C in order to achieve a sufficient enough temperature difference between internal and external temperatures to obtain representative measured HLC data for the property (Wingfield, J. , 2011). A minimum ΔT value of 10°C is considered to be appropriate, in order to ensure that the direction of heat flow is from the internal space to the external environment (Johnston et al., 2013). This limits the use of the coheating test, as weather conditions required to achieve this state are usually only present in the UK during the winter months. It presents additional issues, as external temperatures are not controllable, and often fall below 0°C during December -

February. This can create a larger ΔT than desired, which may influence the measured HLC values obtained.

A coheating test was undertaken in February 2011 in order to assess the impact of an increased temperature difference on the measured HLC data, and the data is included in Appendix 5. The property was in a physical state as at Phase 5 of the retro-fit programme, and achieved an air pressure test result of 4.74 $m^3/(h.m^2)$ @ 50Pa. An internal temperature of approximately 22°C was maintained for several days, creating an average ΔT of 15K. The internal temperature was then increased by 10C to 32°C, resulting in a mean ΔT of 22 K. The resultant data, both original and corrected for solar gains, is shown in Figure 5-9.

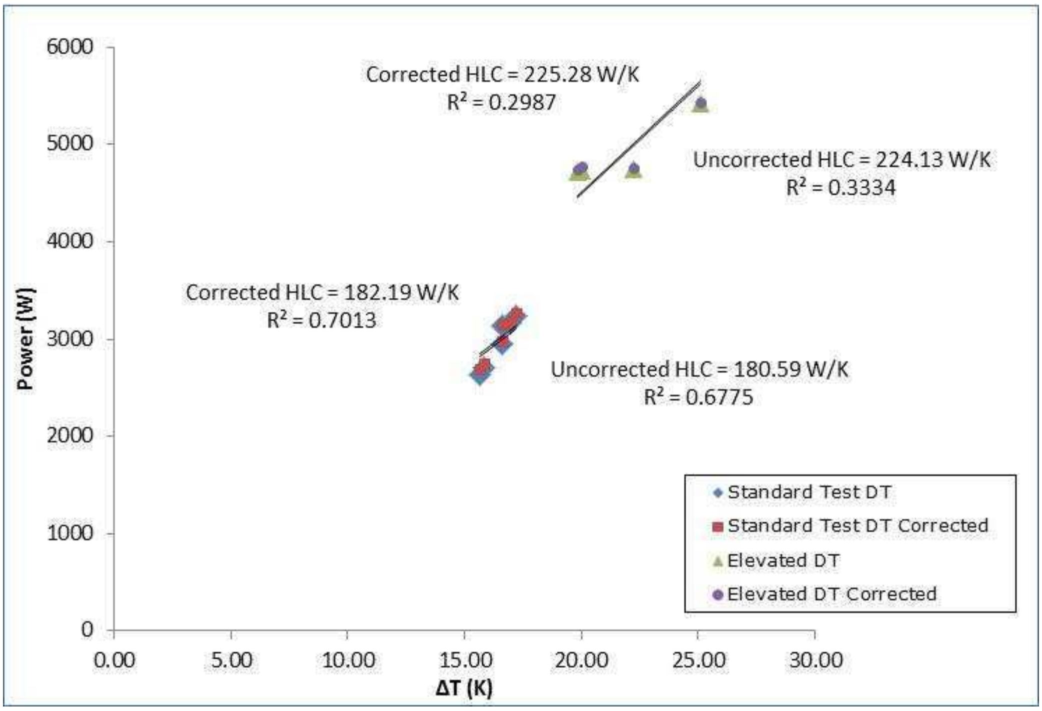


Figure 5-9 - E.On House Coheating Test - ΔT Variances

At the time of the coheating tests, the HLC calculated using the SAP-based methodology provided a predicted value of 204.21 W/K when corrected for local wind speeds relevant at the time of the coheating test, using the spreadsheet included in Appendix 3. The measured HLC data for the test undertaken with a lower ΔT produces a HLC of 182.19 W/K, whilst a value of 225.28 W/K is obtained when a higher temperature difference is employed. This shows an apparent discrepancy between the calculated and measured HLC data of approximately +/- 22 W/K (10%). The effect of solar radiation on the results is minimal in the case of the test period. The experimental error associated with the test could account for up to 8% variance in the results, but may not fully explain the divergence of the experimental results from the predicted HLC data. The r^2 value relating to the test undertaken with an enhanced temperature is low, which could indicate lack of reliability in this data.

When the data from both of the coheating tests is combined, it provides a HLC of 205.46 W/K, as displayed in Figure 5-10. The R^2 value also presents a good level of confidence in the data. The measured value of 205.46 W/K is now almost identical to the calculated design-stage data (205.21 W/K). This is of interest, as it demonstrates the sensitivity of the test to the conditions relevant at the time it is undertaken. It appears that, for reliable and robust data to be obtained, it is essential to complete the procedure over several days with varying external temperatures to achieve a range of ΔT conditions.

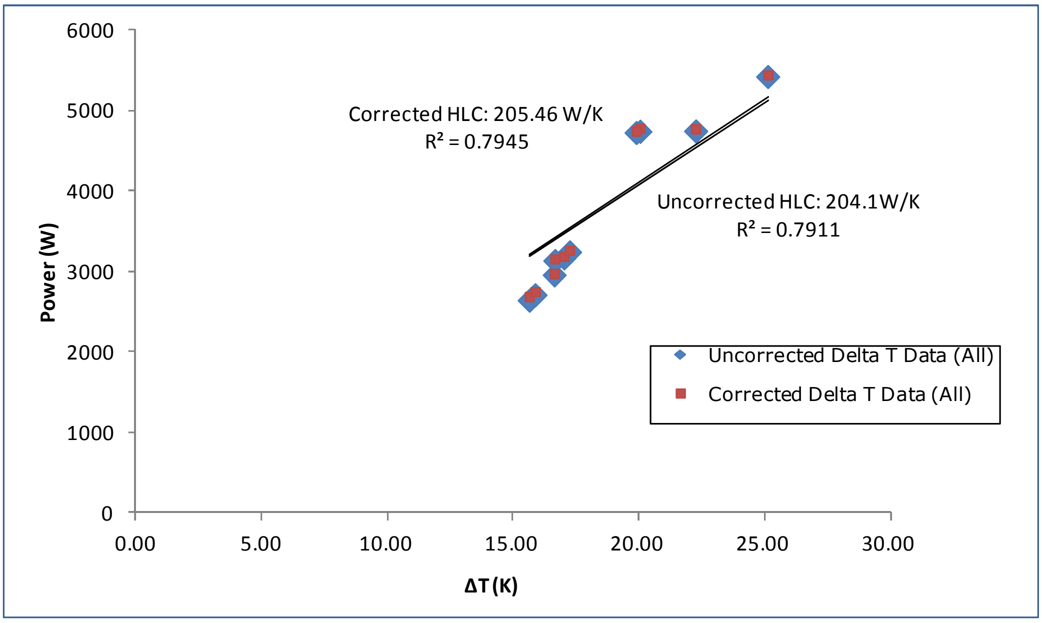


Figure 5-10 - E.On House Coheating Test - Combined Delta T Data

For the combined dataset, an average ΔT of 18.6 K was calculated, which is almost twice the minimum level of 10 K commonly maintained during a coheating test. Indeed, at no point during the testing period was such a low ΔT noted. Despite this, the measured HLC was comparable to the predicted value. There may be scope to undertake the procedure in warmer months with elevated internal temperatures where necessary. However, the practicalities of this may be limited, in terms of potential damage to the dwelling due to excessive heat inputs.

5.10 Coheating Test – Impact of Solar Radiation – April 2012

A final coheating test was completed following the installation of undercroft insulation at the end of Phase 6 (SAP Case 11) of the staged improvements to the E.On House, and the data is included in Appendix 5. At this time, the fabric of the property was improved, but no specific airtightness work was undertaken. An air pressure test result was not obtained at this time, so the previous result of 4.54 $m^3/(h.m^2)$ @ 50Pa has been utilised in the calculations. The design-stage HLC was calculated to be 177.3 W/K. The results of the coheating test are contained in Figure 5-11.

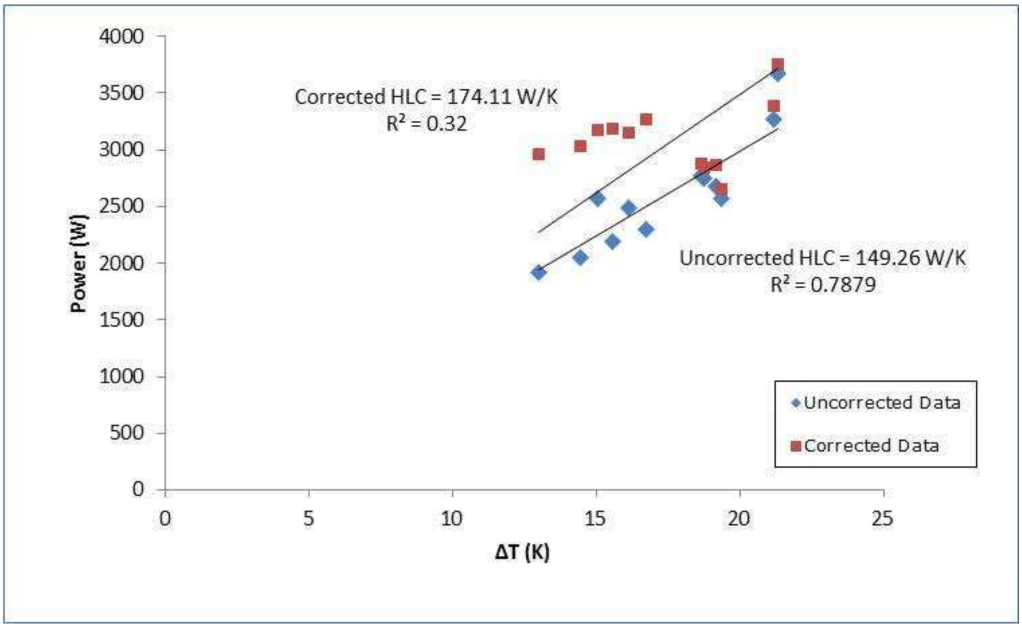


Figure 5-11 - Coheating Test Data - Impact of Solar Radiation

The uncorrected measured HLC was found to be 149.26 W/K, approximately 28 W/K (16%) lower than the SAP calculated estimate. However, once corrected using local daily solar radiation data, the HLC increases to 174.11 W/K, and the gap between the predicted and actual values is reduced to only 3 W/K, which is within the +/- 8% error limit that may be attributable to the accuracy of the monitoring and recording equipment. The r^2 value has reduced following solar correction, due to the spread of the data being increased as a result of temperature and solar radiation fluctuations.

The level of solar effects apparent is not unexpected, due to the test being undertaken in springtime conditions. However, the data does illustrate that correction for solar gains is an essential step in the coheating test calculation and data analysis process. No adjustment would have led to the conclusion that the house was significantly outperforming the design-stage predicted HLC value, which could be misleading and lead to underestimation of energy and space heating demands. The data also shows that, with careful application of the full coheating test practical and analytical processes, it could be possible to obtain reliable data across a wider timescale than solely in winter months.

5.11 Air Tightness, Wind Speeds and HLC Values

Several of the coheating tests completed during the fabric assessment of the E.On House coincided with the improvements work on-going as part of the retro-fit project programme. This data is shown in Table 5-22.

Table 5-22 - E.On House HLC & Airtightness Values

	Air Pressure Test Result ($m^3/(h.m^2)$ @ 50Pa)	**Predicted Background Only HLC (SAP Embedded Wind Speed Data)**	**Predicted Background Infiltration Only HLC (Local Daily Wind Speed Data)**	**Measured Coheating Test HLC (Solar Corrected)**
Phase 3	**8.6**	**229.00 W/K**	**205.26 W/K**	**210.02 W/K**
Phase 5	**4.74**	**212.28 W/K**	**204.21 W/K**	**205.46 W/K**
Phase 6	**4.74**	**207.64 W/K**	**177.33 W/K**	**174.11 W/K**

It is interesting to note that the magnitude in reduction of measured HLC value does not appear to correlate directly with the airtightness improvements implemented between Phases 3 and 5. The data derived directly from the SAP methodology does show a noticeable reduction in HLC when assumed national monthly average wind speed data is used in the calculation. When local wind speed data is applied to the model, the pattern in reduction is similar to that observed on-site, with a greater decrease in both predicted and measured HLC apparent due to the fabric upgrades undertaken between Phases 5 and 6.

This highlights a potential flaw in the SAP baseline methodology, in that the use of generic wind speed data could be significantly affecting the accuracy of the design-stage calculations. For example, if the SAP HLC for Phase 3 is taken, it provides an indicative HLC benchmark of 229 W/K. However, the values observed on site were almost 20 W/K lower than this at 210.02 W/K. This presents the unusual situation where the measured HLC is outperforming the design-stage prediction. However, when the generic wind speed data is replaced with values obtained from a local weather station based 150m from the test property, the measured HLC is now more comparable with the predicted HLC of 205.26 W/K.

The same trend can be seen in the other two datasets presented in Table 6.21. In essence, when local wind speed data is applied to the calculation of the design-stage HLC, the generic SAP HLC is reduced by between 8 and 30 W/K. In all cases, this divergence is significant enough to present the perhaps misleading position that the house is performing more favourably in reality than expected. When the data is realigned by use of the semi-empirical model, it appears that the E.On House does perform in line with, but does not out-perform, design-stage expectations.

5.12 Conclusions

In general, it can be seen that the E.On House does appear to be performing in line with design stage calculated data. However, this observation can only be made following extensive detailed analysis and assessment of the design-stage information used to derive the predicted HLC values. If a concerted effort had not been made to challenge the assumptions and inputs provided by the original assessor, the situation where the dwelling was reflecting a significant post-construction improvement in performance would have been apparent. Indeed, a HLC in excess of 400 W/K, as originally indicated for the dwelling following the Phase 1 improvements, now seems highly improbable in hindsight.

Utilising amended details of dwelling area, elemental areas, elemental u-values and thermal bridges, produced a baseline HLC of 257.04 W/K for the Phase 1 case – a reduction of one third of the initial value. This was further reduced to 252.60 W/K when the background infiltration only case was calculated, removing the effects of assumed natural ventilation strategy from the model. The same methodology was applied to all of the fabric and airtightness cases present throughout the retro-fit works programme. The results obtained throughout the study are summarised in Figure 5-12.

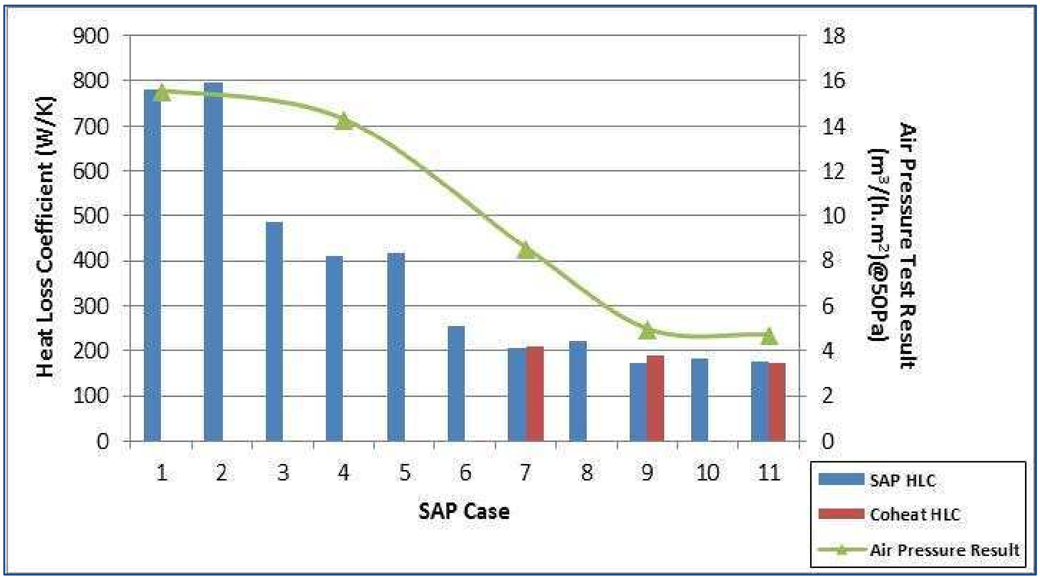


Figure 5-12- Summary of Experimental Data

To enable more direct comparison to be made between predicted and measured HLC values, local wind speed data was integrated into the background infiltration only SAP calculations for the corresponding coheating test dates. This process showed that the use of generic wind speed data in the SAP methodology could undermine the validity of the predicted HLC, as this is based on a fixed average monthly dataset for the East Pennines. When the embedded default data was replaced with empirical data from a local weather station (150m from the test dwelling), the SAP generic HLC was reduced by between 8 – 30 W/K. In some cases, this reduction was in the region of 15% of the initial SAP data. This magnitude of variance resulted in the as-built E.On House appearing to outperform the design-stage HLC predictions prior to adjustment using a semi-empirical approach.

In addition, the data obtained during the series of coheating tests clearly demonstrates the critical importance of applying solar correction to the raw power input that is derived from the testing methodology. This is especially relevant when conducting the process in autumn or spring conditions, where solar radiance levels can be significant. In terms of the work relevant to this study, the correction factor ranged from 1 W/K in the case of the elevated ΔT test undertaken in February 2011, to 45 W/K at the time of the MVHR upgrade works in late March 2011. This represents a 25% increase in HLC in the latter example, which is not an insignificant amount.

In terms of the use of a standardised internal dwelling temperature of 25°C, the evidence presented here would suggest that the main concern is actually to obtain data for a range of ΔT values. If the external temperatures on all of the days of the coheating test remain largely the same, or correspond with a time when there are generally high or low ΔT values, this may contribute to unreliability within the data.

Investigation into the performance of the MVHR system installed as a retro-fit measure in the E.On House revealed that it was not performing to manufacturer predicted efficiency levels and displayed imbalance in supply and extract flow rates. A large divergence in coheating and SAP generated HLC values was partially attributed to additional heat losses arising due to the house being placed in a pressurised state, and also to the inefficiency of the system.

As part of a separate study into further fabric upgrades applied to the E.On House beyond the scope of this research project, assessment of the cavity wall performance was undertaken. This involved placing a series of 21 heat flux sensors on the internal surface of the external walls in one room within the property. A cumulative averaging method was then used to calculate u-value of the wall, and it was found to be 1.01 W/m^{2}K (Wood, C., 2013). This is twice the magnitude of the calculated u-value of 0.55 W/m^{2}K used within the SAP design-stage model.

Further investigation is currently in progress to determine the validity of this result, as at present the measured u-value is calculated from a localised area of the external wall area. However, should the higher u-value of 1.01 W/m^{2}K be found to be correct, it could have great implications in terms of the predicted HLC for the property. An increase in fabric heat losses would be observed in the region of 30 W/K, which is not an insignificant amount. In relation to the E.On

House, this amounts to an increase in space heating energy of approximately 1400 KWh/year (10%), amounting to a cost of £58.94 per year in the case of Phase 6 (the highest performing condition of the E.On House).

When this margin of increase is extrapolated across the existing homes in the UK, £1.6 billion seems to be a high price for the consumer to pay for sub-standard installation of cavity wall insulation, using a unit base rate for mains gas supply of £0.0421/kWh as obtained from the rates used in analysis undertaken by the Energy Savings Trust (Energy Saving Trust (EST), 2014). In addition, the repercussions for the energy demand projections used to measure progress against Government energy efficiency targets would be far reaching, as the resulting underestimation in required energy supply would undermine the accuracy of current evaluations of future needs.

The extensive investigative work associated with the E.On House has enabled a detailed understanding of the fabric performance of the property to be obtained. It has also highlighted some of the key areas of error and uncertainty in both the application of the SAP methodology and use of the coheating test in order to determine an indication of the performance gap through use of the HLC as a benchmark measure. Further evaluation of several of these factors will be undertaken in Chapter 7.

6 THE NEW-BUILD CONTEXT

As explained in Chapter 5, the Tarmac Masonry Research Houses project comprises a pair of semi-detached traditional brick-built dwellings that meet the minimum requirements of the Code for Sustainable Homes (CfSH) Level 4 and Level 6. The Tarmac Level 6 property (referred to herein as The Tarmac House) is utilised in this work as an example of a new-build dwelling. This was selected rather than the Level 4 property as it was uninhabited for several months, allowing coheating tests and assessment of the MVHR system operation to be undertaken. In addition, it provided an opportunity to evaluate a high performance new build property as compared to the E.On House retrofit project.

New build housing in the UK presents an opportunity to make progress towards the UK Government targets to reduce energy demand and carbon emissions in line with the EU 20-20-20 programme. Whilst only 1% of the total UK housing stock comprises of such properties (Department of Energy and Climate Change (DECC), 2009, p. 6), the potential to significantly lower household energy consumption and minimise reliance on mains gas and electricity through improved building fabric and the integration of clean and renewable technologies cannot be ignored. As more dwellings are replaced due to obsolescence, the overall quality of homes will gradually increase naturally due to the improvements being made in newer properties.

Concerns have been raised regarding the desire of the UK population to purchase new homes, due to the general design and layout of such dwellings. A study by the Future Homes Commission (2012) observed that small room sizes, lack of storage and poor natural daylighting levels, poor sound insulation and overcrowded developments/lack of privacy were all cited as reasons why people would prefer to purchase a slightly older property.

Evidence is required in order to persuade the house-buying public that, whilst new-build homes may be more compact and have less innate character than older properties, the energy saving potential of a newer property is considerable enough to make compromises in other areas of the dwelling worthwhile. Understanding of the cost/benefit relationship relating to the integration and operation of renewable energy systems is also limited, with the default position being that individuals revert to ‘known’ fuel supplies such as natural gas and electricity in the face of limited evidence of cost savings (Balcombe *et al.*, 2013).

The Tarmac House project aims to assess the true as-built performance of a highly efficient property, in order to contribute to the evidence base, which may demonstrate that new houses can perform, are a sound investment and are able to provide a good living environment.

6.1 Scope and Methods of Investigation

As outlined previously in Chapter 4, the main techniques that will be utilised throughout the evaluation work will be the interrogation of the design stage SAP assessment, in conjunction with whole house coheating tests, heat flow monitoring and MVHR system evaluation. The experimental work was largely reliant upon the opportunity to access the Tarmac House at opportune times when the residents were away from home. This meant that there was limited opportunity to perform repeat tests or extensive investigations.

In terms of the coheating test, the standard protocol described in Section 4.5.1, with regard to equipment and procedure, was followed. The location of the position of each group of electric fan heaters, circulation fans, power meters, thermostats and dataloggers is shown in Figure 6-1. The property was divided into two zones (the upper and lower floors), with data collected from a datalogger located centrally in each zone.

Several analyses were used to calculate the measured HLC, including linear regression of the data prior to solar correction and linear regression of the data using a solar adjustment derived from multiple regression. The theory behind each method has been detailed in Section 4.5.2, with results presented in this chapter as each test is considered.

Air pressurisation testing, infra-red thermography and MVHR system evaluation work is also used for evaluation purposes, following the approaches described in Chapter 4. In addition, the thermal effectiveness of the party wall was investigated to assess whether manufacturer predicted levels of performance were being realised in practise.

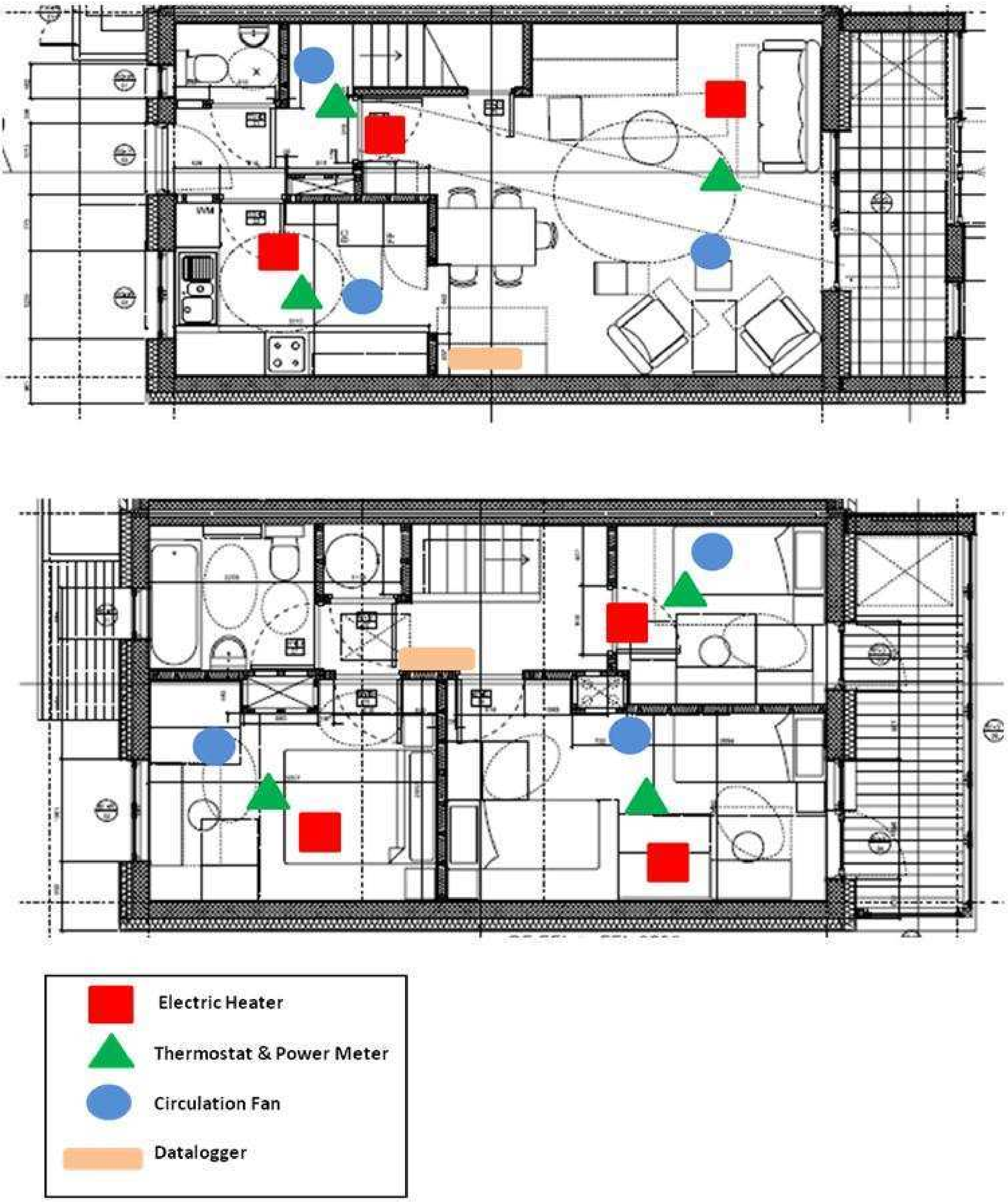


Figure 6-1 - Tarmac House - Position of Coheating Test Equipment

6.2 The New-Build House

In terms of design, the philosophy applied to the Tarmac House was to maximise the thermal potential of the building fabric in terms of thermal mass and passive solar gains and to minimise heat losses from the building envelope. Whilst achieving minimum energy requirements and enhanced carbon savings, the design team also sought to use existing and available, rather than bespoke, products and services in order to reduce costs and maximise the potential for application of a repeatable design suitable for large scale mainstream housing developments. Therefore, the primary aim of the Tarmac Masonry Homes Research Houses project was to design and construct energy efficient traditional masonry homes that are straightforward and cost effective to construct and mass produce, whilst being visually appealing and affordable for potential home owners to purchase, maintain and operate.

The CfSH Level 6 property has a floor area of 94m^2, comprising a single large reception room, kitchen and cloakroom/WC on the ground floor, and three bedrooms and a bathroom on the upper floor. A full height sunspace area provides additional space to the rear of the main living areas, as shown in Figure 6-2 (the externally rendered property).

Figure 6-2 - The Tarmac Research Homes

The design of the property incorporates high levels of insulation in the ground floor/foundation, external wall, party wall and roof construction. The properties of the main building envelope are detailed in Table 6-1.

Table 6-1 - Summary of Fabric and Ventilation Characteristics of the Tarmac House (CfSH Level 6)

Parameter	**Specification**	**U Value (W/m^2K)**
External Walls	215mm DuroxSupabloc lighweight concrete blocks with 150mm expanded polystyrene (EPS) external insulation and rendered finish	**0.15**
Party Wall	Two 100mm Tarmac Hermalite blockwork skins filled with 100mm Isover RD glass mineral wall roll	**n/a**
Internal Walls	Blockwork	**n/a**
Internal Wall Finish	13mm lightweight plaster	**n/a**
Ground Floor	Tarmac Heatsave Plus System - pre-cast concrete beams with pre-formed expanded polystyrene (EPS) infill panels and structural concrete topping	**0.14**
Upper Floor	Pre-stressed hollowcore planks with 65mm screed	**0.15**
Roof	Timber trussed asymmetric roof with traditional felt, battens and concrete tiles	**0.11**
Windows/Doors	Softwood casement frames with argon filled double glazing and IG composite doors	**1.50**
MVHR System	Nuaire MRX Box 90l	**n/a**

An MVHR system was installed in the property due to the high levels of airtightness that were inherently achieved through careful design and product specification. In addition to this, a number of renewable energy technologies were used to further enhance the low energy and carbon load of the property. The two semi-detached houses are heated by means of a shared Okofen biomass wood pellet boiler, capable of generating up to 10 kW output. It uses renewable carbon neutral pellets, and has individual controls incorporated to allow each property to set a different heating regime.

Hot water is provided by two roof mounted flat plate solar thermal panels (total area 3.05 m^2). The hot water storage cylinder has 25 litres of dedicated hot water storage per m^2 of solar panel. The panels are designed to provide up to 70% of occupant hot water demand, and the biomass boiler supplements any additional hot water that may be required at peak times. In addition, a photovoltaic array of 22m is installed on the south facing roof elevation. The panels are mounted at 22°C to the horizon and have an output capability of 3.50kW peak of electricity. Within this property, the panels are designed to generate sufficient energy to power the lights, pumps and domestic appliances.

Rainwater is harvested from the roof and collected in an underground storage tank, which has a capacity of 1000 litres. This feeds all toilets, washing machines and garden watering requirements, and helps to achieve the target internal potable water usage of 80l/person/day.

It can be seen that, if all of the elements of the integrated building materials and systems perform to their expected levels, the Tarmac House does have the potential to provide a high quality living environment whilst proving cost effective and efficient for the residents to manage. The remainder of this chapter seeks to investigate whether the guiding principles of the design have been realised in practise.

6.3 Design Stage Assessment

With respect to the Tarmac House, the assessment of the design stage model was less complex than in the case of the E.On House, as it was a new-build property and no further fabric alterations were made after construction. The key stages undertaken during the research associated with this property are outlined in Table 6-2.

Table 6-2 – Tarmac House Key SAP Analyses

Reference Name	Description
Case 1	SAP 2005 Assessment (With MVHR)
Case 2	SAP 2009 Assessment based on Case 1 data input (With MVHR)
Case 3	SAP 2009 Assessment with as-built data (With MVHR)
Case 4	SAP 2009 Assessment with as-built data (Natural Ventilation)
Case 5	SAP 2009 Assessment - adjusted thermal bridge data (With MVHR)
Case 6	SAP 2009 Assessment - adjusted thermal bridge data (Natural Ventilation)
Case 7	SAP 2009 Assessment - Case 5 data adjusted for local wind speed (With MVHR)
Case 8	SAP 2009 Assessment - Case 6 data adjusted for local wind speed (Background Infiltration)

The information from the original SAP worksheet (Case 1), completed by an independent assessor in October 2009 using NHER software based on SAP 2005 methodology, was transferred into the SAPPER 9 SAP 2009 platform with no resulting impact upon the HLC calculation (Case 2). This value was 58.83 W/K, built up as shown in Table 6-3, based on a ventilation scenario utilising the installed Nuaire MVHR system details.

Table 6-3 - SAP 2005/2009 Tarmac House HLC Values (MVHR In Operation)

	Fabric Heat Loss (W/K)	Thermal Bridges (W/K)	Ventilation Heat Loss (W/K)	Heat Loss Coefficient (HLC) (W/K)
Tarmac House - SAP Data	42.85	3.53	12.45	58.83

In terms of the remainder of the information, whilst it is not within the scope of this research to analyse it in detail, it was interesting to observe that large divergences could be seen between the SAP and EI Ratings and Primary Energy values for the dwelling associated with the SAP 2005 and SAP 2009 methodologies. A brief assessment revealed that the reasons for this discrepancy were mainly related to changes regarding assumed occupancy and internal temperatures in the newer SAP version, which impacted upon the space heating requirement. Also, the costs and savings associated with renewable energy systems had been updated in the underlying database in SAP 2009, and as the Tarmac House has several such systems integrated into the design, this resulted in different treatment of the same data within the model. This made it difficult and impractical to compare the two models in detail, due to the baseline embedded data being considerably different.

6.4 Air Pressure Testing

In order to assess the airtightness of the dwelling, an air pressurisation test was completed by a third party certified assessor utilising the blower door methodology described in Section 2.3.1. An initial test was undertaken after completion of the construction phase in March 2010, with a result of 1.71 $m^3/(h.m^2)$ @ 50Pa. A second test was undertaken in May 2011 following the research undertaken within this study, which produced a value of 1.45 $m^3/(h.m^2)$ @ 50Pa.

The results from the air pressure tests show that the Tarmac House is performing well in terms of air permeability. As detailed in Section 2.3.1, Part L of the current UK Building Regulations specifies a minimum level of 10 $m^3/(h.m^2)$ @ 50Pa, whilst best practice denotes an air permeability of 3 $m^3/(h.m^2)$ @ 50Pa (Energy Saving Trust (EST), 2005). As part of the design philosophy for the property, an air permeability target was set of 2 $m^3/(h.m^2)$ @ 50Pa. The results from post-construction test confirm that this level has been met and exceeded.

It is interesting to note that the infiltration levels for the property have decreased noticeably with time. This could be due to differences within the testing equipment used on each occasion, as there was a long period between the two test dates and different contractors were employed. Error within the test equipment or procedure could affect the reliability and comparability of the data, with a study of 500 homes showing variances of up to 28% observed in measured results (Sherman, M. *et al.*, 1986, p. 5). In addition, environmental conditions at the time when the test is conducted may be a contributing factor to the results obtained. Persily (2013, p. 380) observed that high wind speeds may increase the pressure test data by up to 15%, and that repeated tests on the same property could show a divergence of up to 25% due to seasonal effects.

Generally, it would be assumed that air-tightness of buildings would decrease over time, due to settlement, the drying out process, and cracks and shrinkage developing in building materials (Johnston et al., 2004). Indeed, studies have shown increases in air permeability of between 25% and 80% one year from completion (Miles Shenton *et al.*, 2007, p. 31; Warren et al., 1980, p. 22). There is, however, some counter-evidence to suggest that this is not always the case.

The natural accumulation of dust particles and other matter may have contributed to the apparent improvement in building air-tightness observed in the Tarmac House. Research undertaken by the NHBC (National House Building Council (NHBC), 2011a) aimed to investigate the effect of the passage of time on the airtightness of properties through the repeat testing of 25 homes after a period of one to three years had elapsed. The data showed that almost three-quarters of the properties did have higher pressure test results at the time of the second test, but the remaining dwellings remained consistent or improved on original air tightness levels. It is therefore possible for the situation apparent in the case of the Tarmac House to occur.

6.5 Initial Coheating Test

In December 2010, a coheating test was undertaken in relation to the Tarmac House, utilising the methodology outlined in Section 2.3.2 and Section 4.5, and the data is included in Appendix 5. Solar data was obtained from a local weather station situated 150m from the test dwelling, in order to correct the raw power data for solar contribution using multiple regression analysis. Two test conditions were imposed on the property, firstly with no additional ventilation and then with the MVHR system in operation. Figure 6-3 shows the HLC values derived from the original and solar adjusted data for the unventilated case, whilst Figure 6-4 relates to the test when MVHR was in operation.

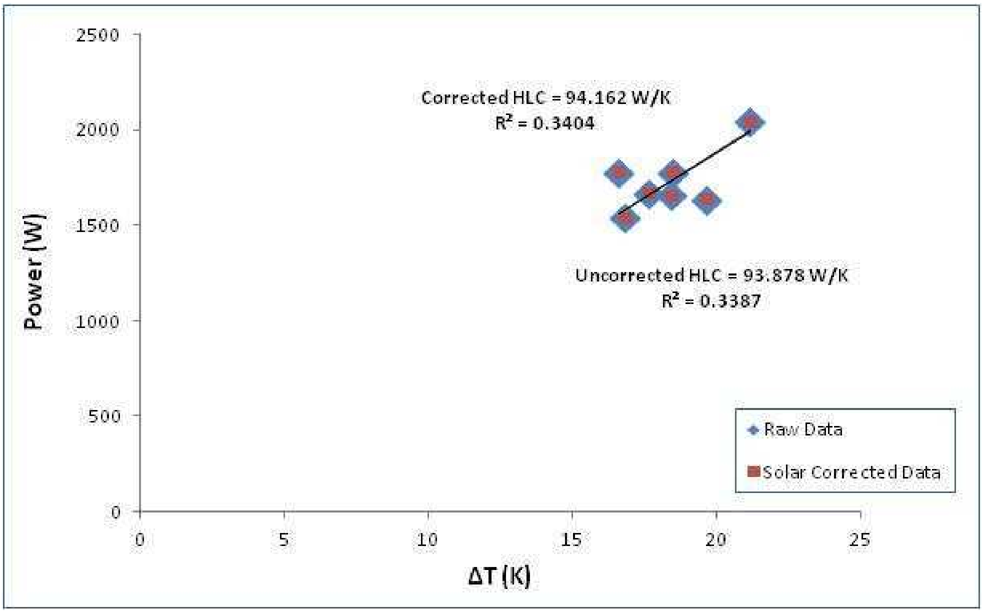


Figure 6-3 - Tarmac House December 2011 Coheating Test Data – No Ventilation

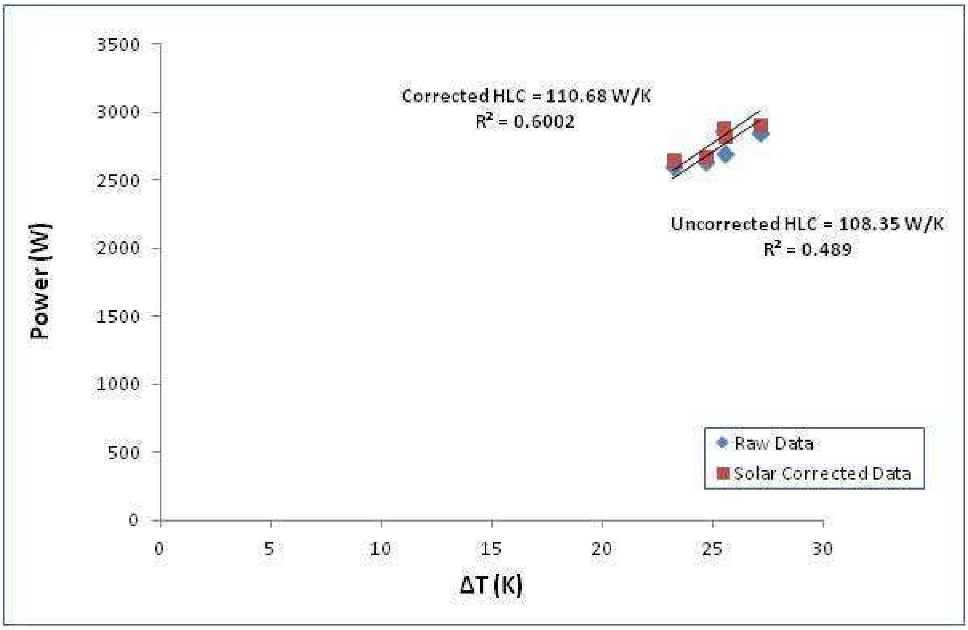


Figure 6-4 - Tarmac House December 2011 Coheating Test Data - MVHR in Operation

The impact of solar gains is minimal in both of the tests, resulting in an adjustment in the data of less than 0.5 W/K in the case of the test with no ventilation and 2.33 W/K when the MVHR ventilated state is considered. This is not surprising, as the experiment was conducted during a period of low solar radiation due to cloud cover and snowfall. Indeed, the high ΔT values observed reflect the unusually low external temperatures experienced during the winter of 2010, as internal temperatures were maintained at between 22°C and 23°C for the duration of the test. The R^2 values are not particularly high for any of the datasets, although correction for solar gains does improve the fit of the data slightly. This could be partly due to error within the test, or potential impacts of heat loss to the adjoining property arising from variances in internal temperatures across the party wall.

An uplift of approximately 15 W/K is observed in the corrected HLC value when the MVHR system is in operation. This matter will be considered more fully in Section 6.7. However, it is concerning to note that the corrected measured HLC of 110.68 W/K is almost twice that of the 58.82 W/K predicted value when the MVHR system is in operation. This is the ventilation case relevant to the SAP 2005 data provided by the original assessor, so the two values should be directly comparable.

6.6 Modified SAP 2009 Assessment

In order to try to understand possible reasons for the performance gap observed, the design stage drawings and specifications, as well as post-construction notes, were studied in relation to the Tarmac House. The work revealed that there were some discrepancies between the original SAP 2005 assessment and the final design details relevant to the property. The amended data was inputted into the SAPPER 9 software (Case 3), and a divergence of approximately 13.21 W/K (18%) was apparent, as shown in Table 6-4. The unadjusted model data relates to the original SAP 2005 assessment (Case 1&2), while the adjusted model values refer to the SAP 2009 version (Case 3).

Table 6-4 - Tarmac House SAP 2009 Original and Adjusted Data

	Fabric Heat Losses (W/K)	Thermal Bridging (W/K)	Total Fabric Heat Losses (W/K)	Ventilation Heat Losses (W/K)	Heat Loss Coefficient (W/K)
Unadjusted Model (With MVHR in Operation)	42.85	3.53	46.38	12.45	58.83
Adjusted Model (With MVHR in Operation)	53.14	3.65	56.79	15.25	72.04
Difference	10.29	0.119	10.41	2.80	13.21
Adjusted Model (Natural Ventilation)	53.14	3.65	56.79	35.99	92.78

A naturally ventilated condition was also modelled, in order to assess the impact of this strategy on the property. It is observed that, due to the air tight nature of the property, the HLC value increases significantly when natural ventilation is included. This is of interest, as occupants may open windows even when MVHR systems are installed, thus undermining the benefits of having such a system.

An attempt was made to quantify the contribution of each aspect of divergence between the original SAP 2005 model and the newly-created SAP 2009 version. As in the case of the E.On House, each parameter was altered independently using a one at a time approach, in order to estimate the W/K difference attributable to each factor. Table 6-5 shows the information obtained during this exercise.

The 9.97 W/K value derived from this process is 3.25 W/K lower than the difference observed between the two models (13.22 W/K). This is possibly due to the overall impact of the larger floor area measured, which is applied to some of the calculations that are embedded in the methodology and so the direct influence is difficult to isolate and quantify. The combined effect of changes to element u-values and areas (excluding doors and windows) amounts to less that 2 W/K of the total difference, suggesting that the information made available to the original assessor was in line with that studied here. However, the treatment of doors and windows has affected the model significantly, with over 80% of the discrepancy attributable to this aspect. This is mainly due to the addition of a larger glazed door and a window to the rear of the property, which appear to have been omitted in the earlier model.

Table 6-5 - Tarmac House - HLC W/K Variances for Key Input Data

Parameter	Tarmac House – Unadjusted Model	Tarmac House - Adjusted Model	HLC Contribution (W/K)
Floor Area	87.88m^2	91.36m^2	Accounted for in alterations
Air Permeability	1.8	1.71	-0.35
Door Details – Solid (area and u-value)	2.15m^2 1.5W/m^{2}K	1.83m^2 1.5W/m^{2}K	+6.08
Door Details – Glazed (area and u-value)	Included	4.33m^2 1.5W/m^{2}K	Included
Window Details (area and u-value)	13.54m^2 1.5W/m^{2}K	15.16m^2 1.5W/m^{2}K	+2.34
Floor Details (area and u-value)	43.94m^2 0.15W/m^{2}K	45.68m^2 0.14W/m^{2}K	-0.16
Wall 1 Details (area and u-value)	49.82m^2 0.12W/m^{2}K	48.19m^2 0.15W/m^{2}K	+0.92
Wall 2 Details (glazed) (area and u-value)	23.27m^2 0.15W/m^{2}K	25.32m^2 0.15W/m^{2}K	+0.35
Roof Details (area and u-value)	43.94m^2 0.10W/m^{2}K	45.68m^2 0.11W/m^{2}K	+0.67
Thermal Bridging	Assessor Calculated (y value 0.0196)	Assessor Calculated (y value 0.0196)	+0.12
Total			**+9.97**

Up until this point, there has been no change made to the level of thermal bridging included in the original SAP 2005 worksheet (Case 1). However, the Y value of below 0.02 used by the assessor does appear to be very low, considering that default levels in SAP 2005 were set at higher levels than this. They were specified as 0.04 for enhanced accredited construction details, 0.08 for accredited details, and 0.15 as the standard value for when no robust information was available for use in the assessment (Energy Saving Experts, 2011). The exact process that the assessor used to derive the value of Y used in the original SAP 2005 model is unknown. As calculated psi values were not given to the assessor, it is probable that this value is an error.

Investigation using infra-red thermography shows that there are some obvious areas of heat transfer and thermal bridging. This is apparent in Figure 6-5, where there are noticeable heat losses occurring at the floor slab/wall junction, at window sills and surrounds, and at the junction between walls. In the image on the right-hand-side, the service box is visible to the side of the doorway, revealing that the integrity of the building airtightness perimeter boundary has been compromised due to service penetrations.

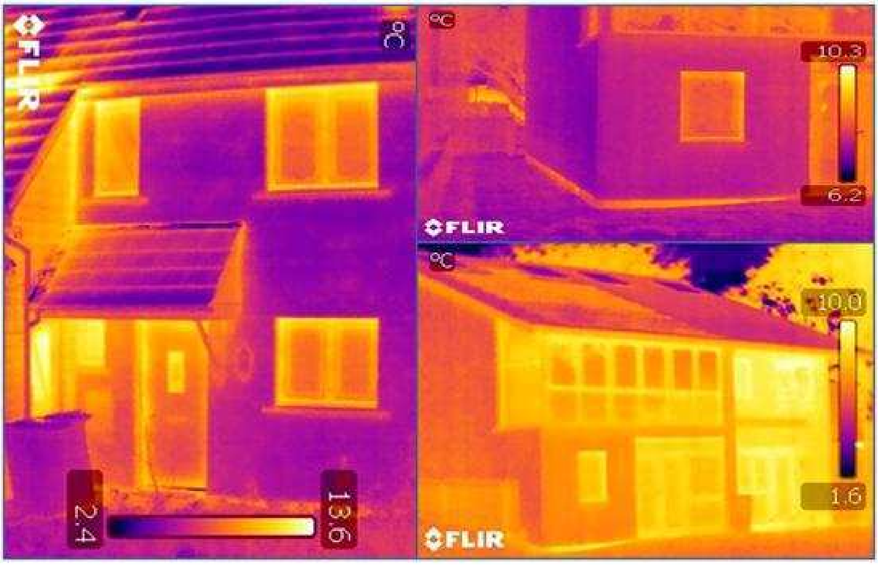


Figure 6-5 - Thermal Images of Tarmac House

This evidence suggests that, in reality, the design stage predicted level of thermal bridging is unlikely to have been achieved in practise. As such, analysis was undertaken to determine the impact of higher levels of thermal bridging on the final HLC value. The amended details outlined in Table 6-5 were used, with the various thermal bridging Y default values that were applicable in SAP 2005 methodology applied to the data, as shown in Table 6-6 (Case 5 and 6).

It can be seen that the Y value used can have a significant impact on the data, with thermal bridging calculations varying from 3.65 W/K to 27.93 W/K within a Y value range of 0.0196 to 0.15. In terms of impact on the predicted HLC, within the Y value range applied to the data the contribution to heat losses attributable to thermal bridging varies from 5% to 29%, which demonstrates the sensitivity of the HLC to this parameter.

The SAP methodology would normally dictate that where exact details of thermal bridges are unknown, the default value of 0.15 should be used. However, it would seem reasonable to assume that the Tarmac House, given that it has been constructed as an exemplar research house, would have been constructed to meet at least accredited construction details, although the thermal imaging survey undertaken has revealed some potential lack of attention to detail during the construction process.

Table 6-6 - Assessment of Different Levels of Thermal Bridge Values

	Thermal Bridging Y Value	Fabric Heat Losses (W/K)	Thermal Bridging (W/K)	Total Fabric Heat Losses (W/K)	Ventilation Heat Losses (W/K)	Heat Loss Coefficient (W/K)
MVHR Ventilation Strategy	0.0196 (as SAP Worksheet)	53.14	3.65	56.79	15.25	72.04
MVHR Ventilation Strategy	0.04 (Enhanced Accredited Construction Details)	53.14	7.45	60.59	15.24	75.83
MVHR Ventilation Strategy	0.08 (Accredited Construction Details)	53.14	14.90	68.04	15.24	83.28
MVHR Ventilation Strategy	0.15 (SAP Default Value)	53.14	27.93	81.07	15.25	96.32
Natural Ventilation Strategy	0.0196 (as SAP Worksheet)	53.14	3.65	56.79	35.99	92.78
Natural Ventilation Strategy	0.04 (Enhanced Accredited Construction Details)	53.14	7.45	60.59	35.98	96.57
Natural Ventilation Strategy	0.08 (Accredited Construction Details)	53.14	14.90	68.04	35.98	104.02
Natural Ventilation Strategy	0.15 (SAP Default Value)	53.14	27.93	81.07	35.99	117.06

A Y value of 0.08 will therefore be used in relation to the thermal assessment of the Tarmac House, in line with this standard. This would account for an additional 14.90 W/K heat loss in the design-stage model, with the resultant effect on the HLC values shown in Table 6-7 (Case 5).

Table 6-7 - Tarmac House - Final SAP 2009 Data

	Fabric Heat Losses (W/K)	Thermal Bridging (W/K)	Total Fabric Heat Losses (W/K)	Ventilation Heat Losses (W/K)	Heat Loss Coefficient (W/K)
Unadjusted Model (With MVHR in Operation)	42.85	3.53	46.38	12.45	58.83
Adjusted Model (With MVHR in Operation)	53.14	14.90	68.04	15.24	83.28
Adjusted Model (Natural Ventilation)	53.14	14.90	68.04	35.98	104.02

Following the alignment of the data to reflect the actual construction details of the Tarmac House, it was then necessary to prepare the design-stage modelled data in order to enable direct comparison with the coheating test results. The methodology employed in Section 5.6.2 was employed, to calculate background infiltration only and MVHR ventilation scenario HLC values. Local wind speed data was also inserted into the model to enable local effects to be taken into account, rather than national average data. Table 6-8 shows the background infiltration only values derived using this approach, for both the unventilated and mechanically ventilated conditions (Case 7 and 8).

Table 6-8 - Tarmac House - Background Infiltration Only Design-Stage HLC Values

	Fabric Heat Losses (W/K)	Ventilation Heat Losses (W/K)	Heat Loss Coefficient (W/K)
Tarmac House - Background Only Infiltration	68.04	2.04	70.08
Tarmac House - MVHR In Operation	68.04	11.32	79.36

The two values are quite similar, with the MVHR system imposing an approximately 9.8 W/K increase in HLC when in operation. The background only infiltration HLC values included in Table 6-8 will be utilised as the design-stage performance benchmark data in relation to the Tarmac House.

6.7 Re-evaluation of Coheating Test Data

A re-evaluation of the coheating data presented in Section 6.5 and included in Appendix 5 was undertaken following the normalisation of the original design-stage data, taking into account variances in the construction of the property. The resulting comparisons are shown Table 6-9. Whilst previously a divergence of up to 90% had been observed between the SAP 2009 model and the coheating test results, this has been reduced by a considerable amount following adjustment of the design stage original SAP 2005 model (Case 1) to reflect final as-built details (Case 7 and 8).

Table 6-9 - Tarmac House - Comparison of Predicted and Measured HLC Values

	SAP Heat Loss Coefficient (HLC) W/K	Regression Analysis Heat Loss Coefficient (HLC) W/K	Difference (W/K)	Difference (%)
Tarmac House - Background Infiltration Only	70.08	94.16	24.08	34.36%
Tarmac House - MVHR in Operation	79.36	110.68	31.32	39.47%
Difference (W/K)	9.28	16.52		
Difference (%)	13.24%	17.54%		

It can be seen that, in both the background infiltration only and MVHR ventilation scenarios, there is still a significant difference of 24 W/K and 31.32 W/K respectively between the SAP derived HLC and that measured in-situ. This amounts to an underperformance in the region of 35-40%. Experimental error could be contributing up to +/- 8% variance in each test, but this would only account for a maximum divergence of approximately 9 W/K. Clearly, further analysis is required in order to attempt to understand the reasons for this discrepancy.

When the design-stage and measured HLC values are considered, the modelled case shows a 9.28 W/K uplift for MVHR operation, while the measured data presents an increase of 16.52 W/K. This results in a 7.24 W/K difference in the additional heat losses attributable to the operation of the MVHR system. Evidently, the use of an MVHR system does increase energy demand above that which is observed when no mechanical ventilation is in operation.

In order to determine whether the actual function of the MVHR system, rather than the methodology used to derive the theoretical and post-construction HLC data, was affecting the results, further analysis of the MVHR system was undertaken. As in the case of the E.On House, system flow rates were measured at each supply and extract duct using a Testo 417 vane anemometer, in order to evaluate air throughout through the MVHR system.

The results from the experimental work are shown in Table 6-10, which show that there is a slight imbalance between the supply and extract rates which imposes a pressurised state on the property. This could result in the absolute loss of warm air that cannot be heat recovered, whilst impacting on natural infiltration levels in the property and air movement through the building fabric.

Table 6-10 - Tarmac House MVHR System Flow Rate Data

	Supply Flow Rate (l/s)	Supply Flow Rate (ACH)	Extract Flow Rate (l/s)	Extract Flow Rate (ACH)	Balance
Tarmac House - MVHR System Evaluation	57.27	0.95	53.36	0.89	+0.06ACH

The manufacturer literature for the Nuaire MRX Box 90l MVHR system installed in the Tarmac House states an optimum flow rate of 55.55 l/s (Nuaire, 2009), which is very close to that seen in practise at the time of testing. The comparison would suggest that the system is generating an air flow in the region of that required for effective performance, although it is over twice the magnitude of the 21 l/s minimum extract rate stipulated for a three bedroom property in Part F of the Building Regulations.

An additional energy requirement was calculated to account for the pressurised operation of the system, as follows:

0.06 x 91.36 x 0.33 = 4.28 W/K

In this instance, 0.06 represents the additional ACH associated with the system imbalance, whilst 91.36 m^3 relates to the dwelling volume and 0.33 is a factor applied to account for the specific heat capacity and density of air. This resulted in an increased theoretical heat loss amounting to 4.28 W/K.

Within the SAP 2009 methodology, an assumed ACH rate of 0.5 is used in the assessment of MVHR function. In this case, the theoretical air throughput level is not being achieved by the system at the time of the coheating test, and so an adjustment is required in order to ensure that the comparison of HLC values is being completed on equal terms. The measured supply and extract flow rates are considerably higher than the SAP assumption, at 0.95 and 0.89 ACH respectively (although these levels are in line with manufacturer recommendations).

It is necessary to adjust the ventilation calculations to reflect the actual ventilation levels over and above the default value of 0.5 ACH used previously. The ventilation heat loss component of the HLC was re-evaluated using an ACH of 0.95. This led to a visible increase in this parameter of 6.53 W/K that can be attributed to the higher ACH measurements observed on site.

The total increase in theoretical heat loss, when the MVHR operation and installation is considered, equate to approximately 10.81 W/K. However, this value then requires a reduction to be considered to account for the impact that the pressurised state may have on the effective background infiltration rate. When this effect is considered (3.6 W/K), the actual increase in overall heat losses amounts to 7.21 W/K. The difference between the predicted and measured values is reduced to almost zero. Both cases now display an uplift of approximately 9 W/K for the use of the MVHR system as compared against the baseline background infiltration only case, as shown in Table 6-11.

Table 6-11 - Tarmac House MVHR System Adjusted Data

	SAP Heat Loss Coefficient (HLC) (W/K)	Regression Analysis Heat Loss Coefficient (HLC) (W/K)
Tarmac House - Background Infiltration Only	70.08	94.16
Tarmac House - MVHR in Operation (Assumed 90% Efficiency)	79.36	110.68
Difference (W/K)	9.28	16.52
Heat Loss Due to System Imbalance (W/K)	n/a	7.21
Heat Loss Associated With MVHR Condition (W/K)	9.28	9.31

Unfortunately, due to the positioning and wiring configuration of the MVHR control box in the Tarmac House loftspace, it was not possible to connect temperature probes within ductwork or a power meter to measure the energy demand of the system. Therefore, post-commissioning efficiency calculations could not be undertaken in relation to this property

However, it would appear that the efficiency of the system is close to the 90% assumed within the SAP 2009 model. When measured additional heat losses are accounted for in relation to system flow rates, the calculated and coheating test data is in agreement with regard to ventilation effects (+9 W/K), leading to the conclusion that efficiency levels are probably being met. However, in the case of the coheating test, the 9 W/K could be attributed partly to experimental error.

6.8 Possible Causes of Fabric Underperformance

The rationalisation of the predicted and measured HLC to account for operational ventilation effects has demonstrated that the MVHR system is functioning at a level that appears to correspond with that assumed in the SAP 2009 model. Also, confidence in the details relating to the building fabric that have been inputted into the theoretical model is relatively high, as comprehensive design stage information was obtained and scrutinised, and compensation has been included for potentially higher thermal bridging effects. However, there is still a considerable difference in both data sets, even following the adjustment of the original SAP assessment undertaken in Section 6.6. This information is summarised in Table 6-12.

Table 6-12 - Tarmac House HLC Data Summary

	SAP Heat Loss Coefficient (HLC) W/K	Regression Analysis Heat Loss Coefficient (HLC) W/K	Difference (W/K)	Difference (%)
Tarmac House - Background Infiltration Only (Original Model)	n/a	n/a	n/a	n/a
Tarmac House - MVHR in Operation (Original Model)	58.83	94.16	35.33	60.05%
Tarmac House - Background Infiltration Only (Adjusted Model)	70.08	94.16	24.08	34.36%
Tarmac House - MVHR in Operation (Adjusted Model)	79.36	110.68	31.32	39.47%

The coheating test value for the scenario where the MVHR strategy is included can be reduced by 7.21 W/K, as this has been found to be attributable to differences between the assumed and actual function of the system. A coheating test value of 103.47 W/K was subsequently calculated, reducing the divergence between the predicted and measured HLC when the MVHR is in operation to 24.11 W/K – a similar magnitude of 35% above the SAP derived value. Low external temperatures, affecting the ΔT, may also account for up to 10 W/K, although this may be accounted for within the range of experimental error associated with the methodology.

The impact of the potential contributors to the divergence in theoretical and physical performance of the Tarmac House are summarised in Table 6-13.

Table 6-13 - Impact of Potential Contributing Factors on Design-Stage and Post-Construction HLC Values

	No MVHR In Operation		MVHR In Operation	
	SAP Heat Loss Coefficient (HLC) W/K	Regression Analysis Heat Loss Coefficient (HLC) W/K	SAP Heat Loss Coefficient (HLC) W/K	Regression Analysis Heat Loss Coefficient (HLC) W/K
HLC Value From Original Assessment/Coheating Test	80.97	94.16	58.83	110.68
Adjusted Value(Design-Stage Information Review)	+11.81	n/a	+13.21	n/a
Thermal Bridge Adjustment (y = 0.08)	+11.24	n/a	+11.24	n/a
Adjustment for Background Only Infiltration & Local Wind Speed	-33.94	n/a	-3.92	n/a
MVHR Flow Rate Adjustment	n/a	n/a	n/a	-7.21
ΔT Adjustment	n/a	-9.42	n/a	-10.35
Final HLC Value	70.08	84.74	79.36	93.12

The performance gap has been reduced considerably from the original 50% magnitude observed between the original assessment values and the measured coheating test HLC data. In the case of the naturally ventilated condition, the adjustment for background infiltration only effects considerably reduced the calculated HLC, which would be expected due to assumptions regarding occupant intervention and standardised ACH rates associated with the calculation of natural ventilation heat losses. Normalisation of the data eventually resulted in an underperformance being apparent, of approximately 14.5 W/K (20%). This was due to equal adjustment (-10 W/K) from the SAP and coheating data contributions.

In terms of the case with MVHR in operation, the apparent performance gap has been decreased from almost 50% to 17 % (14 W/K). The build-up of this reduction is more complex, with an additional 20.5 W/K attributable to modifications to the SAP model, and a reduction of 17.56 W/K applied to the coheating data to account for compromised MVHR operation and environmental conditions present during the testing period. It is interesting to note that the divergence in absolute terms is almost identical for both the background infiltration only and MVHR in operation cases. However, caution should be given to the reduction attributed to low ΔT influences, as a difference in the HLC would not be expected to be observed as the heating demand should be proportional to the temperature differential (and hence a linear relationship). There may be other considerations relating to physical conditions that are contributing to the lack of alignment in data, such as the presence of snowfall.

This leads to a conclusion that the source of the reduced post-construction performance is most probably associated with the physical building fabric of the property, as ventilation effects and many of the errors and assumptions related to the modelled data have been removed or explained. Whilst it was not possible, due to limitations of time and resources, to undertake rigorous assessment of the dwelling, the opportunity was presented to evaluate the as-built performance of the party wall between the two Tarmac Houses.

6.9 Assessment of Party Wall Performance

As shown in Section 3.1.2, a study by Leeds Metropolitan University (Lowe et al., 2007; Wingfield, J. et al., 2010; Wingfield, J. et al., 2007; Wingfield, J. et al., 2009) observed a large discrepancy between the predicted and measured HLC data at Stamford Brook and in housing in Bradford (the Eurisol Project). Further evaluation of the party wall heat flux and temperature profile as part of that work revealed a thermal bypass mechanism that existed within the party wall cavity.

In order to assess whether the party wall constructed between the two Tarmac properties was functioning as intended, an investigation into the heat flow and temperature profile within and across the dividing wall was undertaken. The summary data from this assessment is included in Appendix 6. As Figure 6-6 and Figure 6-7 illustrate, a series of nine heat flux sensors (Hukseflux HPF01 Heat Flux Plates) were installed in a matrix on each side of the party wall.

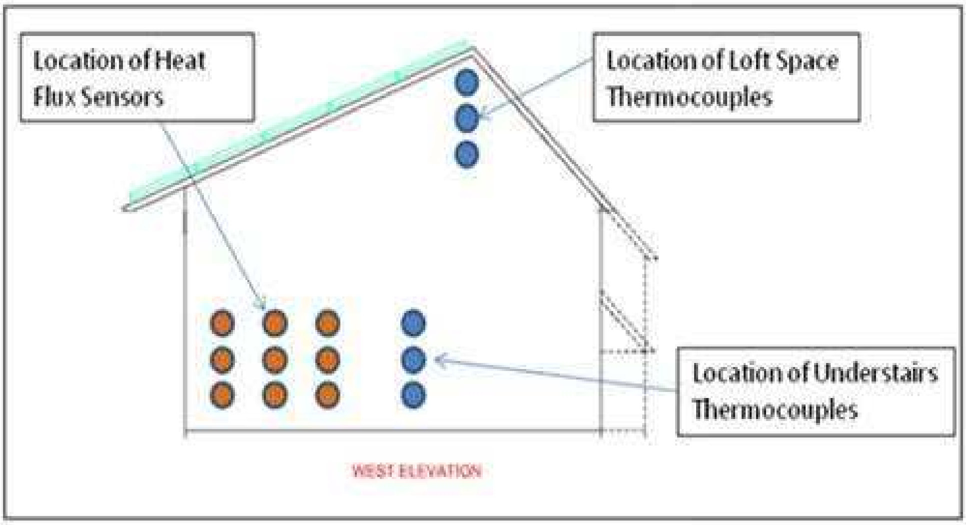


Figure 6-6 - Party Wall Evaluation - Location of Sensors

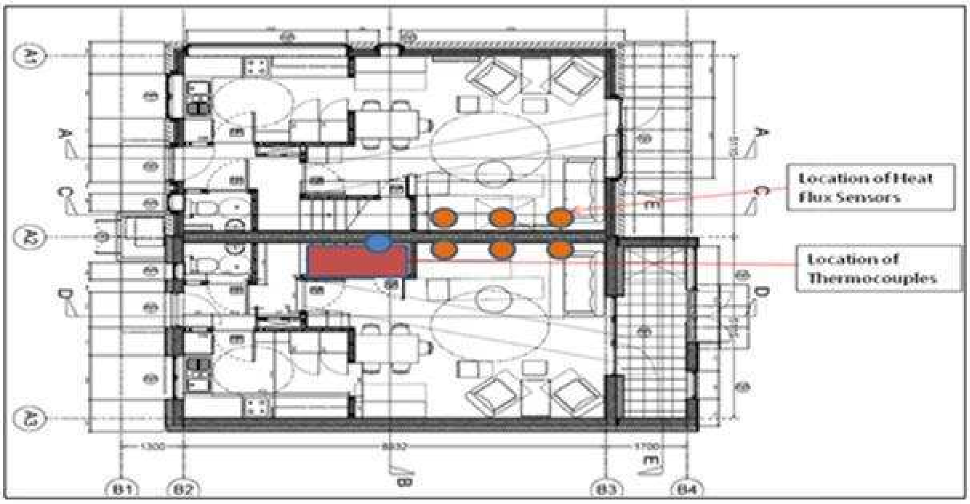


Figure 6-7 - Party Wall Evaluation - Schematic of Sensor Locations

In addition, thermocouples were used in order to measure temperature in the party wall cavity in the heated space (under stairs) and loft area, accessed from the Tarmac House Level 6 property and placed in the positions shown in Figure 6-8. The internal temperature of each property and the external temperature were also recorded over the experimental time period.

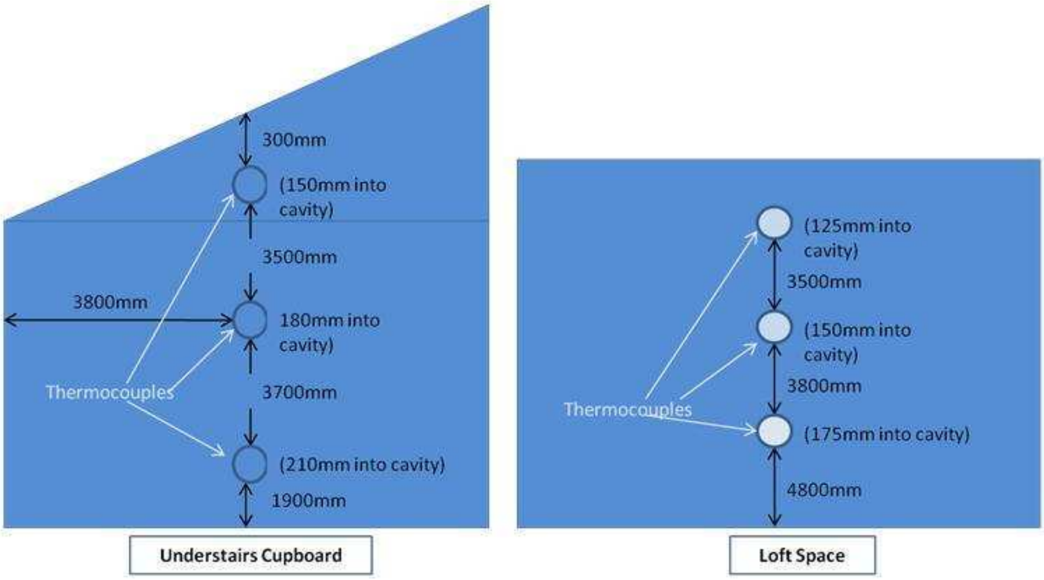


Figure 6-8 - Party Wall Evaluation - Position of Thermocouples

Figure 6-9 displays the temperature data recorded over a two week period. It can be seen that the temperature in the cavity fluctuates in line with the internal room temperature of the property. Conversely, the temperatures in the loft space follow the general trend of the external temperature.

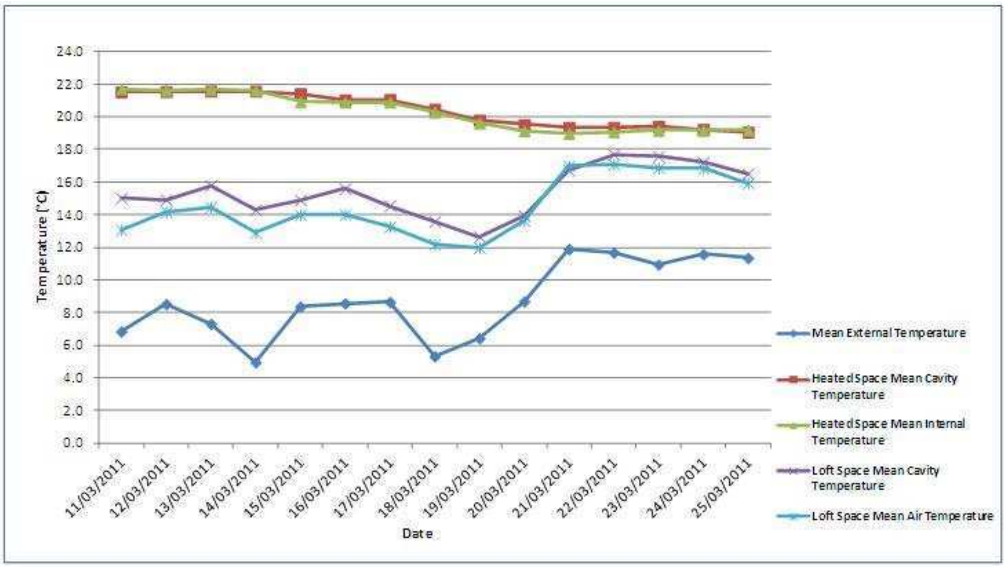


Figure 6-9 - Tarmac House - Internal, External and Within Wall Cavity Temperature Data

This profile is as would be expected, as the air temperature in a well-insulated loft space is influenced by external temperatures rather than the internal temperature of the property, as heat gains from the living space would be minimal. Wingfield (2007) studied the effect of an uninsulated cavity on temperatures within the wall both above and below the ceiling level using cavity socks to prevent air flow. When no barrier was present, they observed that the cavity temperatures below ceiling level generally followed the external temperature, and the loft cavity temperature fluctuated in line with external temperatures (approximately 10-15°C above external temperatures).

When a barrier was placed in the cavity to prevent the potential thermal bypass, the temperatures in the loft cavity continued to follow the external temperature, but the difference between cavity and external temperatures was significantly reduced. The profile of the cavity temperatures below the ceiling level changed dramatically, with cavity temperatures now following the trend of the internal temperatures of the dwelling rather than being responsive to external temperatures. In this study, the party wall between the two Tarmac Houses shows temperature profiles which reflect the 'insulated' condition in the work by Leeds Metropolitan University, demonstrating that the cavity insulation is performing satisfactorily.

Heat flux sensors installed on either side of the party wall were used to monitor the heat transfer in and out of the cavity over a 3 month period. The results are shown in Figure 6-10 and Figure 6-11.

The heat flux in each property follows the general trend of the internal air temperature. The recorded values fluctuate between approximately -3.0 and +4.0 W/m^2, clustered around the zero point. Error associated with the measurement and recording equipment used in the experiment could potentially result in a deviation of +/- 1.5 – 2.0 W/m^2 in the data for each side of the party wall, and so could be a cause of this variance. Wingfield (2009) studied heat flux in a party wall cavity before and after filling with insulation, and the results are reproduced in Figure 6-12.

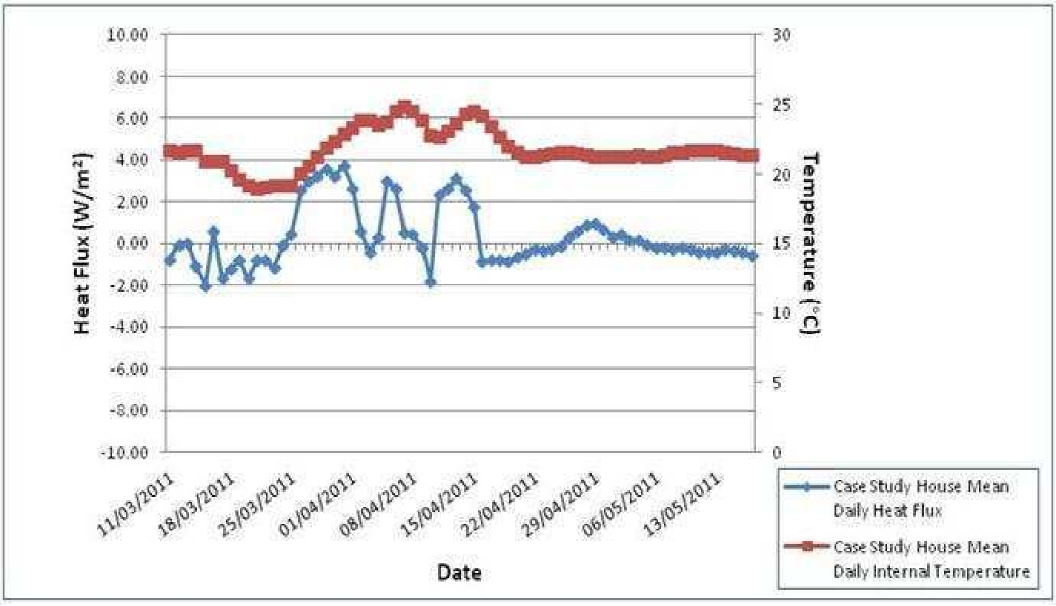


Figure 6-10 - Tarmac Level 6 House - Daily Mean Heat Flux and Internal Temperature Values

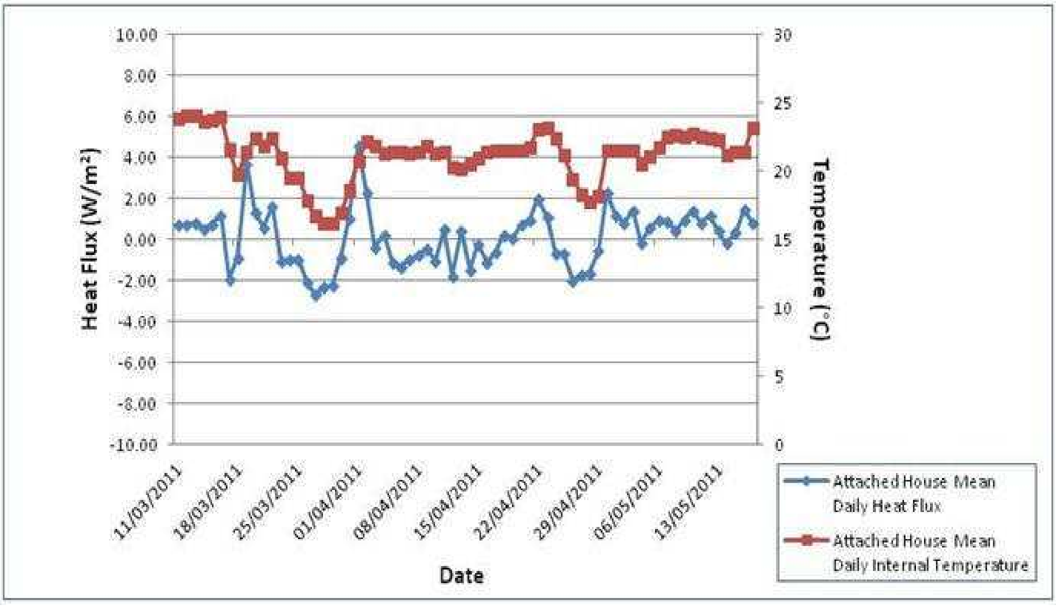


Figure 6-11 - Attached Level 4 House - Daily Mean Heat Flux and Internal Temperature Values

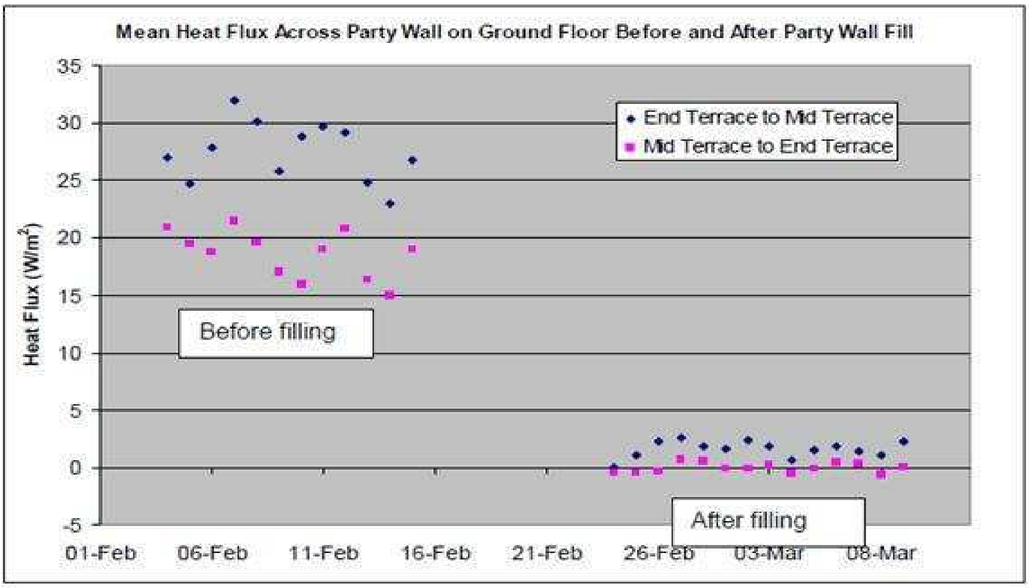


Figure 6-12 - Heat Flux Data from a Comparable Study
Source Data: (Wingfield, J. et al., 2009)

It can be seen that the heat flux values were significantly higher before filling, ranging between 30-40 W/m^2. After effective filling of the cavity, the recorded data falls to levels which compare favourably to that observed in this study. This provides strong evidence that the cavity wall insulation in place in the party wall between the two Tarmac Houses is functioning effectively.

Therefore, it has been concluded that there are potentially no apparent defects within the party wall that could be contributing to the observed performance gap apparent within the Tarmac House data. In the absence of any further diagnostic testing of building elements, an evaluation was made as to the potential impact that environmental effects may have had on the coheating test data, to ascertain whether the high heating demands were related to the low external temperatures and consequential high ΔT values observed during the testing period.

The Tarmac House coheating test was undertaken in December 2010, with external temperatures falling as low as -4.5°C and ΔT values ranging from 16.6°C to 27°C during the testing timeframe. Analysis undertaken with regard to the E.On House suggested that a 7°C difference in ΔT could impact upon the measured HLC by +/- 10%. If this does hold true, it is possible that external conditions could be contributing to the higher coheating test data, and that the Tarmac House HLC value could be increased by up to 10 W/K. If a reduction in measured coheating test data is made, this would still result in an unexplained observed performance gap between design and actual HLC data of approximately 14 W/K in each test case.

6.10 Conclusions

It can be seen that the Tarmac House does perform to and exceed the design-stage air tightness target of 2 $m^3/(h.m^2)$ @ 50Pa, with the most recent measured value of 1.45 $m^3/(h.m^2)$ @ 50Pa being achieved in practise. However, the whole house heat losses appear to exceed those predicted by the original assessor using SAP methodology (Case 1), with almost twice the predicted HLC being measured in practice.

Detailed analysis of the design stage data enabled the construction of an adjusted SAPPER 2009 model (Case 3 and 4), using amended details where appropriate. This increased the initial HLC, with MVHR in operation, from 58.83 W/K to 79.36 W/K, when changes were made to the dwelling characteristics, and background only infiltration levels were adjusted to account for local wind speed data (Case 7 and 8). In the case of a ventilation condition with background infiltration only, a HLC value of 70.08 W/K was derived using the same process. The impact of thermal bridging on the overall fabric performance of the property was also assessed, with values being increased in the design stage model to account for heat losses revealed by thermal imaging surveys.

This enabled comparison of the coheating test data obtained for the two ventilated conditions. In each case, a large divergence was apparent between the predicted and measured HLC data, with the coheating test result being 35-40% greater than that obtained using SAP methodology as summarised in Figure 6-13.

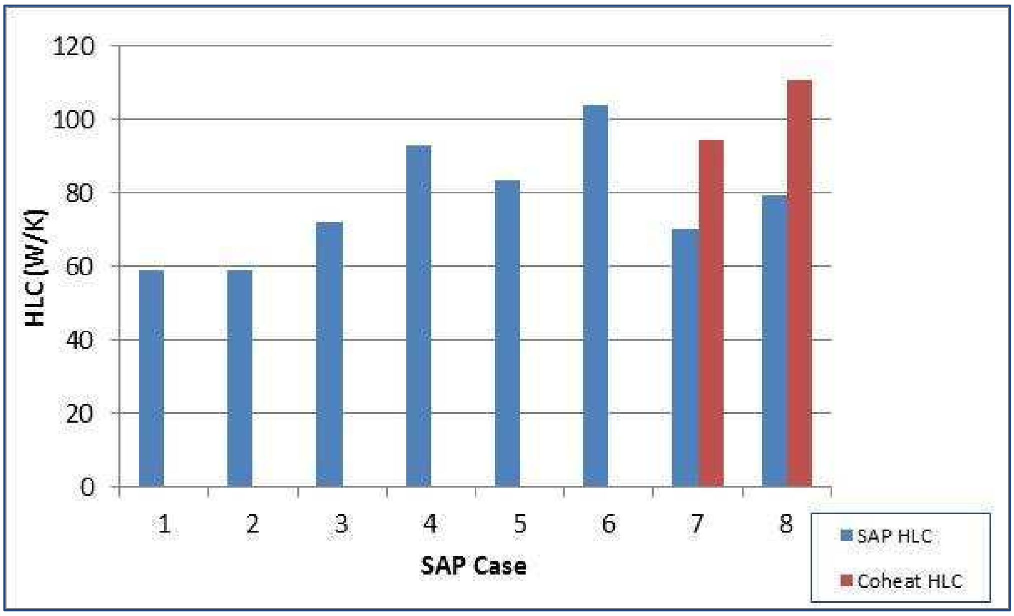


Figure 6-13 - Summary of Experimental Data

Investigation into the function of the MVHR system showed that there was a slight pressurisation effect due to an imbalance in supply and extract flow rates. Consequently, the measured coheating test HLC value was adjusted by 7.21 W/K. The modelled and experimental data showed agreement in an uplift for mechanical ventilation against background infiltration only state of approximately 9 W/K.

Evaluation of the function of the party wall over a period of several months showed that there was no unexpected heat loss occurring via this potential heat loss pathway. No other diagnostic work was possible due to time and resource limitations.

During the period of on-site testing, extremely low external temperatures were experienced which led to high ΔT values being observed. The work undertaken in respect of the E.On House showed that these conditions could lead to an elevation in measured HLC of up to 10%. However, it is possible that this could be within the scope of the error of the test methodology, and it is also improbable that the temperature difference alone would cause a significant change in HLC value.

The work undertaken here demonstrates that thorough analysis of the data that is provided by both design-stage models and post-construction testing is essential in order to gain a true understanding of dwelling thermal performance. In both the naturally ventilated/background infiltration and MVHR in operation models, assumptions and errors within the calculated and measured HLC datasets contributed almost equally to an augmented gap between theoretical and as-built performance.

However, whilst it can be concluded that there is some level of underperformance associated with the Tarmac House, it is not possible to accurately estimate the magnitude of this without further investigative work relating to the building fabric. In-situ evaluation building element u-values could further inform the study, alongside more extensive coheating tests to confirm the validity of the coheating test data. This was not possible during the course of this work, as following the coheating test, the house was fully occupied for the remainder of the research project period, meaning that a repeat test could not be undertaken in order to verify the data obtained. Some of the adjustments made in this study may still not be correct, and so the work here is only indicative of what could be the true HLC values for the designed and measured cases.

The investigation work relating to the Tarmac House has revealed areas of possible error in both the SAP model and coheating testing methodology, which will be further evaluated in Chapter 7.

7 EVALUATION OF THE PERFORMANCE GAP

The evidence presented in Chapter 3 and observed in the example retrofit and new-build properties (Chapters 5 and 6) provides a strong case for the existence of a performance gap between the design stage and measured energy efficiency data relating to UK homes. The final summarised adjustments made to the Tarmac House analysis (Table 6-13) demonstrate that the potential sources of error in the derivation of the SAP model and coheating test HLC values may, in some cases, contribute significantly to the overall divergence observed.

Several key areas have been identified as recurring themes of consideration within similar research projects that have been undertaken to evaluate housing performance, as summarised in Figure 7-1.

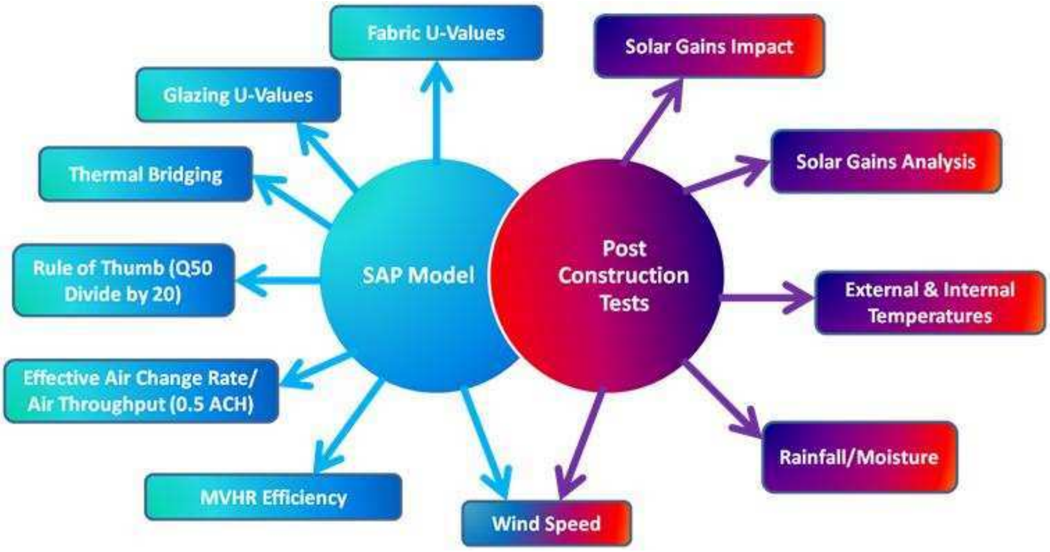


Figure 7-1 - Key Themes for Consideration in Performance Gap Evaluation

Studies such as those undertaken by Leeds Metropolitan University at Stamford Brook and Elm Tree Mews have attempted to account for and reduce the gap in performance between design stage and measured data. In addition, several sensitivity analysis exercises have been performed relating to BREDEM 8, BREDEM 9 and SAP methodologies to identify significant parameters in terms of outcomes of the model (Firth et al., 2010; Palmer et al., 2012; Quigley, 2010).

However, there has been little or no work to date that quantifies what this actually means in terms of impact on HLC values, and the relationship between variance of the HLC and the energy demand and carbon emissions levels of individual households. The calculated HLC may be useful in estimating the consequences of either failing to meet or improving upon design stage modelled dwellings.

In combination, as in the case of the Tarmac House, the underestimation of the SAP 2009 HLC and the overestimation of the coheating test HLC could be presenting a gap in performance that is not entirely representative of the true situation of a given property. In addition, the measured HLC data derived from the coheating test could be sensitive to environmental effects and experimental error, which may lead to an increase or decrease in the W/K value obtained. Therefore, further investigation regarding the sensitivity of the predicted and measured HLC to the factors outlined in Figure 7-1 will be undertaken throughout the remainder of this chapter.

7.1 SAP Methodology

In order to assess the impact of various input parameters on the output data resulting from the SAP methodology, a detailed sensitivity analysis was undertaken. At the time that this exercise was performed, SAPPER 8 (SAP 2005) was the modelling software available to the author due to license restrictions. The SAP assessment provided by the original assessor for the CfSH Level 4 Tarmac House was utilised in a one at a time differential sensitivity analysis, as the impact of renewable energy technologies within the model were less pronounced as compared to the CfSH Level 6 Tarmac House property.

The assessment was limited to variance of the input data contained in the first sections of the SAP methodology, prior to the calculation of the HLC, as detailed in Table 7-1. All of the building element u-values (fabric and glazing) were altered in a single permutation during this preliminary review, in order to ascertain the general effect of varying these parameters prior to more detailed investigation in further analytical work.

Table 7-1 - SAP 2005 Sensitivity Assessment - Input Data

Parameter	***Input Data***
% Energy Saving Lightbulbs	1-100% in use
Orientation	N/NE/E/SE/S/SW/W/NW
Q50	Design & As Built values
Ventilation Type	Natural with passive/intermittent vents 0 vent & positive input from loft
Ventilation Type	Natural with passive/intermittent vents 1 vent & positive input from loft
Ventilation Type	Natural with passive/intermittent vents 2 vent & positive input from loft
Ventilation Type	Natural with passive/intermittent vents 3 vent & positive input from loft
Ventilation Type	Natural with passive/intermittent vents 4 vent & positive input from loft
Ventilation Type	Positive input ventilation from outside 0/1/2/3 vent
Ventilation Type	Positive input ventilation from outside 4 vent
Ventilation Type	Whole house centralised mechanical extract ventilation
Ventilation Type	Whole house decentralised mechanical extract ventilation
Ventilation Type	Balanced whole house ventilation no heat recovery
Ducting Type	Flexible ducting (in use factor 1.7) uninsulated (in use factor 0.70)
Ducting Type	Rigid ducting (in use factor 1.4) insulated (in use factor 0.85)
Ducting Type	Rigid ducting (in use factor 1.4) uninsulated (in use factor 0.70)
Heat Recovery Efficiency of System	50-90%
Specific Fan Power	W(litre/sec) = 0.5-2.5
U Values	W/m^2K = +1-50%
Thermal Bridges	y = 0.04 - 2

As expected when following the SAP calculation protocols and methodology, there are certain parameters that do not affect the HLC value, such as % of energy saving lightbulbs, dwelling orientation, and specific fan power of the MVHR unit. However, the same factors do contribute to an overall change in carbon emissions and primary energy, but this is largely due to adjustments in the energy required for lighting and pumps/fans, rather than connections with the HLC and the way it is used in calculations throughout the model.

Orientation does influence the adjustment for solar gains made within the model, but this is applied after the HLC value has been derived and so is not relevant to this analysis. Ducting type had some impact on the HLC value but, as this variable is selected based on standardised data relating to the materials used, it is considered that there is little subjectivity in the interpretation of the correct information to input into the model.

Of the remaining parameters, the observed variances are shown in Table 7-2, with the full worksheet included in Appendix 7.

Whilst the initial exercise was useful in gaining a deeper understanding of the SAP methodology, it did not present any findings that were either unknown or unexpected. In terms of the u-values and thermal bridges, their impact on the HLC was due to increases in fabric heat losses with no difference observed in ventilation heat loss data. The opposite situation is observed with respect to parameters relating to the ventilation strategy, such as the q50 air pressure test result, ventilation type and heat recovery efficiency. The q50 result used here causes an improvement in performance, due to the value being reduced (reflecting increased air tightness) within the variance of the input parameter.

Limited conclusions can be drawn from the data presented in Table 7-2, apart from that in all cases excepting the q50 data, the HLC is increased when dwelling performance is decreased. The magnitude of this increase is lesser when the carbon emissions and primary energy values are considered, due to other factors apart from the HLC value impacting upon these final outputs.

Table 7-2 - SAP 2005 Sensitivity Assessment – Overview of Impacts

Parameter	Variance Applied	Fabric Heat Losses	Ventilation Heat Losses	Heat Loss Coefficient	EI Rating	Total Carbon Emissions	SAP Rating	Primary Energy
Q50 Test Result	Design & As Built values	No Change	-16%	-3%	No Change	-2%	No Change	-1%
Ventilation Type	Natural with passive/intermittent vents 0 vent & positive input from loft	No Change	+25%	+25%	No Change	+14%	No Change	+8%
Ventilation Type	Natural with passive/intermittent vents 1 vent & positive input from loft	No Change	+28%	+26%	No Change	+14%	No Change	+8%
Ventilation Type	Natural with passive/intermittent vents 2 vent & positive input from loft	No Change	+32%	+26%	No Change	+14%	No Change	+9%
Ventilation Type	Natural with passive/intermittent vents 3 vent & positive input from loft	No Change	+37%	+27%	No Change	+13%	No Change	+9%
Ventilation Type	Natural with passive/intermittent vents 4 vent & positive input from loft	No Change	+43%	+28%	No Change	+13%	No Change	+10%
Ventilation Type	Positive input ventilation from outside 0/1/2/3 vent	No Change	+31%	+26%	No Change	+14%	No Change	+17%
Ventilation Type	Positive input ventilation from outside 4 vent	No Change	+50%	+30%	No Change	+15%	No Change	+20%
Ventilation Type	Whole house centralised mechanical extract ventilation	No Change	+21%	+27%	No Change	+7%	No Change	+17%
Ventilation Type	Whole house decentralised mechanical extract ventilation	No Change	+21%	+27%	No Change	+14%	No Change	+17%
Ventilation Type	Balanced whole house ventilation no heat recovery	No Change	+31%	+26%	No Change	+14%	No Change	+18%
Heat Recovery Efficiency of System	50-90%	No Change	up to + 53%	up to +11%	No Change	up to + 3%	No Change	up to +6%
U Values	W/m^{2}K = +1-50%	up to + 42%	No Change	up to +34 %	No Change	up to + 9%	No Change	up to +21%
Thermal Bridges	y = 0.04 - 2	up to + 45%	No Change	up to +36%	No Change	up to + 9%	No Change	up to +23%

In order to evaluate the SAP methodology in greater detail, a second exercise was undertaken utilising SAPPER 9 (RUSFA) software and the SAP 2009 model platform. A generic model was developed using the E.On House construction details as a basis, but adjusted to reflect a dwelling that would meet current building regulations standards. The input data used within the model is summarised in Table 7-3. The minimum standards for building fabric performance, in terms of u-values, were derived from Part L documentation (Department for Communities and Local Government (DCLG), 2010b), whilst the air permeability value of 7 $m^3/(h.m^2)$ @ 50Pa was obtained from good practise guidance developed by the Energy Saving Trust (2008a). The Energy Saving Trust indicates that this air tightness value reflects standards generally being achieved in current new-build properties that are built to meet minimum compliance levels.

Table 7-3 - SAP 2009 Assessment - Model Dwelling Details

Building Element	**Input Data**
Dwelling Floor Area	107.815m^2
Air Permeability	7 $m^3/(h.m^2)$ @ 50Pa
Wall Area & U-Value	86.653m^2 0.21W/m^2K
Floor Area & U-Value	55.116m^2 0.21W/m^2K
Roof Area & U-Value	55.116m^2 0.16W/m^2K
Window Area & U-Value	28.52m^2 1.6W/m^2K
Door Area & U Value	28.52m^2 1.6W/m^2K
Party Wall Area & U Value	32.096m^2 0W/m^2K
Thermal Bridging	Default y=0.15
MVHR System	Titon HRV2 Q Plus (Assumed default data of 90% efficient & 0.5 ACH)

A SAP 2009 model was developed for the property with two different ventilation strategies – with natural ventilation and with the MVHR in operation. This enabled comparison of the impact of the various assumptions and calculations contained within the background methodology for calculating heat losses in each approach. In terms of baseline data, the following values (Table 7-4) were generated for the two scenarios when the unaltered data detailed in Table 7-3 was inputted into the model.

Table 7-4 - Baseline Data for SAP 2009 Model Dwelling

	Total Fabric Heat Loss (W/K)	Ventilation Heat Loss (W/K)	Heat Loss Coefficient (W/K)	Space Heating Demand	SAP Rating	SAP Band	EI rating	EI Band	Carbon Emissions (kg/year)	Primary Energy (kWh/year)
Model Dwelling - Natural Ventilation	121.98	48.59	170.57	5,604.87	80	C	81	B	2,133.43	11,132.21
Model Dwelling - MVHR in Operation	121.98	39.49	161.47	5,236.78	79	C	80	C	2,230.31	11,720.09

It can be seen that ventilation strategy has an interesting impact on the data. Whilst the MVHR system reduces the HLC by approximately 9 W/K when the MVHR system is in operation, the final carbon emissions and primary energy outputs are increased by 97 kg/year and 588 kWh/year respectively. This is due to the increased energy required to operate the system, which is calculated in later stages of the SAP methodology. However, throughout the analytical work, this difference will remain relatively constant. Therefore, any changes in HLC, carbon emissions and primary energy will be due to the adjustments made to the input data in addition to these values.

A number of variables were adjusted in each of the baseline models, in order to investigate the impact that divergence from the dwelling design-stage data might have on the HLC and the resulting carbon emissions and energy requirements of the property. In addition, several of the assumptions contained within the SAP methodology were investigated. Appendix 8 contains the full output from this exercise, whilst the following sections provide a summary of the key observations.

7.1.1 Fabric Factors

Whilst in the initial analysis of the SAP 2005 model all of the fabric and glazing u-values were adjusted in one simulation, in the SAP 2009 study each element u-value was adjusted individually in order to obtain a more localised indication of the impact of each separate component. In each case of the wall, floor, roof, glazing and party wall elements, the u-value was varied from +1% to +50% and -1% to -50% of the original data. This enabled assessment of both reduced and enhanced fabric performance. Figure 7-2 shows the resultant data for the MVHR in operation scenario. The impact of the changes on the calculated HLC are virtually identical for both the natural ventilation and MVHR in operation models, as the u-value variances only affect the magnitude of fabric heat losses with no change to the ventilation component.

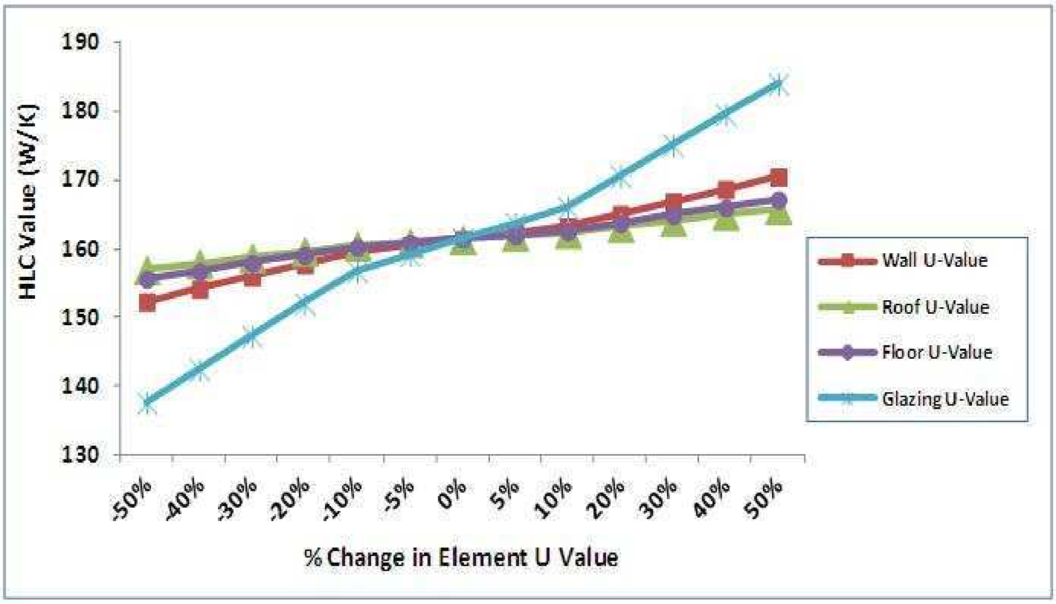


Figure 7-2 - MVHR In Operation Model - Impact of U-value Adjustments

It can be seen that, in all cases, the increase or decrease in u-value can be observed as a linear function of the HLC value. Therefore, linear regression can be used to approximate the absolute change in HLC value per 1% change in u-value for each building element.

The data contained in Table 7-5 shows that a considerable change to the inputted u-value would be required in order to have a large impact upon the predicted HLC when considering the opaque building elements. However, with reference to windows and doors, due to the initial larger baseline u-value, the impact of a change in specification or poor installation could be of greater significance in terms of fabric performance. Indeed, a 50% underperformance in this building component could cause a 23 W/K increase in HLC.

Table 7-5 - Relationship Between Element U-values and HLC

	Wall	Floor	Roof	Party Wall	Glazing
HLC W/K Change for 1% U-Value Change	0.182 W/K	0.116 W/K	0.088 W/K	0.32 W/K	0.464 W/K
% Change in U-Value for 1 W/K HLC Change	5.49%	11.36%	8.62%	3.10%	2.15%

The treatment of party walls is also quite sensitive to changes in u-values above the 0 W/K assumed by the SAP methodology, with a 50% increase (equivalent to 0.5 W/m^2K) resulting in a HLC increase of 16 W/K. This, again, re-emphasises the importance of removing the cavity wall bypass mechanism and the significance of the changes made to 2010 Part L of the Building Regulations in terms of minimum party wall construction specifications. It is relatively unlikely that slight increases in elemental u-values would cause great changes in the HLC, but the compounded effect in several areas could contribute to an overall gap in observed and expected performance.

When considering thermal bridging, for each 0.01 change in y value, the HLC increases by approximately 2.3 W/K. This reflects the sensitivity of the HLC to thermal bridging calculations, as it would take a 4% change in y value to increase the HLC by 1 W/K, which, due to the low nature of the initial values used, does not allow a large margin of error. This is of importance in the context of accredited and enhanced accredited construction details, where the default 0.15 y value is decreased to 0.08 (-50%) and 0.04 (-76%) respectively. In the

Building Regulations compliant model employed here, the impact of improving thermal bridging properties could reduce the HLC by 16 W/K or 25 W/K, depending on the magnitude by which the y value is decreased. This is comparable with the case of the Tarmac House, where the y value inputted had a significant impact on the data, with thermal bridging calculations varying from 3.65 W/K to 27.93 W/K within a y value range of 0.0196 to 0.15.

Perhaps of equal importance is the impact that increasing y values can have on the HLC. In the case where a y value of 0.5 is used in the calculation, the HLC is increased by 80 W/K (65% above the original value). Whilst this does not represent an entirely normal situation, as the default y value in SAP 2009 would be 0.15, it does appear to have been used either intentionally or in error in the case of the E.On House. It can therefore be seen that careful consideration of thermal bridging levels within both the design and construction of a building is extremely important in order to meet expected thermal performance levels.

7.1.2 Air Tightness Values

The baseline dwelling model included an inputted air pressurisation test result of 7 $m^3/(h.m^2)$ @ 50Pa, as this was considered to provide a fair representation of the air tightness levels currently being achieved in mainstream new build housing developments. In order to assess the effect of different air tightness levels on the HLC value, a range of values were inputted into both the naturally and mechanically ventilated scenarios. This exercise resulted in the data presented in Figure 7-3.

As would generally be expected, at very low airtightness levels the MVHR system enables the dwelling to achieve a saving in HLC when compared to a natural ventilation strategy. This situation reverses as the property becomes increasingly permeable, with MVHR becoming less advantageous at q50 results above a value of between 7 and 8 $m^3/(h.m^2)$ @ 50Pa.

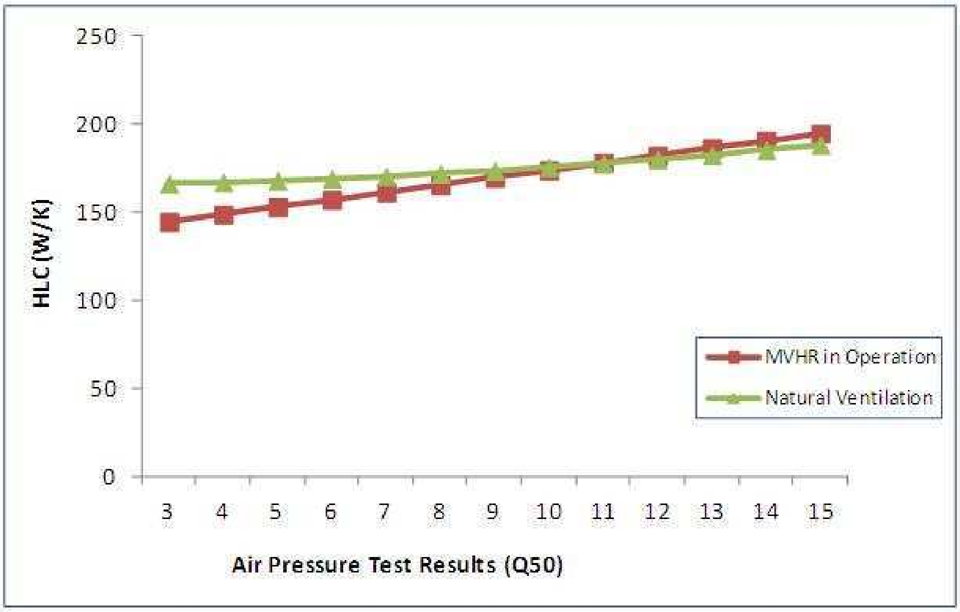


Figure 7-3 - Impact of Air Tightness on Calculated HLC Values

In terms of the quantifiable impact of airtightness on HLC data, an increase of 4.2 W/K and 2.2 W/K was evident in the mechanically and naturally ventilated states for each increment of 1 $m^3/(h.m^2)$ @ 50Pa. To obtain a 1 W/K change in HLC, the air tightness would need to increase or decrease by 3.2% (MVHR) or 4.2% (natural ventilation). This shows that the mechanically ventilated scenario is slightly more responsive to variances in measured airtightness.

7.1.3 Conversion of q50 Result to Ambient ACH

As previously explained in Section 3.1.1, an air pressure test result can be used to calculate infiltration rates of a given property. The value from the test certificate can be entered directly into the SAP model, which contains an embedded equation in order to convert the infiltration at 50Pa to an operational infiltration value. Sherman (1987), developed a rule-of thumb equation in order to convert the q50 data into units of ACH relevant in ambient environmental conditions, as shown previously in Section 3.1 (Equation 3.1).

The SAP methodology includes a default value of 20 for *N*, which is automatically included in the calculation and cannot be changed. This is a simplified method of the technique developed by Sherman, as it does not take into account environmental conditions or the individual characteristics and location of the property under consideration. Durbal (1988) observed that the correction factor, rather than being fixed at 20, may require variation to a value of between 10 and 30, to account for differences in the characteristics of each test. Therefore, it could be reasonable to suggest that the automatic division by 20 could be an influencing factor in the inaccuracy of performance stage data.

A range of division values of between 0 and 30 were applied to the baseline model in order to convert the q50 data to ambient air changes. The assessment of the influence of the application of different values within the calculation is not straightforward, due to the relationship between the division factor used and the resulting HLC not being simply linear in nature. This is apparent in the data displayed in Figure 7-4.

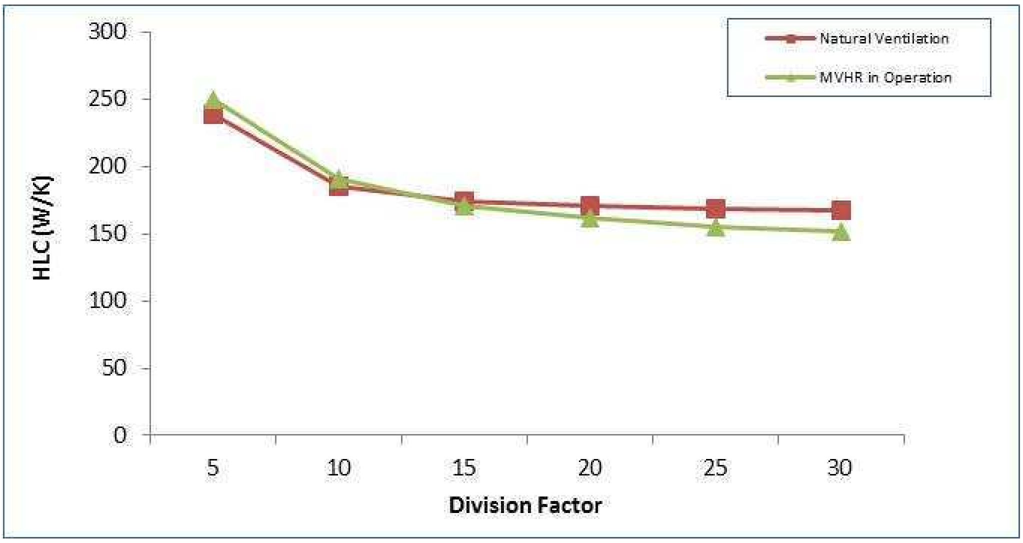


Figure 7-4 - Impact of Divide by 20 Rule on HLC Values

More variation is evident in the case of the dataset when MVHR is in operation, with a difference between minimum and maximum calculated HLC values of 97.35 W/K, as compared to 71.13 W/K in relation to the naturally ventilated scenario. A 1% change in division factor afforded a change of between -10.69 W/K and -0.17 W/K for the naturally ventilated case, and -11.7 W/K and -0.66 W/K when MVHR was taken into account.

In terms of evaluating the impact of different division factors further, both ventilation strategies produce an increased HLC value when a low division factor is used. When the q50 result is divided by 5, for example, this effectively imposes a higher air permeability level on the dwelling calculated effective infiltration rate. Dividing by a factor of 30 would result in the use of a lower air tightness value, simulating a reduced q50 result. This relationship is shown in Figure 7-5.

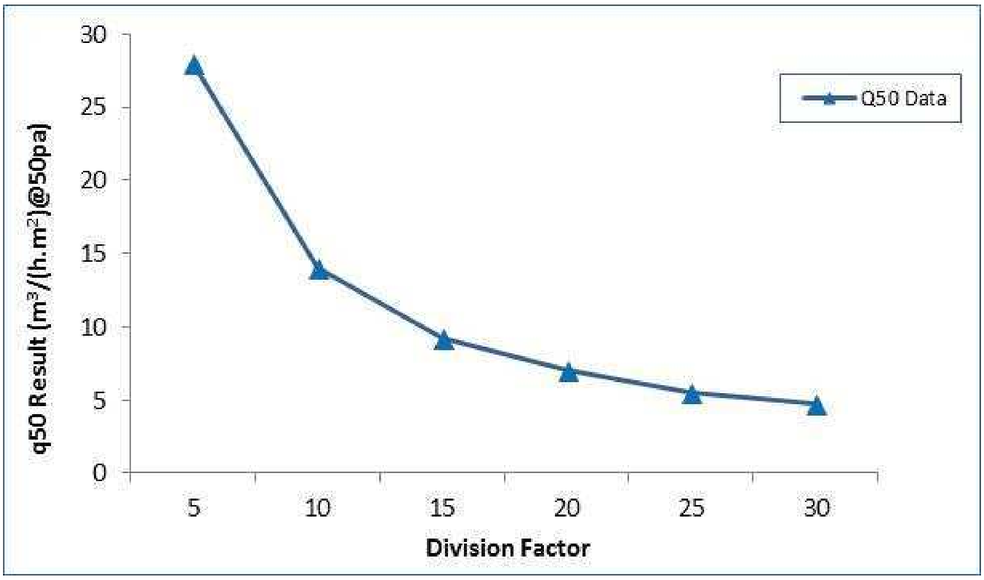


Figure 7-5 - q50 Values Associated with Division Factors

The baseline q50 value is 7 m^3/(h.m^2) @ 50Pa, which is observed when a division value of 20 is utilised in the air permeability equation. In reality it is unlikely that the airtightness of a dwelling would actually be compromised sufficiently to result in a pressurisation test result of 28 m^3/(h.m^2) @ 50Pa, which would be required to simulate effective background infiltration conditions in the same property when a division factor of 5 is applied. When the q50 value of 7 m^3/(h.m^2) @ 50Pa is divided by 10, this represents a q50 result of 14 m^3/(h.m^2) @ 50Pa. Even this level of divergence would not normally be expected in the case of a newly constructed property.

The impact of the division factor on equivalent q50 data reduces as it increases towards the default level of 20 and beyond, and observed variance within the HLC data derived for both ventilation strategies in the modelled house reduces. At division factors ranging between 15 and 30, an average change in HLC of 8.12 W/K (no MVHR) and 7.68 W/K (with MVHR) would be associated with a 1% change in division factor. To obtain an increase in HLC of 1 W/K, the division factor would need to increase by 0.13% or 0.14% for the naturally and mechanically ventilated conditions respectively.

7.1.4 Effective Air Change Rate Calculations

Within the SAP methodology, in order to calculate the effective air change rate (EACR) for a property following the derivation of the adjusted infiltration rate, a series of embedded equations are utilised depending on the ventilation strategy employed. In the case of both natural and mechanical ventilation, an air throughput or air change rate of 0.5 ACH is included in the formulae, as shown in Equations 7.1 and 7.2 (Department of Energy and Climate Change (DECC), 2011d, p. 153):

$$EACR = 0.5 + (\text{Adjusted Infiltration Rate}^2 \times 0.5)$$

Equation 7-1 - Natural Ventilation (Department of Energy and Climate Change (DECC), 2011d, p.153)

$$EACR = \text{Adjusted Infiltration Rate} + 0.5 \times (1 - \text{System Efficiency in Use}/100)$$

Equation 7-2 – Mechanical Ventilation (Department of Energy and Climate Change (DECC), 2011d, p. 153)

It can be seen that this assumption could be significant within the calculation of dwelling ventilation heat losses. In the case of the MVHR systems installed in each of the retrofit and new-build example houses, the air throughput through the system was measured to deviate from the assumed 0.5 ACH. This is especially true of the Nuaire unit within the Tarmac House property, which had a measured supply and extract flow rate of 0.95 and 0.89 ACH respectively. Also, in naturally ventilated homes, ventilation rates are largely uncontrolled and are dependent upon user intervention. Therefore, it could be that the value of 0.5 ACH may be exceeded or in some cases not maintained.

The manipulation of the SAPPER 9 software in order to implement changes to the use of default 0.5 ACH values in embedded algorithms proved to be quite difficult. In order to achieve data that would be the equivalent of making changes to this factor, the air pressurisation test results that would produce an equivalent variance to the EACR value were calculated. This was achieved through use of the excel worksheet included in Appendix 3, amended to reflect the physical characteristics of the baseline Building Regulations compliant house. Through this process, it was possible to derive SAP 2009 data that reflected the impact of changes to the assumed 0.5 ACH value in both ventilation states, as detailed in Table 7-6.

Table 7-6 – Impact of Assumed 0.5 ACH on HLC Data

	Natural Ventilation	MVHR Ventilation
HLC W/K Change for 1% Change in ACH (0.05ACH)	0.369 W/K	0.293 W/K
% Change ACH for 1 W/K HLC Change	2.71%	3.41%

It can be seen that the values associated with each ventilation case are quite similar, although, due to the additional impact of the 0.5 ACH within the natural ventilation equation, this scenario is more sensitive to changes made to the input data. In absolute terms, a 0.1 ACH increase in value resulted in an approximately 2 W/K or 10 W/K increase in the HLC associated with the MVHR and naturally ventilated states. This demonstrates that there is perhaps some need to include the ability to specify different EACR values within the SAP input ranges, as in some cases a dwelling may be penalised with regard to this design parameter. It also emphasises the requirement to use the correct design-stage data when comparing HLC values to those derived from the coheating test, as the use of natural ventilation modelled data could lead to a misinterpretation of performance.

7.1.5 MVHR Efficiency

Within the SAPPER 9 software, the details relating to the function of an MVHR system are drawn from an integrated database containing specifications provided by the relevant manufacturer. By virtue of the nature of this information, the SAP methodology then uses optimum performance details as the basis for further ventilation heat loss calculations. In the context of the systems used in both of the retrofit and new-build example properties and the model developed for sensitivity analysis, an assumed system efficiency of 90% was utilised in the original workbook.

The impact of this assumption was assessed through manual input of a range of efficiency values in the region of 50-90%. For every 10% decrease in efficiency levels, an increase in HLC value of 3.71 W/K was observed, as shown in Figure 7-6.

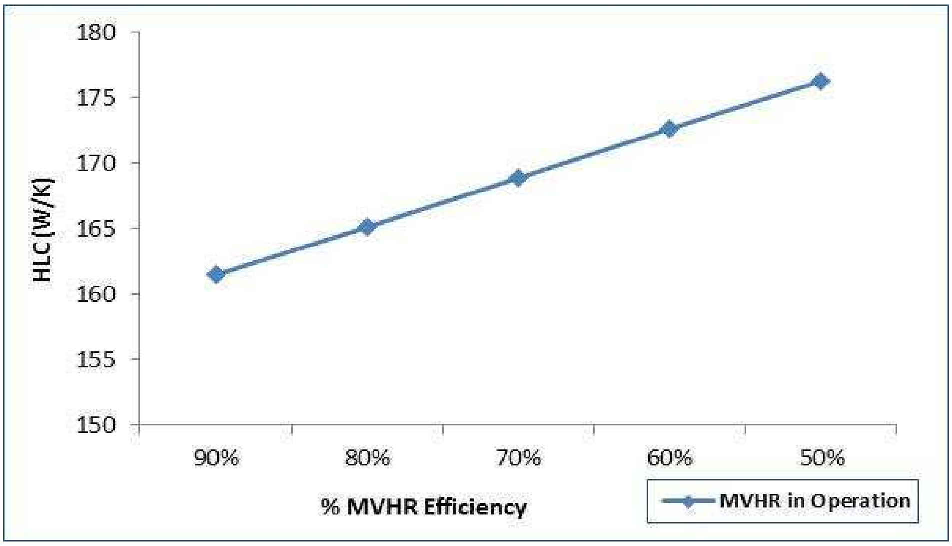


Figure 7-6 - HLC Response to % MVHR Efficiency Levels

This is comparable to the data presented in Chapter 5 in relation to the Titon system installed in the E.On House, where HLC increases of 3.2 W/K and 3.4 W/K were calculated for the system working at 9-14% reduced efficiency. In terms of normalised effect on the HLC value, with regard to the sensitivity assessment modelled dwelling, a 2.7% change in efficiency level would be required to alter the HLC by 1 W/K. This demonstrates the sensitivity of this parameter, and therefore clearly relates the importance of correct design, installation and commissioning of MVHR system units, ductwork and outlets.

7.1.6 Wind Speed

The SAP methodology assumes a simple linear relationship between wind speed and infiltration values, with higher wind speeds leading to increased HLC data. Within the SAPPER 9 software, the wind speed data is automatically inserted and cannot be adjusted. During the assessment of the coheating data, local wind speed data, measured at the time of the experiment, was inserted into a bespoke spreadsheet in order to calculate semi-empirical effective infiltration rates. In all cases, the local wind speeds were lower than those embedded in the SAP model. This effectively meant that the theoretical air movement through the building fabric calculated using the SAPPER 9 software was, in some cases, significantly higher than that actually occurring in the as-built dwelling.

In terms of the coheating test, analysis of the data suggests that the impact of wind speed on the in-situ HLC is not as straightforward as assumed in SAP 2009. The model uses a generic weather data set, which utilises monthly average value for a location in the East Pennines. As such, it is not representative of the local conditions present during a short term coheating test.

Figure 7-7 and 7-8 show two examples of the relationship between wind speed and HLC for data relating to the E.On House with a background infiltration only ventilated condition. In the case of both tests, the SAP calculated HLC increases steadily as wind speed increases.

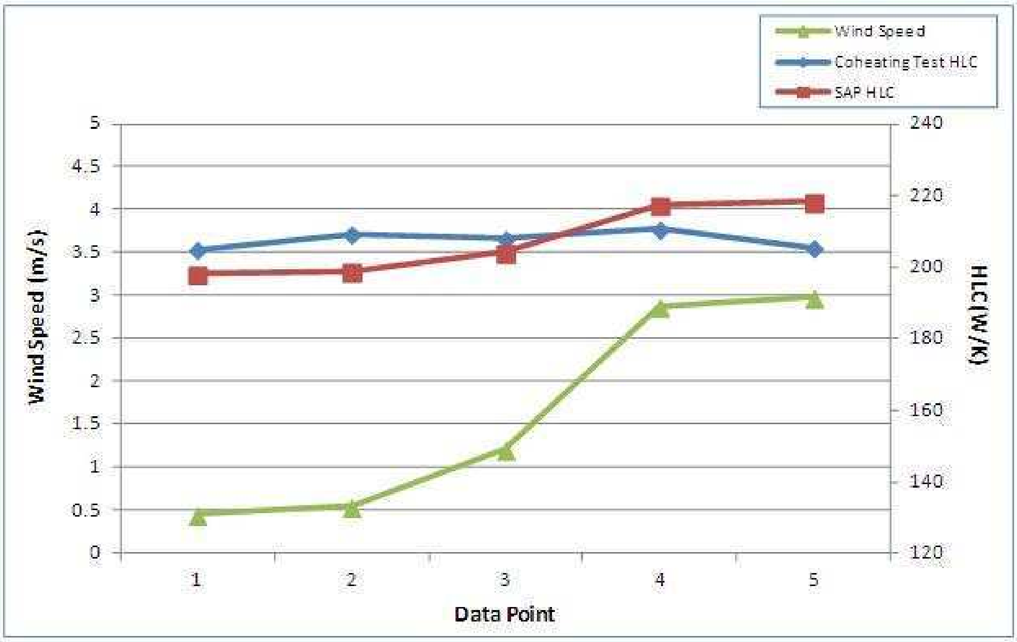


Figure 7-7 - Impact of Wind Speed on HLC Data – E.On House Coheating Test November 2010

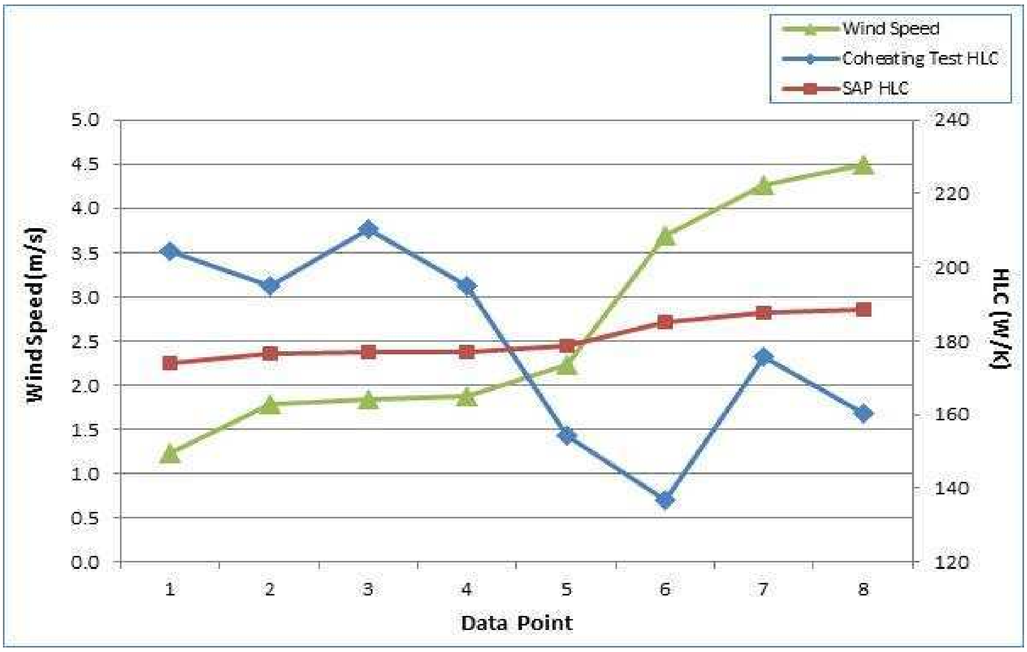


Figure 7-8 - Impact of Wind Speed on HLC Data - E.On House Coheating Test April 2012

The relevant average wind speeds dictated by the SAP 2009 integrated dataset are 5.1 m/s for November and 4.5 m/s for April. The wind speeds observed during the November 2010 test ranged between 0.5 and 3.0 m/s. Those recorded throughout the April 2012 experimental period reached the SAP 2009 assumed levels on one day, but were lower for the remainder of the duration of the test.

In terms of impact on the theoretical HLC data, the November HLC (background infiltration only) using the SAP 2009 assumed wind speed of 5.1 m/s would be 235.11 W/K, but this ranges between 197.97 W/K and 217.17 W/K when the generic wind speed value is substituted with specific site-based data. In the case of the April coheating test, the SAP model provided a background infiltration only default wind speed HLC value of 188.48 W/K, whilst the semi-empirical predicted HLC data ranged between 171.38 W/K and 188.46 W/K.

In both of the examples shown in Figure 7-7 and 7-8, at higher wind speeds the SAP methodology appears to underestimate the HLC when compared to the measured post-construction data. Chai-Yu (1981) observed that wind effects provide the predominantly influencing factor on fabric infiltration rates at wind speeds of greater than 3.5m/s and ΔT values of less than 20K. In conditions outside of this range, the internal and external temperature difference is the predominant factor affecting fabric infiltration levels.

At the time of the November experiment, wind speeds were 3 m/s or below and ΔT values were consistently in excess of 20K. The coheating test HLC values are generally uniform in these conditions. The April 2012 test results show greater sensitivity to wind speed than those associated with the November 2010 data. Three of the wind speed values exceed 3.5 m/s, and the ΔT on these days was approximately equal to or greater than 20K.

The conditions relevant at the time of data points 1-5 in the April test comprised of lower wind speeds and ΔT values ranging between 15.5K and 19K. The impact on the coheating test HLC is quite pronounced, with an average of

192 W/K and 158 W/K for high wind speed/low ΔT and low wind speed/high ΔT respectively. Whilst the divergence in values observed in different wind conditions is significant, the complexity of the interrelated impact of environmental elements on the results derived from the coheating test methodology means that it cannot be solely attributed to the impact of wind speed. The higher external temperature present during the days of greater wind speed would also impact upon the HLC data.

However, the results do concur with the recommendations made by the NHBC (National House Building Council (NHBC) Foundation, 2013) which suggest that where possible, coheating tests should be undertaken in conditions with low wind speeds in order to minimise the effect of this parameter on the data obtained. The April 2012 SAP 2009 HLC was calculated to be 177.3 W/K, with the solar corrected value derived using multiple regression analysis being 174.11 W/K. This shows that regulation of the data over several days can occur if a variety of environmental conditions are experienced during the experimental period.

It can be seen that environmental factors can have a pronounced effect on the predicted and measured HLC data. The relationship between temperature, wind speed and solar radiation is quite complex and the parameters are interrelated. This makes it difficult to isolate the absolute effect of each individual factor. However, it is perhaps a missed opportunity that the 2014 update to the SAP methodology will not incorporate the functionality for assessors to at least select regional rather than generic national climate data (including wind speed) as part of the scheduled improvements. This amendment could possibly have aided in the production of more location-specific design-stage energy assessments.

7.1.7 Summary

Throughout the sensitivity analysis of each of the considered parameters, a normalised value in terms of % change in factor to achieve a 1 W/K change in HLC has been used to evaluate the impact of each element on thermal performance. This can be applied to the data in order to derive the change in carbon emissions, SAP Rating, Environmental Impact Rating and Space Heating Required Supply attributable to a 1 W/K change in HLC, as summarised in Figure 7-9.

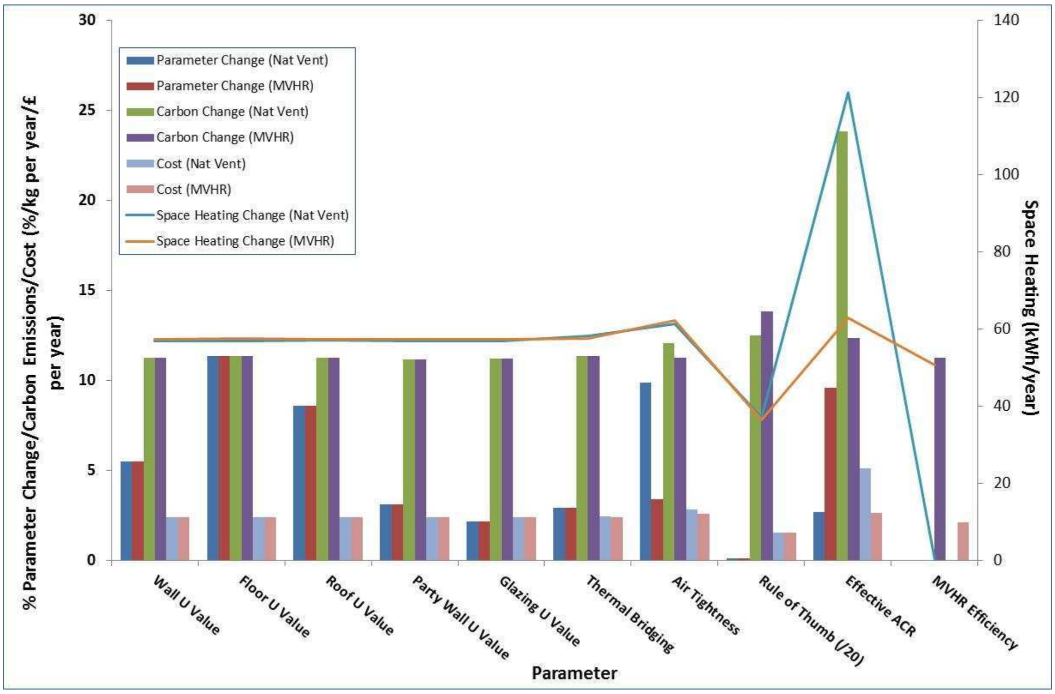


Figure 7-9 - Summary of Sensitivity Analysis Data

In terms of the way in which the values have been obtained, the following assumptions have been made:

- In the case of the change in HLC, a higher percentage value indicates lower levels of sensitivity to divergence from the original parameter value;

- Space heating fuel supplied has been used as a benchmark to estimate increases in dwelling requirements. This accounts for the space heating demand of a dwelling inclusive of inefficiencies in the space heating system (such as boiler performance); and

- The estimated cost of changes to the HLC is calculated based upon a unit base rate for mains gas supply of £0.0421/kWh as obtained from the rates used in analysis undertaken by the Energy Savings Trust (Energy Saving Trust (EST), 2014). Gas has been selected as this is the most common fuel for space heating in the UK, with over 90% of central heating system being supplied by natural gas (Building Research Establishment (BRE), 2005).

Table 7-7 summarises the data obtained from the evaluation of the data.

Table 7-7 – Quantification of Impact of Parameter Sensitivity

	% Parameter Change Required for 1 W/K HLC Change		Change in Carbon Emissions for 1 W/K HLC Change (kg/year)		Change in Space Heating Supplied Energy for 1 W/K HLC Change (kWh/year)		Cost of 1 W/K HLC Change (£/year)	
	Natural Ventilation	MVHR Ventilation	Natural Ventilation	MVHR Ventilation	Natural Ventilation	MVHR Ventilation	Natural Ventilation	MVHR Ventilation
Wall U Value	5.49%	5.49%	11.29	11.29	57.01	57.43	£2.42	£2.41
Floor U Value	11.36%	11.36%	11.34	11.34	56.98	57.53	£2.42	£2.42
Roof U Value	8.62%	8.62%	11.28	11.28	57.06	57.30	£2.42	£2.41
Party Wall U Value	3.10%	3.10%	11.17	11.17	56.97	57.29	£2.42	£2.41
Glazing U Value	2.15%	2.15%	11.24	11.24	56.92	57.29	£2.42	£2.41
Thermal Bridging	2.94%	2.94%	11.35	11.35	58.14	57.51	£2.44	£2.42
Air Tightness	9.90%	3.41%	12.09	11.25	61.45	62.14	£2.84	£2.61
Rule of Thumb (/20)	0.13%	0.14%	12.51	13.83	37.19	36.42	£1.56	£1.53
Effective Air Change Rate	2.71%	9.62%	23.85	12.37	121.42	62.93	£5.10	£2.64
MVHR Efficiency	n/a	2.70%	n/a	11.25	n/a	50.63	£0.00	£2.13

It can be seen that elemental u-values display different degrees of sensitivity when considering HLC values. Floor u-value is the least responsive to under or over performance, whilst windows and doors (glazing) are most reactive. All building fabric u-values display a similar change in carbon emissions, space heating fuel supply and cost to the householder per 1 W/K variance, with values being approximately 11 kg/year, 57 kWh/year and £2.42/year respectively.

The impact of poor consideration of thermal bridges within a construction could be very significant, as only a 2.94% change to the default y value of 0.15 (a variance of 0.0045) is required to effect a 1 W/K HLC increase. The evidence presented in this project and other studies would suggest that such a magnitude of deviation from design stage predictions would not necessarily be unusual in as-built dwellings. The implications of a 1 W/K increase/decrease associated with thermal bridging is not insignificant, representing mean change of 11.35 kg/year in carbon emissions, 57.83 kWh/year in space heating fuel supply and £2.43/year in cost.

In terms of airtightness, changes to the predicted air pressurisation test value produces a different response in the HLC value depending on the ventilation strategy employed in the property. The naturally ventilated model dwelling required a 9.90% change in q50 data to effect a 1 W/K change in HLC value, whilst when the MVHR system was incorporated it increased the sensitivity of this parameter as the % change required to cause a 1W/K difference reduced to 3.41%. However, when carried forward into the variances observed in carbon emissions and space heating levels, both ventilation cases showed a similar level of impact upon absolute values. A change of 1 W/K in the HLC value resulted in an 11-12 kg/year increase in carbon emissions and an additional 61-62 kWh in gas used for space heating. The subsequent impact in cost is £2.61/year.

Two of the main assumptions relating to calculation of infiltration and ventilation rates were considered within the scope of the sensitivity analysis – namely the embedded equation to convert the q50 test result to ambient air changes, and the default effective air change rate of 0.5 ACH. In the case of the conversion of the pressurisation test data, the two different ventilation types displayed a similar high level of sensitivity to adjustments made in this parameter, with only a 0.13 or 0.14% change in the division factor being required to cause a 1 W/K change in HLC. A 1 W/K HLC variation was estimated to result in an average 13.17 kg/year, 36.81 kWh/year and £2.73/year change in carbon emissions, space heating fuel and gas cost.

With regard to the assumed effective air change rate, the naturally ventilated modelled house displayed higher levels of sensitivity to adjustments to the 0.5 ACH value than those observed in relation to the data with an MVHR system included. Indeed, the increase in carbon emissions, space heating fuel requirement and gas cost are approximately half in the MVHR case as compared with the naturally ventilated state. This is as a direct result of the differences in calculation techniques used to quantify the effective infiltration rate for each ventilation strategy.

The level of MVHR efficiency achieved by an installed system is relatively sensitive to change, requiring only a small deviation from the assumed 90% efficiency used as default within the SAP model to cause a shift of 1 W/K. The impact on calculated space heating requirements and cost is relatively low, with values of 11.25 kg/year, 50.63 kWh/year and £2.13/year. When this is considered in relation to the MVHR system installed in the E.On House dwelling, the lowest efficiency level recorded was 76% - an underperformance of 14%. If a change in MVHR system % efficiency of 2.70% is required to cause a 1 W/K change in HLC, then the HLC value could be increased by 5.2 W/K. This may potentially result in an increase in household heating costs of £11 per year.

It can be seen that, within the context of the SAP 2009 methodology, a deviation from the data inserted into the model can lead to a certain level of variation in final outcome values from the model. Many of the parameters that have been evaluated show a similar level of impact on carbon emissions, space heating fuel requirements and cost. Notable exceptions mainly relate to the factors associated with ventilation calculations, such as the calculation of ambient air changes, and effective air change rates.

The range of values indicating the sensitivity of the predicted HLC to changes in input data is quite diverse, ranging from 0.13% to 11.36% change in a parameter required to affect a 1 W/K increase or decrease in HLC. This demonstrates the importance that should be placed upon reconsideration of the original baseline model as the design and construction of a building evolves, in order to ensure that the specification and characteristics of the design-stage model align with those associated with the final as-built property.

7.2 Coheating Test Methodology

The data gathered as a result of the coheating tests undertaken in relation to the example retrofit and new-build houses demonstrates that environmental factors may impact upon the HLC value derived from using this technique. In particular, the necessity to correct data in order to account for solar gains was apparent, especially in tests that were undertaken in the early spring or autumn months. In the case of the E.On House, the coheating tests associated with the upgrade works to the MVHR system took place in March 2011, when solar radiation levels were high, and the adjustment for solar impact increased the HLC by 45 W/K (25%). This is not an insignificant amount, particularly when the value is being used to assess performance against information derived from the SAP methodology.

In addition, the effect of the relationship between internal and external temperatures was also investigated during the coheating work connected to the E.On House. A difference of +/- 10% (22 W/K) was observed when internal temperatures were varied to achieve a difference in mean ΔT of 7°C. This divergence is measured against the HLC calculated by combining the two datasets to produce a HLC based on a full range of ΔT values. It raises the question of how sensitive the methodology is to variance in ΔT, as theoretically, should external temperatures remain very stable and internal temperatures are constant, the environmental conditions at the time of the test could enhance or reduce the final coheating test data. The effects of wind speed and rainfall at the time when a coheating test is conducted may also influence the calculated HLC value.

In order to gain a more full understanding of the impact of environmental factors on the results gained from post-construction evaluation, a thermal chamber was used to undertake a series of coheating tests in controlled conditions. This work is detailed in the following sections.

7.2.1 The Thermal Chamber

The research exercise utilised an environmental chamber that is located in the workshops area of the Department of Architecture and Built Environment. The unit consists of an inner chamber situated within an external box, which forms two zones. The temperature of each zone can be controlled independently, through use of a chiller/air conditioning system and heaters, with temperatures managed via thermostatic controls (differential cut-in of +/- 1°C). Figure 7-10 contains a series of images which show the features and experimental set-up of the chamber.

The outer chamber is constructed of fully insulated composite rigid panels and has an average predicted u-value of 0.6 W/m^{2}K, with internal dimensions of 3.6m x 2.4m x 2.8m. This gives an internal floor area of 8.64m^2 and an internal volume of 24.19m^3.

The specifications of the inner chamber suggest that it is constructed of a highly insulative PIR material, which achieves a manufacturer stated U value of 0.44 W/m^{2}K. The internal dimensions are 1.93m x 1.20m x 2.26m, and the internal floor area is 2.32m^2 with an internal volume of 5.23m^3. The surface area of the outer chamber is 33.6m^2, and that of the inner room is 14.15m^2.

External View of Chamber

Insert Area for Sample Constructions with Insulation

Solid Brick Wall Construction with Thermocouples

Final Wall Constructed with Thermocouples

Outer Surface of Solid Brick Wall

Inner Surface of Solid Brick Wall with Plaster

Instrumentation within Inner Chamber

Figure 7-10 - External and Internal Images of Thermal Chamber

An understanding of the design and operation of different types of hot box chambers was gained through study of British Standards relating to guarded and calibrated hot boxes (British Standards Institution (BSI), 1987, 1996, 1999). Whilst the environmental chamber under consideration does not comply with conventional hot box design standards, as it consists of a full size inner and outer chamber, the information contained in the documents provided useful guidance as to the minimum sample size that would be expected to produce reliable data, and how to reduce the impact of heat losses from the perimeter of the wall sample insert. The key recommendations noted were:

- The linear dimensions of the test area shall be at least 1m and not less than 5 times the maximum thickness of any test element;

- All seals between different components of the hot box assembly should be airtight;
- Any support frame should not be narrower than the thickest element to be tested, and should be insulated at the edges;
- Minimum size of the sample/metered area is 1m x 1m or 3 times the sample thickness, whichever is the greater, to allow for the effect of flanking losses at the edges;
- There should be a minimum of 9 thermocouples on each face, or 1 per 0.5 m^2 surface area;
- A calibration test using a sample of known thermal properties should be undertaken to assess heat exchange with the external environment and flanking losses around the perimeter of the test sample; and
- The test sample should not have any pathways for air leakage, and cavities should be sealed at their outer edges and insulated to provide thermal resistance of at least 2.5 m^2K/W;
- A minimum air temperature difference of 20K is recommended.

For the purposes of the tests being undertaken, a 1.22m wide by 2.15m high (2.623m^2) section was removed from one wall of the internal chamber, which was subsequently replaced with two different wall type sections – a solid brick wall and an externally insulated solid brick wall. This was deemed to be within the guidelines for sufficient sample size in order to obtain reliable results, being greater than 1m X 1m in size and approximately 3 times the length/width of the proposed maximum sample thickness of 45mm. The test sample area could not be made wider than this, otherwise the impact of edge effects would have been too great due to the lack of adequate supporting structure on each side of the construction. The structural integrity of the internal chamber may also have been compromised, leading to risk of warping or possible collapse.

Due to the proposed sample width being up to 450 mm deep, and the supporting internal chamber wall only being 30 mm, it was necessary to place an additional insulative surround on the internal face of the internal chamber wall that could house the masonry samples. This enabled the brickwork to be built into the surround and reduced perimeter flanking heat losses from the sample to the external environment, and modified the u-value of this area of the wall to 0.1 W/m^{2}K.

In terms of instrumentation, a Hukseflux HPF01 heat flux sensor (accuracy +/- 5%) and a T-type thermocouple (accuracy +/- 1°C) was placed on each of the internal surfaces (walls, ceiling, floor and door), and on the external surface of the wall sample, all at a height of approximately 1.5m. This allowed constant measurement of heat flow through the elements and the recording of the temperature of each surface.

In addition, four T-type thermocouples were placed at regular vertical intervals (10cm, 75cm, 140cm and 215cm from floor level) to measure air temperature in the external and internal chambers and to enable evaluation of any stratification effects. A K-type thermocouple (accuracy +/- 1.5°C) was also inserted into the insulated void below the chamber floor, in order to monitor the ability of this construction detail to act as a thermal buffer between the chamber and the external empirical environment.

Figure 7-11 shows the experimental set up. In addition to the internal and external heat flux sensors on each surface and suspended in the air, T-type thermocouples were also embedded in the brick wall section at depths of 5cm, 11cm and 16cm, in line with the external thermocouples. A DT 85 and DT 500 datalogger was used to record information from all of the sensors at 20 minute intervals.

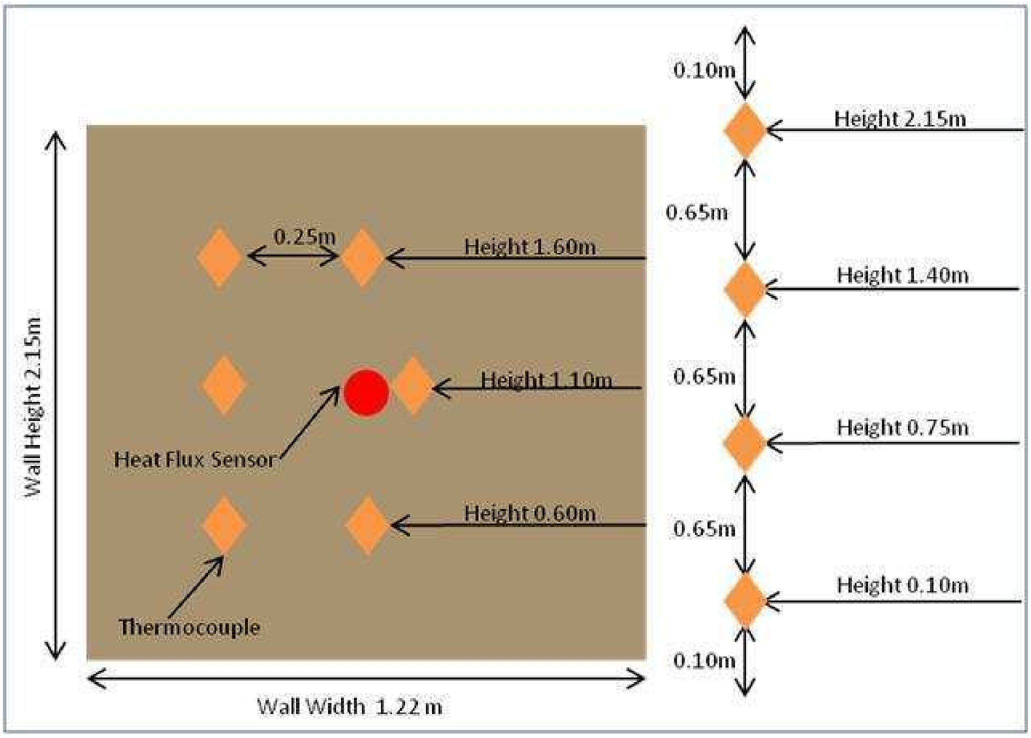


Figure 7-11 - Thermal Chamber Sensor Locations (Wall Section and Air Space)

The coheating test methodology was employed as the means to assess thermal performance of both the internal chamber and the two wall samples, and the impact of different environmental conditions, such as solar radiation level and ΔT. A heater was placed in the internal chamber, with a thermostat attached to maintain temperature at 25°C. A power meter was used to collect data relating to the amount of energy required to achieve a constant internal temperature. The access door to the internal chamber was sealed, as were all points of potential air leakage such as service penetrations.

The test conditions applied, and resulting data, are discussed in the following sections, whilst a full summary of the data derived from the experimental work is included in Appendix 9.

7.2.2 Control Test

In order to establish baseline HLC data for the chamber prior to any alteration work, an initial coheating test was undertaken. The only alteration made to the material aspects of the chamber was the installation of a 320 mm celotex insulation layer to the internal wall surface of the internal chamber. This had a section removed in order to account for the area where the masonry wall samples would later be inserted. In this way, any variation in the derived HLC values could be attributed to changes in the wall section properties, as the remainder of the chamber construction remained constant throughout the experimental work.

During the control test, the internal chamber temperature was maintained at 25°C, whilst the chiller unit was used to set the external temperature at approximately 5°C and 10°C. This achieved ΔT values of 15K and 20K. The resulting coheating test results are shown in Table 7-8. Due to the lack of any natural or artificial light source during the experiment, there was no requirement to make adjustments for lighting heat gains.

Table 7-8 - Thermal Chamber Control Test - Coheating Data

	Mean Internal Temperature (°C)	Mean External Temperature (°C)	Temperature Difference (K)	Mean Total (Wh)	Mean Total (W)	Mean HLC (W/K)
15K Delta-T	25.45	9.92	15.52	3884.80	216.62	14.01
20K Delta-T	25.39	4.93	20.46	5015.00	279.81	13.68

The data shows a considerable increase of 63.19 W when a greater ΔT is imposed upon the research chamber. A 0.33 W/K (2.4%) reduction is observed in the HLC value, which is possibly due to experimental error as in completely accurate conditions the HLC should remain the same as power input should be proportional to ΔT. The full data set is used in Figure 7-12, in order to obtain a mean HLC value for the control chamber via linear regression analysis.

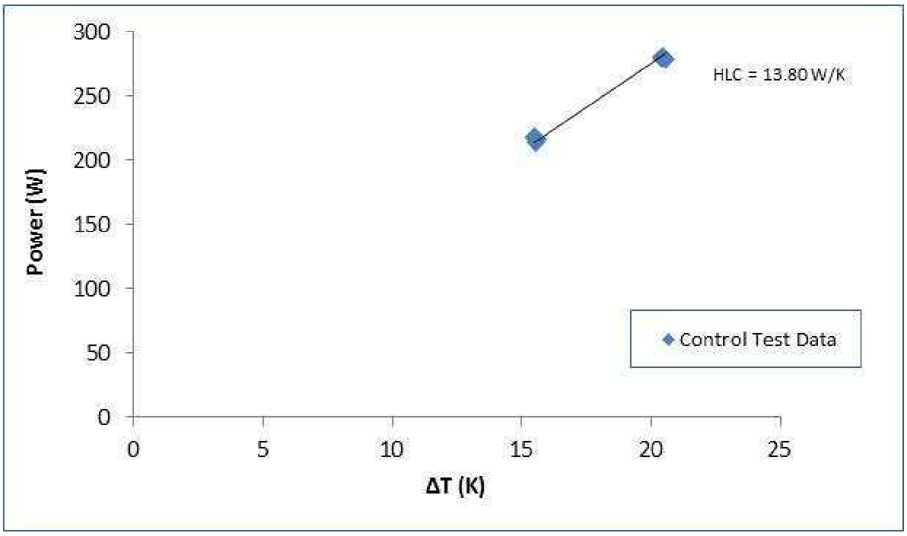


Figure 7-12 - Illustration of Full Control Test Data

In addition to providing a baseline mean HLC of 13.80 W/K, the control tests also presented evidence that the thermal chamber facility had the ability to produce repeatable and reliable data. The range of HLC values obtained varied by a factor of 0.15 W/K (20 K ΔT) and 0.22 W/K (15 K ΔT). In both cases, the magnitude of variance was less than 1.6%, and so is deemed acceptable within the realms of experimental error, which could amount to 7%.

A heat loss model based upon the SAP 2009 calculation methodology was developed in order to assess the predicted heat loss characteristics of the chamber. The HLC generated from this exercise amounted to 11.56 W/K, based on the manufacturer stated u-value data, allowance for the insulated panel, measured element areas, and default values for air tightness (15 $m^3/(h.m^2)$ @ 50Pa) and thermal bridging (y=0.15).

The predicted heat loss was approximately 16% lower than that measured within the chamber, indicating that some of the data inputs within the model were possibly not correct, either due to differences in physical u-values or wrongly made assumptions. Further analysis of the heat flux data gathered during the coheating test showed that the former assertion could be correct. In-situ u-values were calculated using internal and external air temperatures and heat flux data, based on the technique outlined in Section 4.6.2. The calculated u-values were different from those provided by the manufacturer, as indicated in Table 7-9.

Table 7-9 - Control Test - Manufacturer Data and Measured U-Values

	Left Hand Wall	Right Hand Wall	Back Wall	Wall with Insulation	Floor	Ceiling	Door
Manufacturer U-Value Data (W/m^{2}K)	0.44	0.44	0.44	0.10	0.44	0.44	0.44
Measured U-Value Data (W/m^{2}K)	0.52	0.56	0.57	0.14	0.88	0.82	0.72

Even in a simple construction such as the thermal chamber, the measured u-values were, in some cases, considerably different to those provided in manufacturer literature. For example, the mean floor u-value calculated from in-situ heat fluxes was twice that of the expected value. The ceiling also showed a large variance from the original inputted SAP model data.

When the measured u-values were inputted into the SAP 2009 model, the fabric only HLC observed increased to 13.60 W/K, which is more comparable to the 13.80 W/K fabric heat losses obtained using the coheating test methodology. If the total HLC, including assumptions with regard to ventilation strategy, is considered, the SAP result is greater at 15.09 W/K. However, the steady state maintained by the thermal chamber during the tests does not utilise a natural ventilation strategy (as included in the SAP methodology), so the fabric only heat losses provide a more analogous physical state for data comparison.

In order to assess the ability of the chamber to provide repeatable results in a range of weather conditions, spot tests were undertaken when external temperatures ranged from 25°C to -2°C. The HLC and power input data in all cases was found to be almost identical, demonstrating that, when the chamber was heated constantly, it was able to produce reliable data across a range of external weather conditions, due to the fabric performance and insulated ground floor void.

7.2.3 Simulation 1: Solid Brick Wall

Following the completion of the control test, a 1.22m wide by 2.15m high (2.623m^2) section was removed from one wall of the internal chamber in order to construct a solid brick wall to be used as the first sample type. This comprised of an uninsulated 223mm (two brick) thick wall (210mm thick brick wall with 13mm plaster on brick), built in a traditional manner, with no cavity. A theoretical u-value of 2.148 W/m^{2}K was calculated using software developed by the BRE, as included in Appendix 10, whilst the relevant experimental data is located in Appendix 9.

A testing sequence was undertaken, in order to obtain data relating to the performance of the wall when it was subjected to a range of ΔT values (10K, 15K and 20K), with the resultant information contained in Figure 7-13.

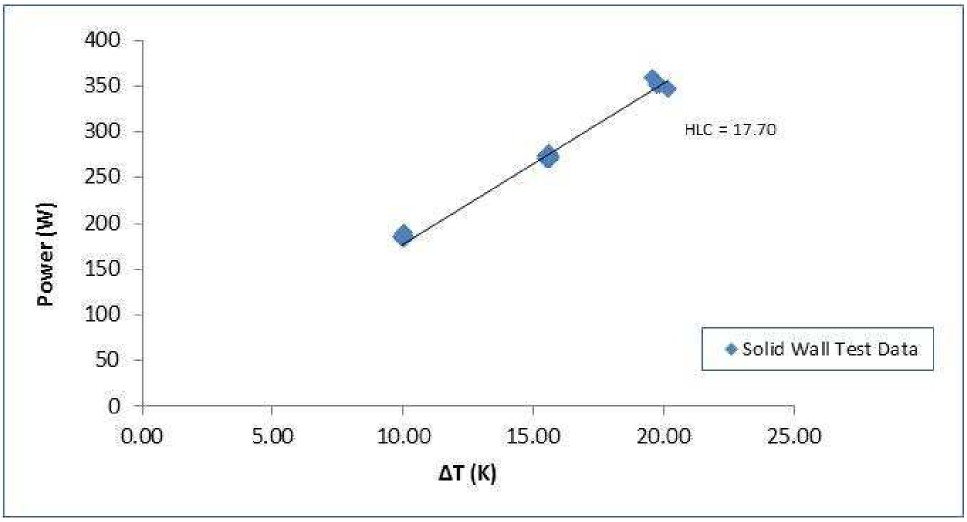


Figure 7-13 - Solid Brick Wall Test - Coheating Data

It can be seen that the mean HLC value obtained for the solid brick wall is 17.70 W/K, an increase of almost 4 W/K over that observed prior to the alterations made to the chamber (13.80 W/K). This is attributable to the installation of the brick wall, as all other material characteristics remained constant, and the error margin of +/- 7% within the experiment may only account for a maximum divergence of up to +/- 2 W/K. In terms of variance of the HLC when different

ΔT conditions were imposed, the solid brick wall reacted differently to the original chamber, as detailed in Table 7-10.

Table 7-10 – Solid Brick Wall Test – ΔT HLC Values

	Mean Internal Temperature (°C)	Mean External Temperature (°C)	Temperature Difference (K)	Mean Total (Wh)	Mean Total (W)	Mean HLC (W/K)
10K Delta-T	24.90	14.88	10.02	4457.00	185.72	18.54
15K Delta-T	25.26	9.68	15.58	6544.00	272.67	17.50
20K Delta-T	24.48	4.65	19.83	8776.00	351.93	17.75

In the case of the control tests, an increase of 63.19W and a 0.33 (2.4%) reduction in HLC was observed when the ΔT was increased from 15K to 20K. In Table 7-10, the same change in conditions produces an increase of 0.25 W/K (1.5%) and rise of 79.26 W with regard to the solid brick wall. Therefore, the altered construction is behaving in a different way, probably due to the lack of any thermal mass and associated insulative/heat retaining properties leading to greater sensitivity to the changes in external chamber temperature.

The increase in HLC when a 10K ΔT is created between the inner and outer chamber temperatures is also much higher than the value at 15K, with a rise in HLC of 1.04 W/K and a power uplift of 86.95 W. The range of HLC values observed varied from 17.2 W/K to 18.8 W/K, with a maximum variance of 1.6 W/K (9.3%). Therefore, ΔT does appear to have a reasonable influence on measured HLC values, although this is largely explained by the +/- 7% error applied to account for equipment precision and sensitivity. Inaccuracy within the experimental set-up could potentially explain the higher than expected HLC calculated for the 20K ΔT simulation.

In terms of u-value assessment, the brick wall section was calculated to have a u-value of 2.148 W/m^{2}K, derived using standard approved methodology (Building Standards Institute (BSI), 2008a). When inputted into the basic SAP 2009 model produced for the chamber, the predicted fabric heat losses increased to 17.87 W/K, which closely match the mean HLC of 17.70 W/K obtained from the series of coheating tests. The heat flux through the solid brick wall section was used to obtain a measurement of in-situ performance, and the u-value was found to be approximately 2.21 W/m^2K, this value being the mean for the entire testing period. This is relatively close to the expected u-value, demonstrating confidence in the u-value calculation technique and providing confirmation that the brick wall construction process was undertaken to a high standard.

Following the tests to obtain a benchmark mean HLC for the solid brick wall construction, further analysis of environmental effects continued with a series of experiments to investigate the impact of solar radiation on the HLC derived from the coheating test. A bank of 100W halogen lights was used to simulate radiation levels of approximately 100W, 200W and 350W. This was achieved through varying the number of lit bulbs in conjunction with a dimmer unit. The solar lighting board is shown in Figure 7-14.

Figure 7-14 - Thermal Chamber - Solar Lighting Board

The internal chamber temperature was maintained at 25°C throughout the tests whilst the external temperature was set at 10°C. This resulted in a constant ΔT of 15 W/K being present during the testing sequence. The data obtained from the experiments is detailed in Table 7-11.

Table 7-11 - Solid Wall Coheating Test - Raw Solar Radiation Test Data

	Mean Internal Temperature (°C)	Mean External Temperature (°C)	Temperature Difference (K)	Mean Total Wh	Mean Total W	Mean HLC (W/K)
100W Solar	25.34	9.89	15.45	5891.00	245.46	15.88
200W Solar	25.10	10.05	15.04	4981.40	230.74	15.35
350W Solar	25.87	10.58	15.29	4749.00	197.88	12.95

In terms of impact upon the test, the lighting rig appears to be increasing external temperatures slightly at higher radiation levels, and internal temperatures appear to be less stable. As greater light intensities are applied to the wall, the mean total power requirement is lowered, resulting in a decrease in HLC. This is due to the impact of heat gains from the lighting affecting the thermal behaviour of the wall. The most noticeable effect is that of the application of 350W solar simulation, which decreases the HLC by 2.4 W/K. This suggests that higher levels of solar radiation can significantly affect the coheating test result, so correction to account for the reduced power input attributable to this effect is essential.

As such, multiple regression analysis was undertaken in order to account for the effects of the varying levels of lighting applied during the experiment. The stability of the conditions in the tests undertaken in different conditions led to full regression being required on the whole dataset from all three scenarios. When taken in isolation, the solar aperture could not be derived due to the extreme similarity between the individual daily test values.

Following correction of the data, the HLC value calculated for 100W, 200W and 350W lighting intensities was normalised to 17.14 W/K, 17.70 W/K and 17.37 W/K for each case respectively. This compares favourably with the original HLC of 17.50 W/K calculated for the solid brick wall in standard conditions with a ΔT of 15 W/K. Therefore, the use of multiple regression techniques appears to be reliable in order to correct for the impact of solar gains, and the remaining divergence lies within acceptable error limits for the data obtained.

Siviour analysis was also used to evaluate the combined solar data, and the results from both this and the multiple regression technique are shown in Figure 7-15 and 7-16.

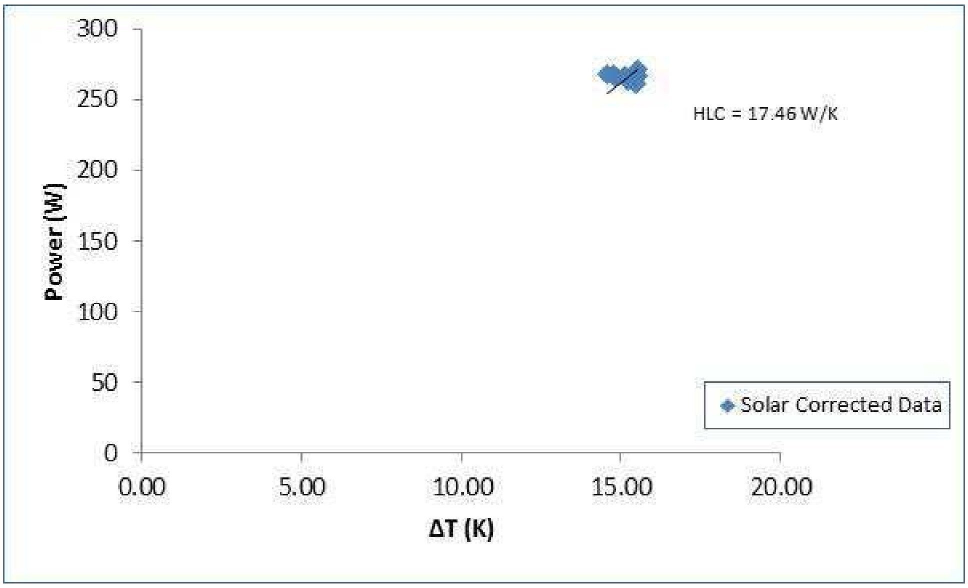


Figure 7-15 - Solid Brick Wall – Solar Correction Analysis – Multiple Regression

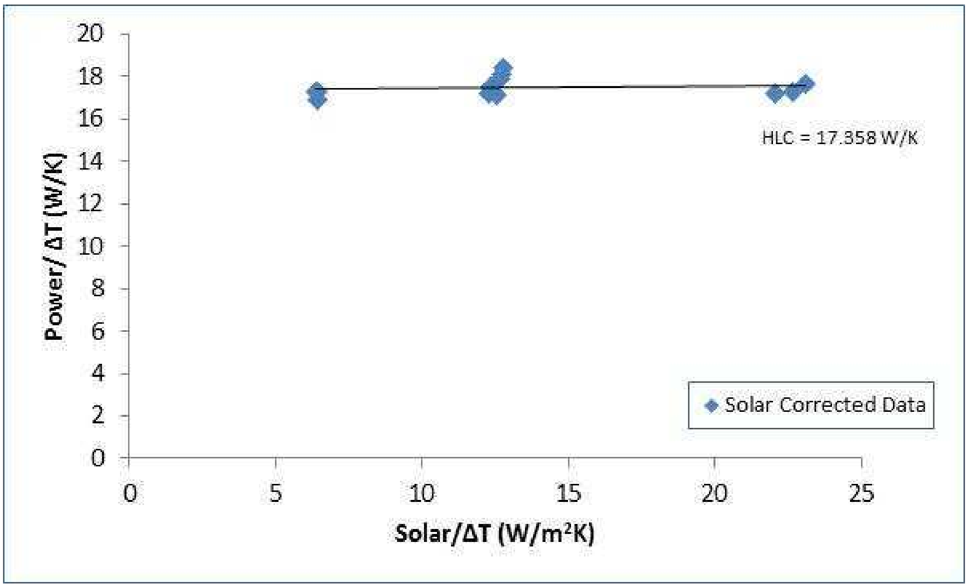


Figure 7-16 - Solid Brick Wall - Solar Correction Analysis – Siviour Analysis

The HLC value of the combined datasets for the 100W, 200W and 350W solar simulations are very similar when analysed utilising the two most commonly employed methods. Multiple regression provides a slightly higher result at 17.46 W/K, which is almost identical to the baseline HLC value of 17.50 W/K observed at a ΔT of 15 W/K during the work undertaken prior to the installation of the lighting rig. Siviour analysis produces a HLC that is lower by 0.1 W/K, but this is still relatively consistent with both the multiple regression and the original control test data. Therefore, both techniques are found to be appropriate and robust in terms of application to normalise raw power data to account for solar gains.

7.2.4 Simulation 2: Solid Brick Wall (External Insulation)

Following completion of the tests undertaken on the uninsulated solid brick wall, the same work was repeated but with additional external insulation applied to the original wall. The sample now comprised of a 325mm thick wall, made up of a 210mm thick brick wall with 13mm plaster on brick and 100mm EPS external insulation and render. The theoretical u-value was calculated to be approximately 0.3 W/m^{2}K, using software developed by the BRE, and the data sheet is included in Appendix 10, whilst the relevant experimental data is located in Appendix 9.

Initially, coheating tests were undertaken to establish the performance of the wall and the response of the fabric to changes in ΔT. Figure 7-17 shows the resultant data, with that obtained for the assessment of the uninsulated wall also included.

The effect of the additional external insulation is immediately apparent, with the mean HLC being 14.16 W/K, representing a reduction of 3.52 W/K, almost 20% of the original value obtained for the uninsulated wall. The variance due to changes in ΔT is demonstrated in Table 7-12.

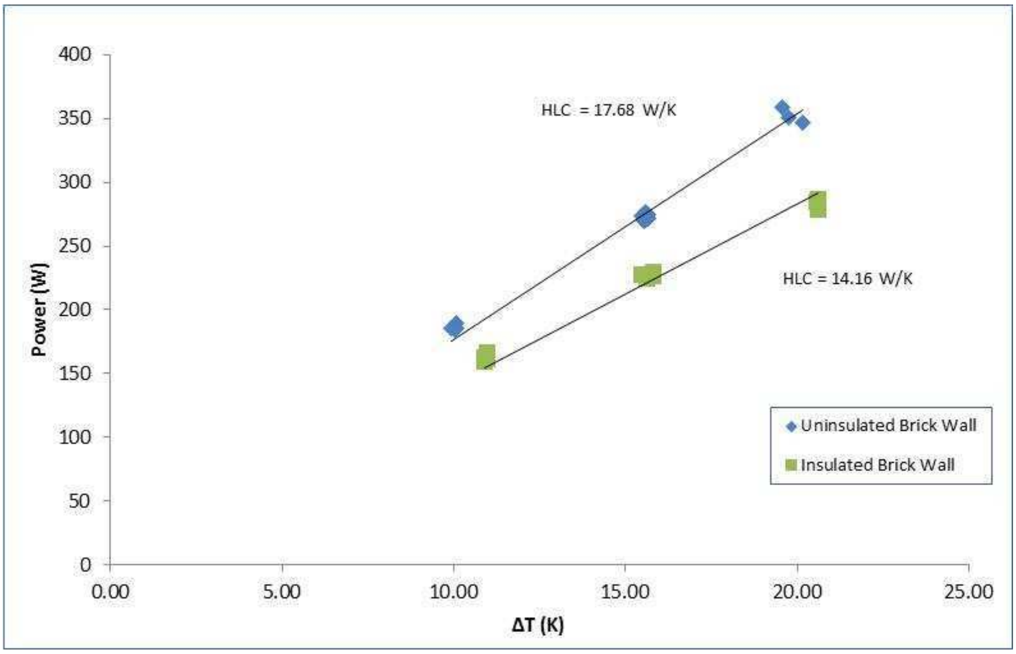


Figure 7-17 - Thermal Chamber Coheating Tests - ΔT Data for Insulated and Uninsulated Brick Wall

Table 7-12 - Comparison of ΔT Data

	Mean Internal Temperature (°C)		Mean External Temperature (°C)		Temperature Difference (K)		Mean Total Wh		Mean Total W		Mean HLC (W/K)	
	Uninsulated Wall	Insulated Wall	Uninsulated Wall	Insulated Wall	Uninsulated Wall	Insulated Wall	Uninsulated Wall	Insulated Wall	Uninsulated Wall	Insulated Wall	Uninsulated Wall	Insulated Wall
10K Delta-T	24.90	26.19	14.88	15.26	10.02	10.93	4457.00	3894.50	185.72	162.27	18.54	14.84
15K Delta-T	25.26	26.11	9.68	10.40	15.58	15.71	6544.00	5082.86	272.67	229.41	17.50	14.60
20K Delta-T	24.48	25.99	4.65	5.39	19.83	20.60	8776.00	6136.40	351.93	284.14	17.75	13.79

It is interesting to note that the HLC follows a strictly linear trend when considered in the context of the insulated brick wall, and yet this is not the situation in the case of the uninsulated wall. The data relating to both of the construction types was reassessed, but the resulting values were identical to those presented here. The difference in behaviour is likely to be due to the additional protection afforded to the insulated brick wall through the EPS insulative layer and potential experimental error in the uninsulated wall tests (+/- 7%). The internal temperature would possibly be less sensitive to changes in external temperature due to enhanced thermal inertia resulting in slower response times.

A series of solar simulations were performed with regard to the insulated solid brick wall, with the results shown in Table 7-13.

Table 7-13 - Insulated Solid Brick Wall – Raw Solar Test Data

	Mean Internal Temperature (°C)	Mean External Temperature (°C)	Temperature Difference (K)	Mean Total (Wh)	Mean Total (W)	Mean HLC (W/K)
100W Solar	25.53	10.05	15.47	5383.50	224.31	14.50
200W Solar	25.69	10.11	15.58	5170.67	215.44	13.82
350W Solar	25.69	10.58	15.11	4489.66	198.18	13.11

It can be seen that, as in the case of the uninsulated brick wall solar tests, the external air temperatures are being affected very marginally by the lighting bank. However, the internal air temperature is much more stable, with a variance of 0.16°C as compared to the previously noted 0.53°C. This is due to the enhanced ability of the wall construction to regulate for solar effects due to the addition of the insulative layer. This could have some relevance in terms of the wider context of hard to treat solid brick wall dwellings, where improvement through use of external insulation might be the only viable option.

In terms of reduction in power requirement due to the impact of solar gains, the insulated wall construction varies by only 26W between the 100W and 350W tests. In the case of the uninsulated wall, the range within the dataset was almost double, indicating that the addition of the EPS layer has reduced the sensitivity of the HLC value due to enhanced thermal capacity.

Multiple regression analysis was applied to the raw data from the coheating test, in order to adjust for the impact of solar effects. The mean corrected HLC values for the 100W, 200W and 350W simulations were 14.86 W/K, 14.64 W/K and 14.46 W/K respectively. These are all very similar to the 14.6 W/K value calculated for the 15°C ΔT case indicating that the regressions analysis has once again provided reliable adjustment of the data.

In terms of the actual performance of the wall, the SAP 2009 model was adjusted to include a sample wall u-value of 0.3 W/m^{2}K, as originally calculated. This produced a fabric heat loss prediction of 13.02 W/K, which is clearly much lower than the measured coheating test mean value of 14.16 W/K. Using the heat flux data for the period relevant to the coheating tests undertaken with no solar intervention, an average calculated in-situ u-value of approximately 0.6 W/m^{2}K was obtained. This resulted in a revised SAP 2009 HLC value of 13.81, which is slightly more comparable with the data derived from the coheating test.

Whilst the calculated mean of the range of HLC values is 14.16 W/K, this differs slightly from the HLC derived using more complex methods such as multiple regression and Siviour analysis, as shown in Figure 7-18 and Figure 7-19.

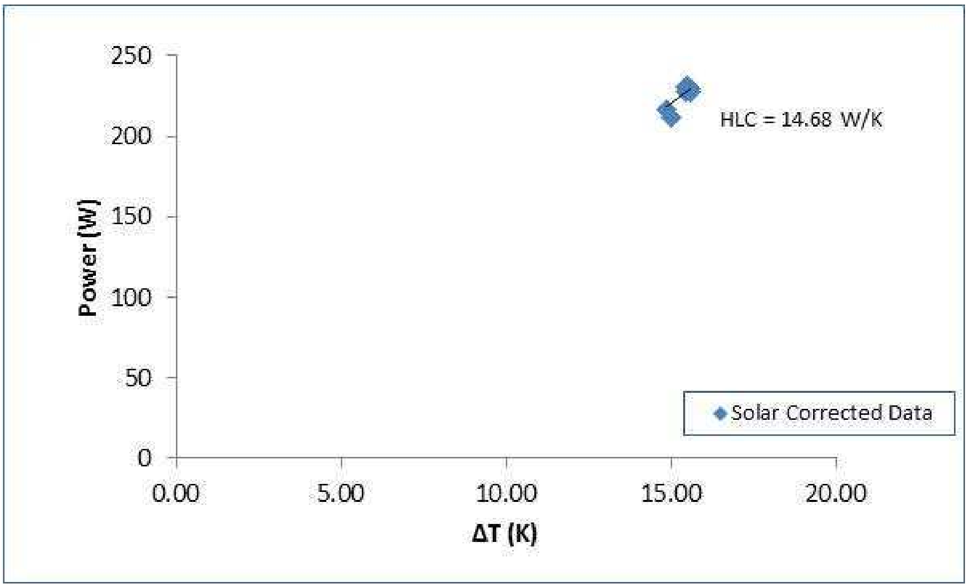


Figure 7-18 - Insulated Brick Wall – Solar Correction Analysis – Multiple Regression

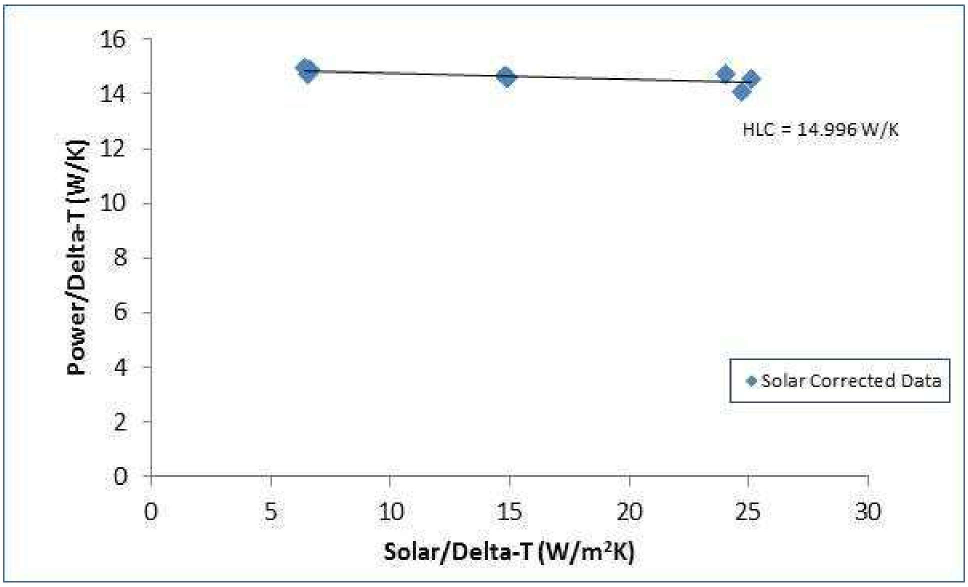


Figure 7-19 - Insulated Brick Wall - Solar Correction Analysis - Siviour Analysis

Both multiple regression and Siviour analyses produce a higher HLC of 14.68 W/K and 14.966 W/K respectively. The base case HLC value of the chamber with the insulated brick wall in place and a ΔT of 15 W/K was 14.6 W/K, which is consistent with the derived multiple regression value. Siviour analysis produces a higher result, which is the converse situation to that observed with the uninsulated solid brick wall, where the result was lower in comparison to that calculated using the multiple regression technique. In both cases, the multiple regression value was almost identical to the original baseline value, which indicates that this method may be less sensitive to other factors within the data that may influence the final solar-corrected HLC value.

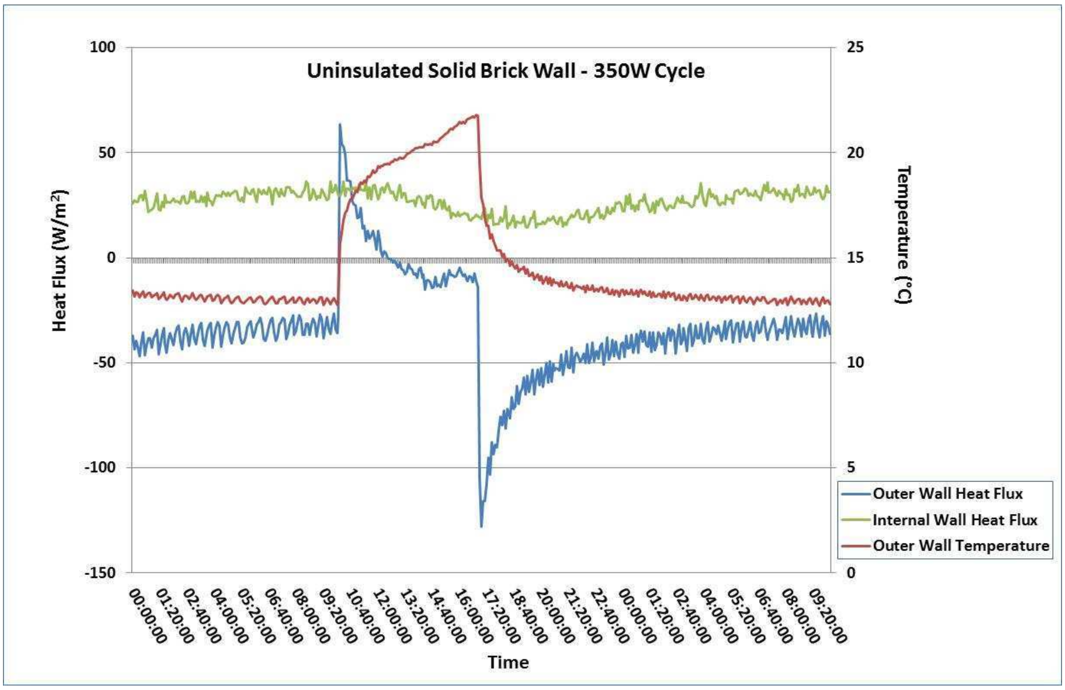
7.2.5 Assessment of Thermal Lag

Following the initial assessment of the impact of a constant supply of simulated solar lighting applied at different levels, a series of experiments were undertaken in order to obtain a deeper understanding of the long-term effect of exposure to radiance on the two types of wall construction under evaluation. The lighting rig was set-up to deliver 100W, 200W and 350W intensities for a period of approximately 6 hours, and then the lamps were switched off for 18 hours. Monitoring of the heat flux, surface temperatures and temperatures within the wall construction provided an indication of the impact of solar effects on the behaviour of the two samples in each scenario, with data included in Appendix 9 and graphs showing the feat and temperature flows relevant to each simulation in Appendix 11.

As shown in the example graphs in Figure 7-20, and the further charts in included in Appendix 11, the two types of wall construction clearly react differently to the lighting cycle. In all cases, the external wall heat flux demonstrates more sensitivity to the heat source provided by the lighting rig, which would be expected as this surface of the wall is closer to the applied heat source. The baseline heat flux condition of the solid brick wall is approximately -30 W/m^2, as compared to -5 to -10 W/m^2 in the case of the insulated wall. This change in heat flow level is solely attributable to the thermal mass incorporated by way of the insulation material, as all other test conditions remained consistent in each set of experiments.

In all of the solar simulations, the uninsulated solid brick wall shows an initial peak in external heat flux which slowly regulates over time as the wall condition stabilises. The heat flux level observed in the 100W test scenario rises immediately to 0 W/m^2 when the lights are activated, which then takes approximately 7 hours to regulate to baseline levels following removal of the light source. A similar situation occurs when 200W of lighting is applied to the wall, although it takes longer for the building fabric to return to original heat flux levels (9 hours). When the 350W lighting bank is utilised, the heat flux peaks suddenly at +50 W/m^2, indicating that heat is flowing into the wall, before gradually decreasing to -15 W/m^2 over a period of 7 hours as the fabric temperature normalises. When the lights are switched off, the heat flow out of the wall increases considerably and then requires a full solar simulation cycle (17 hours) to regulate to pre-test levels.

The insulated wall reacts more immediately to the application and removal of the light source. In the case of the 100W, 200W and 350W tests, maximum heat flows out of the wall are measured at approximately -18 W/m^2, -40 W/m^2 and -55 W/m^2 respectively. The time taken to reach each of these values is 2 hours, 3 hours and 5 hours, showing that the additional heat levels associated with the lights is affecting heat flow out of the insulation and that higher lighting intensities require a longer stabilisation period. Following removal of the lamps, the insulated wall shows a more rapid return to baseline heat flux conditions, with a stabilisation time of 2 hours, 3 hours and 4 hours for the 100W, 200W and 350W scenarios.



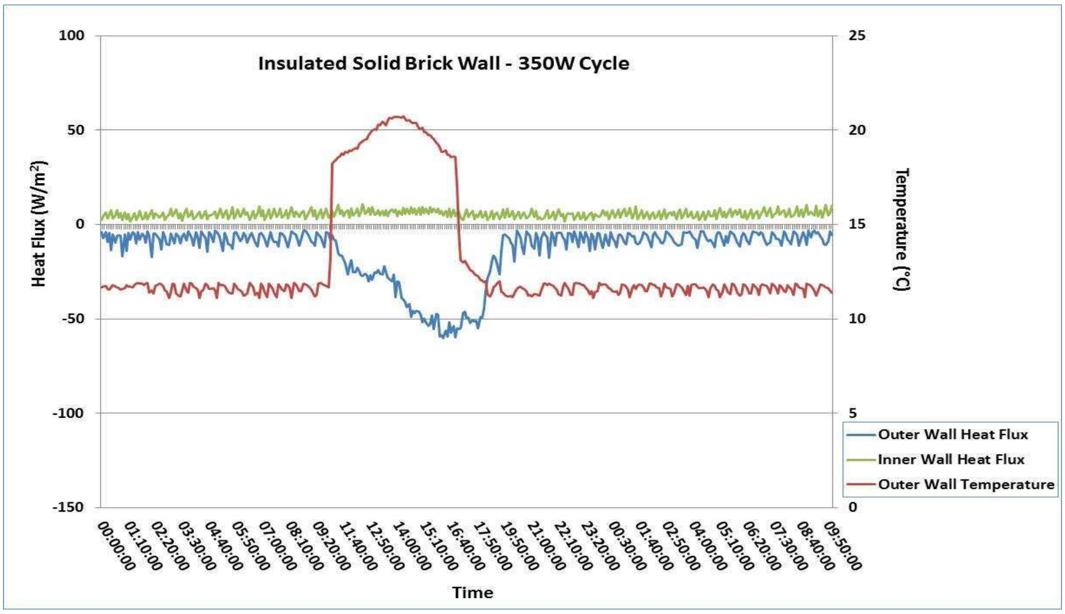


Figure 7-20 - Solar Cycle Simulation - Heat Flux Data

With regard to the heat flux measurements associated with the internal surface of the wall, the insulated brick wall shows no change during any of the tests, and maintains consistent heat flow into the wall of approximately +5 W/m^2 even at high lighting intensities.

More variation is observed in the case of the uninsulated wall. The baseline heat flux level during the 100W and 200W tests is approximately +15 W/m^2, which then decreases slightly to +14 W/m^2 during the period when the lights are in operation. The original heat flux recorded during the 350W test is +18 W/m^2, reducing to approximately +16.5 W/m^2. Whilst this is only a slight change in heat flow into the wall from the internal chamber, it occurs as the heat flowing out of the external wall surface is decreasing due to heat gains from the light source. This effectively means that the electrical power requirement to retain a constant temperature inside the internal chamber will be reduced due to the simulated solar gains.

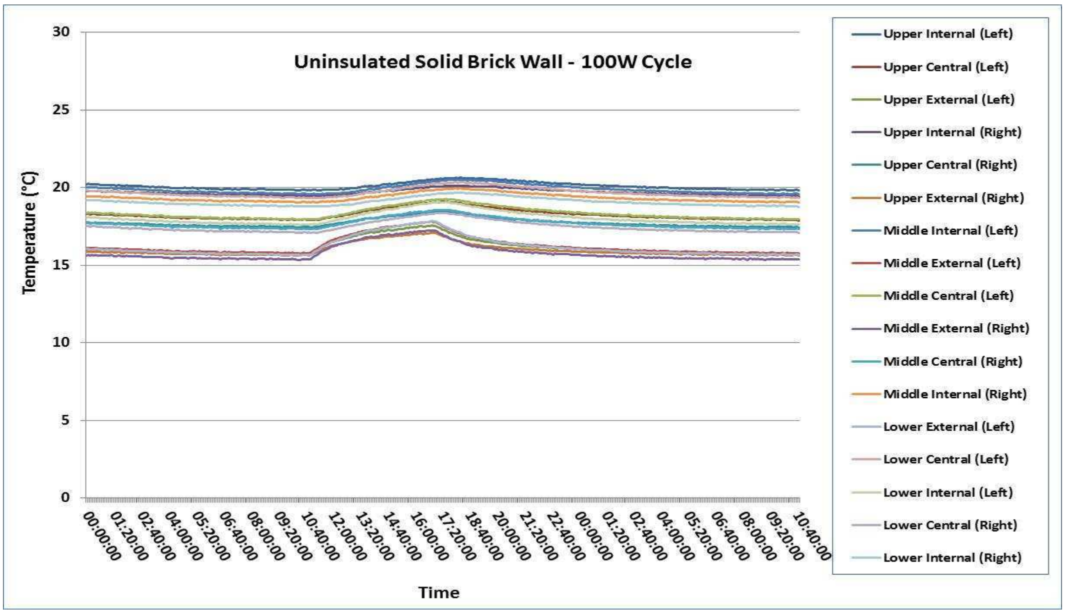
In terms of external surface wall temperature, this follows the opposite trend to the heat flow data, which would be expected as the additional heat gains from the wall would increase surface temperature whilst reducing heat flows. The uninsulated wall shows a baseline temperature in all test conditions of approximately 13°C. In the case of the 100W test, this quickly rises to 14°C and continues to increase to a maximum of 15.5°C, taking approximately 3 hours to stabilise following the removal of the lamps. The 350W simulation results in a greater initial temperature rise to 18°C, increasing to 21.5C, and then requires the full solar cycle timescale (17 hours) to return to the baseline 13°C. The 200W experiment falls between the two extremes, with the temperature peaking at 17°C and a normalisation time of approximately 6 hours.

The insulated solid brick wall displays an immediate reaction to the application/removal of the light source, with no lag time observed in order for temperatures to regulate following removal of the lamps. The baseline temperature is lower than that observed in connection with the uninsulated wall, being 11.5°C in all cases. This rises to 13.2°C, 16.5°C and 20.5°C in the case of the 100W, 200W and 350W simulations respectively.

Whilst the baseline and maximum external wall surface temperatures are different for the two wall constructions, it is interesting to note that the increase associated with the application of the lights is almost identical. This amounts to approximately 2°C, 4°C and 8.5°C for the 100W, 200W and 350W tests in turn. The heat gains will change the surface boundary condition of the wall, which will influence the heat flows in and out of the brickwork.

An example of the effect of the simulated solar gains on the temperature profile occurring within the fabric of the wall sections is displayed in Figure 7-21, and further charts are included in Appendix 11. The insulated wall does not show a significant response at 100W and 200W intensities, with the temperature profile remaining constant throughout the lamps on/lamps off cycle. A slight change can be seen in the 350W test, with temperatures rising slowly during the period when the lamps are in operation. The actual rise in temperature is approximately 0.8°C in the case of each sensor, although due to the thermal mass of the wall construction it takes approximately 10 hours for the wall to return to the original temperature recorded prior to the lights being switched on.

The solid brick wall has a greater response to the enhanced temperature imposed by the heat from the lamps. Even at low levels of solar simulation, the lack of any insulation within the wall construction leads to an increase in wall temperature of between 1°C and 2°C depending on sensor location. The rise in temperature in the external sensors (closest to the light source) is higher than that observed in the thermocouples near to the internal wall surface. A time period of approximately 7 hours is required for the wall temperature to stabilise following the lighting cycle.



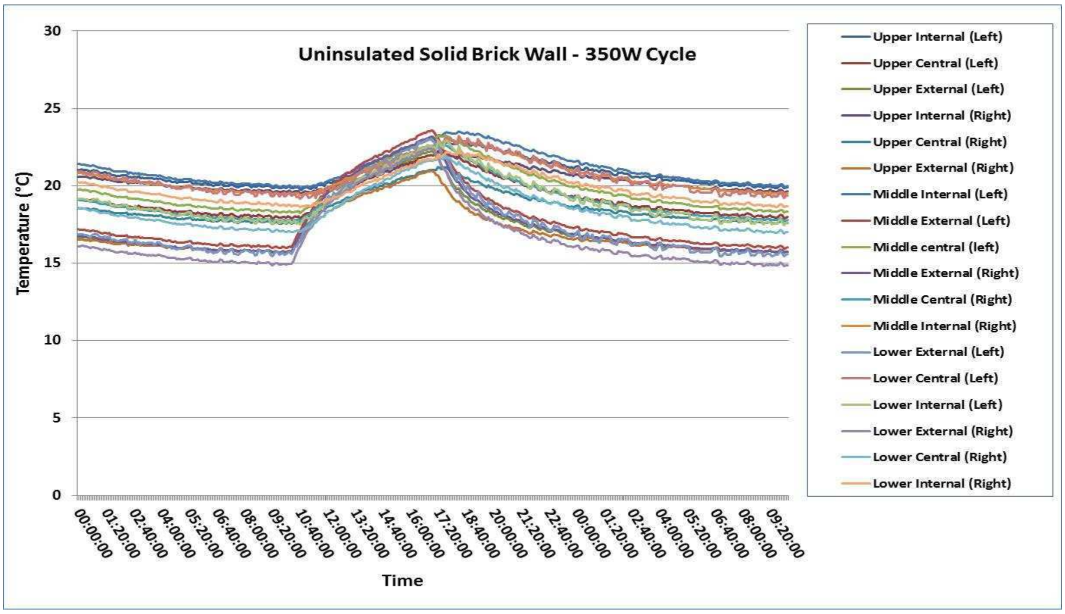


Figure 7-21 - Solar Cycle Simulation - Temperature Profile Through Wall Section

This effect is even more noticeable when higher lighting intensities are considered. When the 200W light source is used, the external sensors show an increase in temperature in excess of 4°C, whilst those closer to the internal surface rise by approximately 1.8°C when the lights are in use. The temperature decreases more quickly when the lighting bank is removed, with original wall temperatures being reached after approximately 9 hours.

As would be expected, the data from the 350W experiment illustrates that the wall reacts strongly to higher levels of solar simulation. Indeed, the external wall sensors show a rapid temperature increase of 7°C, while the temperature closest to the internal wall surface rises by almost 4°C. It then takes the entire duration of the ‘dark’ element of the cycle (approximately 17 hours) for the temperature to stabilise to that existing prior to the lights being applied to the wall.

This demonstrates that the application of external insulation to the solid brick wall provides a buffer to protect the internal environment from the effects of solar gains. The wall temperature is maintained at a steady state throughout the solar simulation cycle due to the heat already stored within the insulative layer. When the solid brick wall is considered with no insulation applied, the wall temperature prior to the operation of the lighting rig is 15-21°C (depending on sensor location), which is noticeably lower than in the case of the insulated wall (approximately 22-25°C). The temperature gradient throughout the wall section is much more pronounced.

The uninsulated wall brickwork temperature reacts immediately when the lamps are switched on and off, and the thermal lag and time taken for the heat imposed by the lights to dissipate is apparent even at low light intensities. At higher levels of solar simulation, a considerable time period is required in order for the wall temperature to stabilise. A similar situation is observed in relation to the heat flux and temperature levels associated with the external wall surface.

7.2.6 Assessment of Moisture Effects

The impact of precipitation on the results of the coheating test is an area of uncertainty in the context of how it may affect the property under consideration and the resulting HLC values. In order to investigate this matter, the insulated brick wall constructed within the thermal chamber was used to evaluate the potential effects of moisture on the data relating to heat losses.

Two scenarios relating to simulated rainfall were applied to the standard test conditions of a constant 10°C external air temperature and 25°C internal air temperature. During the first experiment, a pressure sprayer set to deliver a fine mist of water was used to apply a wetting rate of 1.5 litres per m^2 over the external surface of the wall sample. An additional water volume of 5% was allowed, in order to compensate for losses due to evaporation and poor absorption into the wall. The level of runoff from the surface of the wall was minimal due to the slow rate of water application. During the second test, the same procedure was followed and then the lighting bank was activated to deliver a simulated solar effect of 200W to the wetted wall surface.

The external surface heat flux and temperature data analysed for each test is shown in Figure 7-22 and Figure 7-23 . The effect of the change in conditions had a minimal effect on the internal wall and within wall surface heat fluxes and temperatures due to the external insulation acting as a barrier to the external environment. It is probable that the wetting levels applied would only penetrate into the concrete render layer on the external surface of the wall.

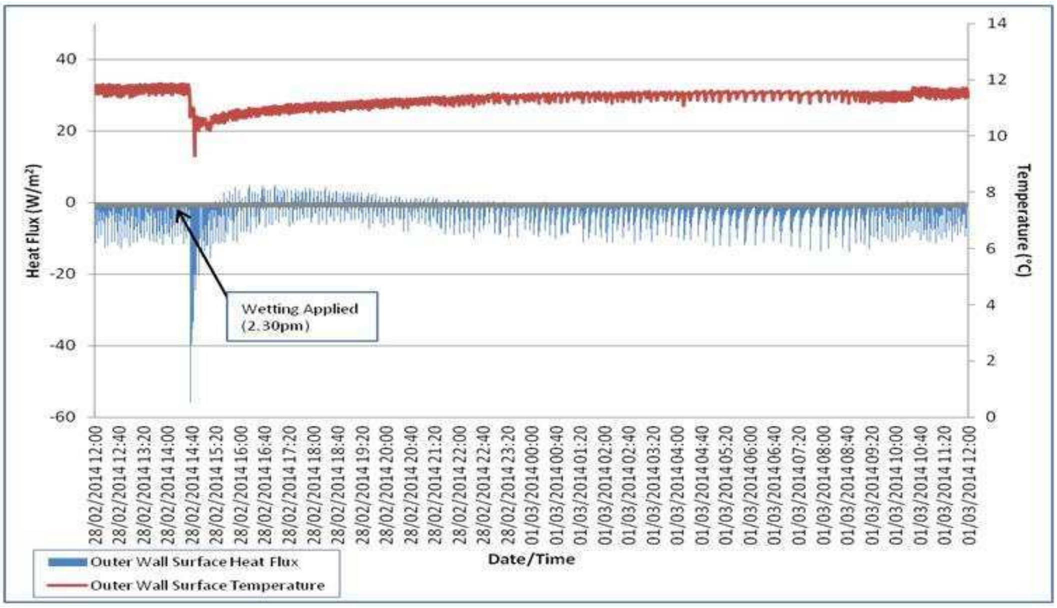


Figure 7-22 - Simulated Rainfall Effect - No Solar Radiation

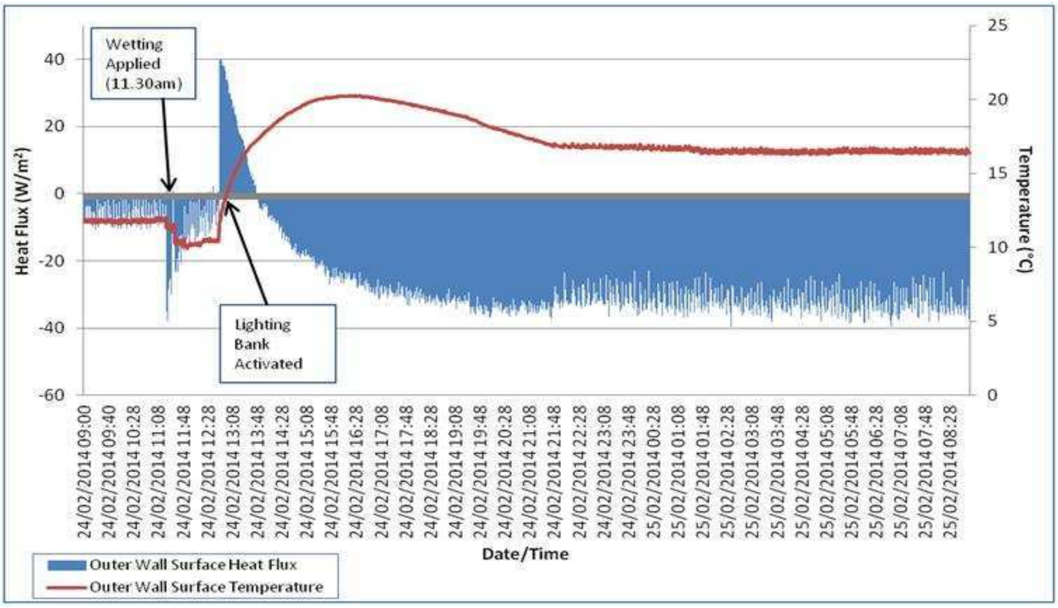


Figure 7-23 - Simulated Rainfall Effect - 200W Solar Radiation

In both of the tests, the baseline level of external surface wall temperature and heat flux prior to any change in environmental conditions is approximately 12°C and -10 W/m^2 respectively. In the case of the experiment with no solar simulation, the heat flux level out of the wall reaches -40 W/m^{2}K before returning steadily to normal levels over a period of 8 hours. As can be observed in the surface temperature data, the wall surface is cooler following the application of water, which results in increased heat movement out of the wall, in addition to increased conductivity and latent heat losses. There is a period of time when the heat flow becomes positive, indicating that heat is flowing into the wall from the external environment. This would occur when the surface temperature of the wall is higher than the temperature of the mass of the concrete render material.

When the same wetting conditions are repeated with the incorporation of an artificial lightsource to simulate solar levels of approximately 200W, the behaviour of the heat flows associated with the wall is significantly different. The heat flow increase out of the wall when the water is applied is similar to the first experiment, at approximately -38 W/m^{2}K, whilst the external surface temperature decreases to 10°C. When the lighting bank is activated, there is a sharp rise in heat flux into the wall, reaching +40 W/m^{2}K, and the surface temperature also increases to 22°C. This is due to the impact of the solar heat source on the mass of the wall, which is cooler than the external boundary conditions. As the render material starts to dry and becomes warmer due to stored heat, it begins to transmit heat back into the external airspace. This results in the surface temperature of the wall gradually decreasing, while the heat flow out of the wall causes a negative heat flux that stabilises at around 35 W/m^2.

In terms of the impact on the total heat losses observed, the thermal chamber has a standard HLC value of 14.86 W/K for the baseline experimental conditions utilised. In the case of the test with no solar radiation, a HLC of 14.59 W/K was calculated, while this reduced to 14.42 W/K for the simulation including 200W solar (uncorrected for solar effects). The baseline HLC for the chamber with 200W light intensity applied, when no rainfall is included and the same ΔT is used, is 14.26 W/K.

The results are not conclusive as to the effect of the rainfall simulation on the HLC value. In the case of the dry and wet tests with no solar radiation, a decrease of 0.27 W/K is observed. However, the same tests but with application of an artificial light source show an increase in HLC of 0.16 W/K. Such differences are slight, and it is not possible to say with certainty whether the changes in HLC are due to the applied moisture levels. Slight differences in test conditions, such as ΔT, may also have similar effects. The experiment may not be sensitive enough to highlight differences in the HLC attributable solely to the change in moisture content, and the variance observed is within the +/- 7% error range of the experiment.

It would be anticipated that, should the same test be repeated on the solid brick wall with no external insulation and render in place, the application of simulated rainfall and solar would be produce a more pronounced effect. This is due to the permeability of the brickwork, which would allow for greater penetration of the moisture into the building fabric. However, due to the limited availability of the thermal chamber for further tests, it was not possible to confirm this theory through experimental work.

7.2.7 Implications for the Coheating Test

The experimental work undertaken using the thermal chamber confirms that the environmental conditions present during a coheating test can affect the data collected and results obtained. Physical construction specification of building elements may also have a large influence on the way in which a building will respond to external stimuli, as shown through undertaking a series of controlled experiments on an uninsulated and externally insulated solid brick wall.

Wind speed and ΔT values can have some impact upon the HLC values derived through use of post-construction on-site experiments. Both wall types showed an increase in HLC at a ΔT value of 10K as compared to the standard baseline ΔT of 15K. This amounted to a 6% and 1.6% increase in HLC value for the uninsulated and insulated wall respectively. When a greater ΔT of 20K was imposed on the wall sections, the uninsulated wall showed an increase of 1.4% whilst the insulated wall HLC decreased by 5.5%. However, the variances observed are largely within the realms of experimental error, and the results are generally stable within a low range of variance.

Recalculation of the data did not reveal any analytical errors, so the difference in behaviour is assumed to be associated with the behaviour of the wall construction. It does demonstrate that individual dwellings do need to be assessed on a specific rather than generic basis, as the materials used and thermal characteristics will directly affect sensitivity to external parameters. This extends to consideration of wind speed, which could lead to a variation in HLC of +/-10% against measured mean HLC values, as in the case of the E.On House in the April 2012 testing period.

With regard to the effect of solar radiation, in the case of the solid brick wall, a 100W, 200W and 350W lighting simulation resulted in a 9%, 12% and 26% reduction in uncorrected HLC values. When an external insulative layer was applied, the same wall displayed a decrease in raw HLC of 1%, 5% and 10% in analogous conditions. This suggests that the insulated layer is successfully reducing the amount of solar heat being absorbed by the brickwork and is increasing stability of the heat flow and temperature profile of the structure. In both cases, multiple regression analysis successfully realigned the raw HLC data to baseline values obtained in comparable ΔT conditions with no solar influence.

In addition to any variations observed within the data attributable due to differences in solar radiation levels, temperature and wind speeds occurring at the time of an on-site experiment, the analytical approach used to evaluate the data could also lead to variance in calculated HLC values. The two cases examined in this study demonstrate that both techniques produce relatively similar results, with a 0.5% and 2% difference observed in the multiple regression and Siviour analysis undertaken in relation to the uninsulated and insulated brick wall.

Some suggestion has been made that a simplified analytical technique could be developed, where raw power data confined to the hours of night-time only is used to obtain a HLC value through use of simple linear regression techniques. This would negate the need to correct for solar gains and subsequent multiple regression or Siviour analysis. However, concern has been expressed as to the impact of heat gains that may remain stored within the building fabric which may continue to affect the HLC data after sunset (National House Building Council (NHBC) Foundation, 2013).

Indeed, the thermal lag observed in the case of the uninsulated wall was considerable, with a regulation time period of 7 hours, 9 hours and 17 hours required following the 100W, 200W and 350W solar simulations. This was reduced to 2 hours, 3 hours and 4 hours after the external insulation was applied. It should be noted that the lamps were switched on to a constant light intensity for 6 hours in each case and then removed for 18 hours. In reality, this may not provide a true representation of conditions experienced on site during a coheating test, as longer or shorter (or indeed very few) sunshine hours may be experienced and solar radiance levels may be intermittent and variable in nature. However, it would appear that a long time period may be required for the influence of solar gains to be removed completely from the test data, which could reduce the amount of usable data to an unacceptably short timescale in any 24 hour period if the hours of daylight (particularly in summer) are ignored. This is particularly true when considering building forms that incorporate low levels of insulation.

In order to actually quantify the effect of the various factors on the results obtained from the coheating test, Table 7-14 shows an estimation of the impact that different factors contributing to variance within the test could potentially have on the measured HLC and household energy costs.

The calculations utilise the SAP 2009 model developed in Section 7.1, which had a calculated HLC of 170.57 W/K and 161.47 W/K for the natural and MVHR-based ventilation strategies respectively. The cost data is based upon the

£ cost/1 W/K values calculated in relation to this model during the sensitivity analysis exercise. The impact on the HLC in terms of W/K increase/decrease has been derived from data relating to the chamber testing regime and the practical coheating tests undertaken on the example retrofit and new-build dwellings. The % change associated with each parameter has been applied to the SAP 2009 model HLC in order to obtain a baseline for comparative analysis.

Table 7-14 - Impact of Coheating Test Variables on HLC and Energy Cost Data

	Difference in W/K	**Cost of 1 W/K HLC Change (£/year)**	**Actual Cost of Variance (£/year)**
Fabric U-Value Underperformance (chamber tests - average 30% underperformance)	+15.6	£2.42	£37.75
Thermal Bridging (Tarmac House - 50% variance)	+22.0	£2.43	£53.46
Underperformance of MVHR system (from E.On House - (9% reduced efficiency)	+11.5	£2.13	£24.50
Underperformance of MVHR system (E.On House air throughput rates - 0.11 ACH pressurisation)	+10.0	£2.64	£26.40
High Delta-T Values (20K) (from case study and chamber data - 7% change for 5K change)	+11.94	£2.42	£28.89
Low Delta-T Values(10K) (from case study and chamber data - 7% change for 5K change)	-11.94	£2.42	-£28.89
High Solar Gains (from case study and chamber data - 17 W/K (10%) change at 350W solar level)	-17.0	£2.42	-£41.14
Medium Solar Gains (from case study and chamber data - 9 W/K (5%) change at 200W solar level)	-9.0	£2.42	-£21.78
Low Solar Gains (from case study and chamber data - 2W/K (1%) change at 100W solar level)	-2.0	£2.42	-£4.84
Solar Gains Correction Technique (from chamber data - 2% change)	+3.5	£2.42	£8.47

In terms of evaluation of the environmental conditions present during a coheating test, the data demonstrates that external temperatures and levels of solar radiation could potentially have a significant upon the resulting measured HLC. This then translates into either an underestimation or overestimation of the whole house heat losses associated with the dwelling under consideration. A cost of £2.42 has been applied for each 1 W/K change, derived from the mean value of all fabric-related data obtained during the sensitivity analysis.

If the observed change in HLC value apparent when a significant or consistent high or low ΔT is present is considered to be of relevance, it would amount to an unexpected increase in space heating fuel supply of up to £30/year. Should the impact of high solar radiation levels not be addressed in the analysis of the data, this may amount to additional expenses of up to £40/year.

It is therefore critical to ensure that such factors are considered carefully when calculating the W/K heat losses using the coheating test methodology. Whilst the physical weather present at the time of an experiment cannot be controlled, the data at least provides an indication of the magnitude of influence that temperature and solar radiation levels might have on the resultant measured HLC value.

It is interesting to note that an underperformance of fabric material u-values has quite a pronounced effect on the household energy cost when the measured coheating test data is considered, amounting to £37.75/year when an average value of 30% underperformance is assumed (as per evidence from existing research). Thermal bridging is also highly sensitive to changes in performance levels. This demonstrates the need to ensure that care is taken during the construction of a building to ensure that it is completed to a high level of precision, and that any substituted materials meet the same specification as those prescribed by the design team.

The cost to the householder above the expected level could be significant if the physical building fails to meet design stage fabric performance levels. This extends to the design, installation and commissioning of MVHR systems, where low efficiencies and imbalances in flow rates can compromise the effectiveness of the ventilation strategy and lead to increased costs for the end-user.

7.3 Impact Quantification Matrix

It has been demonstrated that both the design-stage modelling and post-construction testing techniques are sensitive to a number of factors that may influence the final calculated and measured data. In terms of actual importance and significance of the various elements, the analysis of their impact should comprise of a two-fold process. Not only should the magnitude of their impact be considered, but this should be further assessed within the context of the likelihood or probability that an isolated parameter could lead to a change in HLC value, carbon emissions, space heating fuel supply requirements and cost to the householder.

The findings from the assessment of the contributing sources to divergence in predicted and measured HLC values have been used to develop a methodology to determine the risk associated each factor. Firstly, risk ranking levels for several parameters were defined, including:

- Likelihood – the percentage chance that an error or inaccuracy may arise in relation to each factor

- Impact on SAP HLC – the percentage change in a parameter required to effect a 1W/K shift in HLC value, derived from the SAP sensitivity analysis undertaken in Section 7.1

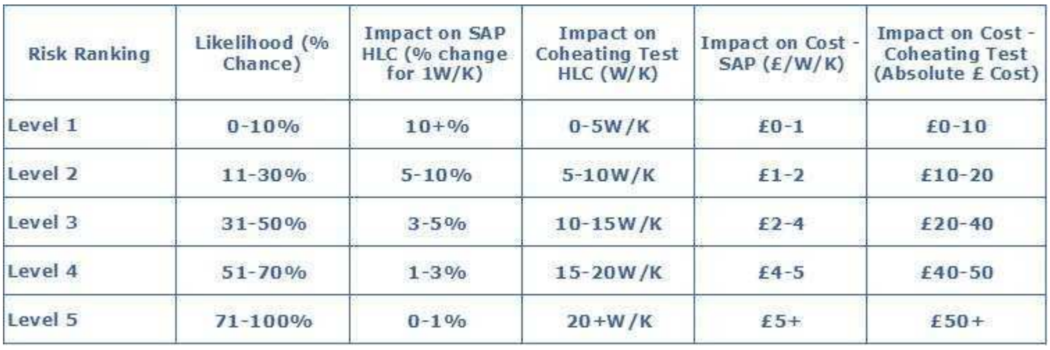
- Impact on Coheating Test HLC – the measured divergence in HLC, given in W/K, observed due to different factors during practical investigative work

- Impact on Cost – SAP (£/ W/K) – the theoretical cost per 1 W/K HLC change derived from the SAP 2009 model as a result of the sensitivity analysis

- Impact on Cost – Coheating Test (£) – the application of the theoretical cost per 1 W/K HLC change obtained during the SAP sensitivity exercise to the measured data resulting from the E.On House, Tarmac House and thermal chamber experimental work. It is an absolute cost of the increase or decrease in supplied fuel cost to a household.

The respective risk ranking ranges are defined in Table 7-15.

Table 7-15 - Risk Ranking - Definition of Ranges



Risk Ranking	Likelihood (% Chance)	Impact on SAP HLC (% change for 1W/K)	Impact on Coheating Test HLC (W/K)	Impact on Cost - SAP (£/W/K)	Impact on Cost - Coheating Test (Absolute £ Cost)
Level 1	0-10%	10+%	0-5W/K	£0-1	£0-10
Level 2	11-30%	5-10%	5-10W/K	£1-2	£10-20
Level 3	31-50%	3-5%	10-15W/K	£2-4	£20-40
Level 4	51-70%	1-3%	15-20W/K	£4-5	£40-50
Level 5	71-100%	0-1%	20+W/K	£5+	£50+

Each of the individual aspects of sensitivity identified in the literature review, desk-based SAP methodology analysis, assessment of the retrofit and new-build dwellings, and experimental thermal chamber work was evaluated using the risk ranking indicators. This enabled the production of a normalised index of significance of the effect of each factor, expressed by way of likelihood of occurrence and magnitude of the influence on HLC and cost factors. This work is detailed in Table 7-16.

Within the context of the SAP methodology, changes in fabric u-values and to the /20 rule of thumb have a low impact on cost to the householder, although the HLC is quite sensitive to changes in party wall and glazing element u-values. A medium risk is assigned to fabric underperformance in the context of the coheating test. The level of airtightness applied to the SAP model is also likely to have a medium effect on both HLC values and fuel costs.

Assumptions and default calculations used within the SAP methodology may also impact upon the predicted HLC for a given property. The standard division factor of 20 as applied to q50 data in order to gain an approximation of ambient air change rate has a medium risk in causing variation within the HLC value, although the manifestation of this in cost to the householder is low. It is the most sensitive parameter in terms of the amount of change required to the division factor in order to cause a change in HLC of 1 W/K. The effects of errors in the calculation and assumed level of 0.5 ACH in the calculation of an effective air change rate are low in terms of impact on the HLC but medium when potential costs are considered.

Table 7-16 - HLC Risk Assessment Quantification Matrix

Risk ID No	Potential Cost Impact	Description	Likelihood (1-5)	Impact on HLC (1-5)	Potential Cost Impact (1-5)	Impact on HLC	Potential Cost Impact
	Risk Ranking					Risk Ranking	Risk Ranking
1.0	SAP Methodology						
1.10	General errors made in SAP model data inputs	Research shows up to 25% of performance gap error could be attributable to this factor	4	2	3	Medium	Medium
1.20	Wall U Value	5.49% parameter change required for 1 W/K HLC Change - cost £2.42 per W/K	2	2	3	Low	Medium
1.30	Floor U Value	11.36% parameter change required for 1 W/K HLC Change - cost £2.42 per W/K	2	1	3	Low	Medium
1.40	Roof U Value	8.62% parameter change required for 1 W/K HLC Change - cost £2.42 per W/K	2	2	3	Low	Medium
1.50	Party Wall U Value	3.10% parameter change required for 1 W/K HLC Change - cost £2.42 per W/K	2	3	3	Medium	Medium
1.60	Glazing U Value	2.15% parameter change required for 1 W/K HLC Change - cost £2.42 per W/K	2	4	3	Medium	Medium
1.70	Thermal Bridging	2.94% parameter change required for 1 W/K HLC Change - cost £2.43 per W/K	4	4	3	High	Medium
1.80	Air Tightness	mean 6.7% parameter change required for 1 W/K HLC Change - cost £2.61 per W/K	3	2	3	Medium	Medium
1.90	Rule of Thumb (/20)	mean 0.135% parameter change required for 1 W/K HLC Change - cost £1.53 per W/K	1	5	2	Medium	Low
1.91	Effective Air Change Rate (0.5 ACH)	mean 6.17% parameter change required for 1 W/K HLC Change - cost £3.87 per W/K	4	2	3	Medium	Medium
1.91	MVHR Efficiency (90%)	2.70% parameter change required for 1 W/K HLC Change - cost £2.13 per W/K	4	4	3	High	Medium
1.92	Wind Speed (use of site-based rather than embedded data)	Up to 15% variance compared to SAP default	4	4	4	High	High

Risk ID No	Factor	Description	Likelihood (1-5)	Impact on HLC (1-5)	Potential Cost Impact (1-5)	Impact on HLC	Potential Cost Impact
						Risk Ranking	Risk Ranking
2.00	Coheating Test Methodology						
2.10	Underperformance of in-situ fabric performance (u-values)	mean 30% underperformance equates to 15.6 W/K increase - cost of £37.75	2	4	3	Medium	Medium
2.20	Underperformance of in-situ fabric performance (thermal bridging)	mean 50% variance equates to 22 W/K increase - cost of £53.46	4	5	5	High	High
2.30	Underperformance of MVHR system (efficiency)	9% reduced efficiency equates to 11.5 W/K increase - cost of £24.50	4	3	3	Medium	Medium
2.40	Underperformance of MVHR system (air throughput rates)	0.11 ACH over supply equates to 10W/K increase - cost of £26.40	4	3	3	Medium	Medium
2.50	High Solar Gains	10% change at 350W solar intensity equates to 17 W/K decrease - saving of £41.14	1	4	4	Low	Low
2.60	Medium Solar Gains	5% change at 200W solar intensity equates to 9 W/K decrease - saving of £21.78	3	2	3	Medium	Medium
2.70	Low Solar Gains	1% change at 100W solar intensity equates to 2 W/K decrease - saving of £4.84	4	1	1	Low	Low
2.80	Solar Gains Correction Technique	2% difference in HLC value equates to 3.5 W/K increase - cost of £8.47	4	1	1	Low	Low
2.90	Thermal Lag	Long standing impact due to heat gains in construction structural materials	5	4	3	High	High
2.91	Wind Speed	Reduced effective infiltration rate and HLC values at higher wind speeds	3	4	4	Medium	Medium
3.00	Other Parameters						
3.10	Lack of SAP model updates to account for changes in specifications during construction process	Research shows up to 65% discrepancy and errors present in up to two thirds of assessments	4	5	5	High	High

The use of generic wind speed within the SAP 2009 model presents a high risk item, as the local conditions relevant to the time of a coheating test generally lead to over-estimation of wind speeds when applied to the University Park CEH site in Nottingham. This can be partially overcome through replacing the default wind speed data in the SAP calculations with data obtained that it is relevant for the timeframe of each experiment. However, this is time-consuming, particularly when undertaking analysis in multiple locations.

Thermal lag is a greater cause for concern as in some constructions it can take a significant period of time for the heat stored in the building fabric to dissipate. As such, the use of night-time only data analysis may not be appropriate as, when thermal lag is considered, the time period of data that can be used to calculate a post-construction HLC may be too restricted to obtain a realistic indication of performance.

More generic matters such as lack of updating of SAP models to reflect the materials actually used on site and general data input errors may present a medium to high level of risk to the accuracy of the HLC value and cost to the householder. This is not surprising, as evidence suggests that the likelihood of these situations occurring is high, and an inaccurate model would generally result in a performance gap being apparent between calculated and measured data if the theoretical information is not updated to reflect the true as-built dwelling.

Thermal bridging presents the highest level of risk consistently in both the SAP 2009 and coheating test risk analyses. It appears that it is critically important to design a dwelling in a simple form that avoids complex junctions, and equally essential for the construction team to pay care and attention during the building process. MVHR efficiency is another high ranking risk item, particularly in terms of cost to the end user. Correct design, installation and commissioning is necessary in order to ensure that optimum efficiency levels are achieved, as it is only at high performance levels that any cost savings will be realised.

7.4 Conclusions

It can be seen that there are many factors that can impact upon the ability of both design-stage and post construction tests to produce a true indication of the fabric performance of a dwelling. The risk level associated with the different contributors varies depending on the likelihood and magnitude of the effect of each area of concern.

In the case of temperature and wind effects, the impact of environmental conditions can be smoothed if the test is carried out over several days. It only becomes truly problematic if extremes of weather are present for significant proportions of the testing timeframe. In this case, some normalisation may be required to account for the effects wind speed. Use of local wind speed and temperature data within the SAP 2009 model could potentially reduce the magnitude of the observed gap between design-stage and as-built performance.

The solar levels experienced during a coheating test are largely accounted for through use of multiple regression or Siviour analysis to adjust the data in order to compensate for the decreased raw power input recorded due to increased heat gains. It would be expected that at least a low level of solar gains would be encountered during the experimental period, but the actual effect on HLC is quite minor. Higher levels of solar radiation do have a pronounced impact on the HLC, but can be compensated for through calculation techniques. However, should a coheating test be undertaken in conditions with consistently medium or high levels of solar intensity, the coheating test HLC data could provide an erroneously low HLC result.

In order to account for discrepancies between design-stage details relating to construction, and those present in the as-built dwelling, it would appear to be beneficial to ensure that the SAP model used to evaluate the property is updated with the correct data. A proportion of the divergence between measured and predicted HLC values can be attributed to the two assessments being based on disparate baseline information (i.e. the details included in the SAP model do not concur with those physically existing on site).

From the analysis undertaken here, it would appear, however, that issues surrounding the calculation and construction of thermal bridges in building structures, along with the failure to achieve optimum MVHR efficiency levels, present the greatest opportunity for improvement of alignment between theoretical and in-situ HLC calculations.

8 CONCLUSIONS AND FURTHER WORK

The need to reduce energy demands and carbon emissions of buildings is becoming increasingly important. Time is progressing towards the 2020 deadline set to achieve the EU targets of 20% reductions in greenhouse gas efficiency and energy consumption, alongside a 20% improvement in energy efficiency, across all EU Member States. The urgency is further compounded by the ambition of the UK Government to achieve 80% reductions in carbon emissions by 2050, and zero carbon new-build homes by 2016. It can therefore be seen that the amount of time available to achieve these aspirations is limited, and whilst progress is being made it may not necessarily be fast enough to meet the final goals within the timeframe provided.

The area of building energy performance is complex, with a number of interrelating factors affecting the overall energy demand of a dwelling. Inevitably, the materials and systems incorporated into a design will have a significant impact upon energy consumption and carbon emissions. Whilst there is an increasing amount of evidence to support the existence of a gap between the predicted and actual performance of UK housing, it is still an area where more work is required to fully understand the causal links between the design and construction processes and the final physical performance of buildings.

Therefore, an overarching aim for this research has been to investigate the potential reasons why a significant difference exists between the designed and actual performance of the UK housing stock, in order to inform industry of the consequences of inaccurate design stage assessments and the underperformance of key construction and systems elements.

Detailed analysis of the SAP 2009 UK Government endorsed design-stage energy assessment model was used to evaluate assumptions and calculations embedded within the methodology, with additional consideration given to the effect of inaccurate or incorrect data on the final data outputs. The investigation of post-construction factors was facilitated through the use of in-situ practical tests, such as air pressure testing, coheating tests, heat flux monitoring and thermal imaging.

There is little evidence of this type of work in published literature, in terms of analysis that considers original SAP datasheets and interrogates the data inputs through replacement with measured data. Through undertaking this process it was possible, in some cases, to largely resolve the discrepancy observed in the SAP and coheating test HLC value. This demonstrates the importance that should be placed on updating theoretical models to reflect the properties of materials and characteristics such as air tightness and thermal bridging that are relevant to the final constructed dwelling.

During the course of the research project, the coheating test was applied to two dwellings with an MVHR system in operation. This work is innovative, and has shown that the assumptions made in the SAP model for the uplift of mechanical ventilation against passive ventilation are relatively sound. The study extended to the in-situ assessment of MVHR efficiency, which highlighted that the system installed in the E.On House was underperforming as compared to manufacturer data. This created a unique opportunity to work with the manufacturer to improve the system, and resulted in changes to the design of the MVHR system configuration that were then applied in the mainstream production of MVHR units.

Through analysis of the data obtained from the coheating tests undertaken in the two test dwellings, it became evident that environmental factors could be affecting the resultant HLC values. Further analysis showed that wind may affect the predicted data considerably, with an 8-30 W/K day to day reduction noted when the generic SAP wind speeds were replaced with site-based data. In some cases, this caused a reduction in HLC that was in the region of 15% of the initial SAP data. This has therefore been shown to be a key parameter to consider when attempting to reconcile design stage and post construction data.

With regard to solar gains, a 25% reduction in HLC was observed on days when high solar gains were recorded within the E.On House data. The results from the thermal chamber showed that high levels of solar radiation caused a 10%– 26% reduction in raw HLC values, depending on building construction type and insulation levels. In all cases, the use of multiple regression and Siviour analysis to correct for solar gains was found to be reliable and repeatable in terms of normalisation of raw power data.

However, of potentially greater concern, is the effect that heat gains from solar radiation can have on the HLC in terms of changing the physical properties of building elements. Work undertaken in the thermal chamber showed that thermal lag and the delayed dissipation of heat stored in brickwork and other materials could impact upon the HLC recorded. In some constructions, a period of up to 17 hours could be required for a structure to regulate to the levels of temperature and heat flow present prior to the impact of solar gains.

This demonstrates that care needs to be taken when assessing in-situ HLC values, as raw power inputs into a property could be reduced for a long period of time in high solar conditions, resulting in artificially low calculated energy demands. It also brings into question the robustness of the argument that the use of night-time only data may be a simpler way to compensate for solar gains, as such an approach could result in evaluation of a very constricted dataset when high levels of solar radiation are present.

The generation of a risk quantification matrix demonstrated that thermal bridging, both during design stage calculations and post-construction, can have a significant effect on the predicted and measured HLC and eventual energy costs to the householder. This is a key finding, as at the present time there is no mechanism within the Building Regulations to assess this aspect of a dwelling once constructed, and it is an area where errors can easily be made within the SAP methodology. In addition, MVHR efficiency was found to be a key influencing factor, largely due to the complexities of installing this type of technology in such a way that it achieves the optimum performance levels specified by the manufacturer and included in the SAP methodology.

There are a number of recommendations for further work, in order to expand on the research presented and to resolve the limitations of this study. These include:

- Evaluation of the reliability and robustness of the coheating test methodology and assessment of improvements that could be made to the procedures and analysis associated with the current technique in order to resolve limitations.
- Extension of the investigative approach utilised within this work to consider a wider dataset, in order to understand the sensitivities of the various parameters for different housing types. The evidence presented here is based on two dwellings which may not be truly representative of the UK housing stock.

- Undertaking further coheating tests on the Tarmac House property, as at present the post construction HLC data relating to this property has been generated from a single experiment;

- Undertaking long term coheating tests within a single dwelling to allow data to be gathered for the same property in a wide range of weather scenarios, and assessment of the effect on raw power inputs and calculated HLC. A significant limitation regarding the post-construction testing data relates to the short timeframes involved in several of the experiments. Equipment failure and timescales imposed by the E.On House retrofit project upgrade programme meant that, in some cases, the testing period was a brief as 3 days. This could impact upon the reliability of the data, particularly when the sensitivity of the test to weather effects is considered;

- Applying the use of in-situ u-value measurements and localised air leakage measurements to gain a deeper understanding of the impact that variance from the design-stage stated values could have on the performance gap;

- Extending the scope of the work to consider space and water heating systems and other integrated technology types such as photovoltaic arrays. It would be valuable to assess the assumptions and embedded default data integrated within the SAP methodology that are associated with these aspects of the model, and compare them with the actual function (energy input and outputs) of systems and the optimum levels of performance specified by a manufacturer;

- Consideration of occupancy influence on the HLC would possibly enhance the understanding of the impact that residents can have on dwelling performance. It was not possible to evaluate this area within this study, due to the E.On House being unoccupied for the duration of the experimental period, and limited monitored data being available for the Tarmac House. Even simply comparing the true energy usage with predicted energy usage, though comparison of energy bills, recorded data and SAP calculated values, could be a useful exercise in assessing the overall performance of a dwelling,

- Utilisation of the thermal chamber to test a wider range of construction types, such as internal insulation, cavity wall insulation and modern methods of construction (lightweight structures), in order to assess the way in which the building fabric is influenced by changes in the external environment. A range of ΔT and solar intensities could be applied, as could different levels of wind speed, moisture/rainfall and humidity;

- Analysis of the financial investment level and length of the return/payback period of the work associated with retro-fit housing improvements could be of benefit to the construction industry and general public, as could further investigation into the implications of contributors the performance gap on carbon emissions.

In conclusion, in order to meet the increasingly stringent design-stage energy demand and carbon emissions levels associated with housing, it is essential that the methodologies used to determine theoretical and measured performance are robust and reliable. De Wita (2002) asserts that it is essential to be aware of uncertainty in building performance at all stages of the process. It is also important to routinely update building models with amended construction and specification details, so that the predicted and actual HLC values can be compared on an equal basis. Without a mandatory regulative requirement to undertake such reviews, it is likely that the apparent performance gap between designed and actual dwellings will persist as any comparison will continue to be based on disparate terms.

REFERENCES

AIMC4 Partners in Innovation. (2013). Pioneering the Volume Production of Homes to Code for Sustainable Homes Level 4. Retrieved 1st September 2013, from http://www.aimc4.com/index.jsp

Ajzen I. (1985). From Intentions to Actions: A Theory of Planned Behaviour, in J. Kuhl and J. Beckman (eds): Action Control: From Cognition to Behaviour, Springer, Berlin, pp. 11–39.

Anderson B. (2006). Conventions for U-Value Calculations - 2006 Edition. BRE. Watford.

Annaratone D. (2010). Engineering Heat Transfer. Springer. Berlin.

ARUP. (2003). Airtightness Case Study – Beddington Zero (Fossil) Energy Development Retrieved 14th August 2013, from http://airtightness.energyprojects.net/links/case_studies/BedZed.pdf

ARUP. (2010). Legislation in the UK Energy Industry: A Guide to Legislation, Policy, Directives and Plans Directly Affecting the UK Energy Industry. London.

Association for Environmentally Conscious Building (AECB). (2008). Projecting Energy Use and CO2 Emissions From Low Energy Buildings: A Comparison Of The Passivhaus Planning Package (PHPP) And SAP, AECB Carbonlite, UK.

Association for Environmentally Conscious Building (AECB). (2009). Comparing Energy Use and CO_2 Emissions from Natural Ventilation and MVHR in a Passivhaus House. AECB Carbonlite. UK.

ATTMA. (2010). Technical Standard 1: Measuring Air Permeability of Building Envelopes (Dwellings). In ATTMA (Ed.). Northampton.
Baehr H., & Stephan, K. (2011). Heat and Mass Transfer - Third Edition. Springer. Berlin.

Baker P. (2011). U-Values and Traditional Buildings - In Situ Measurements and their Comparison to Calculated Values. Technical Paper 10. Historic Scotland Conservation Group. Edinburgh.

Balaras C., & Argiriou, A. (2002). Infrared Thermography for Building Diagnostics. *Energy and Buildings, 34*(2), 171-183.

Balcombe P., Rigby, D., & Azapagic, A. (2013). Motivations and Barriers Associated with Adopting Microgeneration Energy Technologies in the UK. *Renewable and Sustainable Energy Reviews, 22*(0), 655-666.

Banfill P., Simpson, S., Gillott, M., & White, J. (2011a, 8 -11th May 2011). *Mechanical Ventilation and Heat Recovery for Low Carbon Retrofitting in Dwellings.* Paper presented at the Proceedings of the World Renewable Energy Congress 8th -11th May 2011, Linkoping, Sweden.

Banfill P., Simpson, S., Gillott, M., & White, J. (2011b). *The Potential for Energy Saving in Existing Solid Wall Dwellings Through Mechanical Ventilation and Heat Recovery*. Paper presented at the ECEEE 6 -11th June 2011,, Belambra Presqu'ile de Giens, France.

Banfill P., Simpson, S., Haines, V., & Mallaband, B. (2012). Energy-Led Retrofitting of Solid Wall Dwellings: Technical and User Perspectives on Airtightness. *Structural Survey, 30*(3), 267-279.

Bauwens G., Standaert, P., Delcuve, F., & Roels, S. (2012). *Reliability of Coheating Test Measurements*. Paper presented at the First Building Simulation and Optimization Conference, Loughborough, UK, 10-11 September 2012.

Bell M. (2013). Achieving Near Zero Carbon Housing: The Role of Performance Measurement in Production Processes. Workshop on High Performance Buildings; Design and Evaluation Methodologies. 24 – 26 June 2013. Belgium Building Research Institute. Brussels.

Bell M., & Lowe, R. (1998). York Energy Demonstration Project: Final Report. In C. f. t. B. Environment (Ed.), *Leeds Metropolitan University*. Leeds.

Bell M., Wingfield, J., Miles-Shenton, D., & Seavers, J. (2010a). Low Carbon Housing: Lessons From Elm Tree Mews. In Joseph Rowntree Foundation (Ed.). York.

Bell M., Wingfield, J., Miles-Shenton, D., & Seavers, J. (2010b). Summary - Low Carbon Housing: Lessons From Elm Tree Mews. In J. R. Foundation (Ed.). York.

Berge A. (2011). Analysis of Methods to Calculate Air Infiltration for Use in Energy Calculations. MSc Thesis. University of Chalmers. Sweden.

Bergin R. (2011). SAP 2012 - Green Deal, Newbuild and the East Midlands. Retrieved 13th August 2013, from http://rorybergin.wordpress.com/2011/10/19/sap-2012-green-deal-newbuild-and-the-east-pennines/

Bertoldi P., Hirl, B., & Labanca, N. (2012). JRC Report: Energy Efficiency Status Report 2012 - Electricity Consumption and Efficiency Trends in the EU-27. Publications Office of the European Union. Luxembourg.
Blueprint. (2013). Green Street In The Meadows. Retrieved 1st September 2013, from http://www.ourgreenstreet.co.uk/homes/

Boardman B., Darby, S., Kilip, G., Hinnells, M., Jardine, C., Palmer, J., & Sinden, G. (2005). 40% House, ECI, Oxford.

Böhringer C. (1998). The Synthesis of Bottom-Up and Top-Down in Energy Policy Modelling. *Energy Economics, 20*(3), 233-248.

Booth A., Choudhary, R., & Spiegelhalter, D. (2012). Handling Uncertainty in Housing Stock Models. *Building and Environment, 48*(0), 35-47.

Bordass B., Cohen, R., & Field, J. (2004). *Energy Performance Of Non-Domestic Buildings – Closing The Credibility Gap*. Paper presented at the International Conference On Improving Energy Efficiency In Commercial Buildings, Frankfurt, Germany.

Bordass B., Cohen, R., Standeven, M., & Leaman, A. (2001). Assessing Building Performance In Use 3: Energy Performance Of Probe Buildings. *Building Research and Information, 29*(2), 114-128.

Brechling V., & Smith, S. (1992). The Pattern of Energy Efficient Measures Amongst Domestic Households in the UK. The Institute of Fiscal Studies. London.

British Standards Institution. (1999). Thermal Performance of Buildings - Qualitative Detection of Thermal Irregularities in Building Envelopes: Infrared Method ISO 6781:1983 London: BSI.

British Standards Institution (BSI). (1987). BS 874: Part 3: Section 3.1:1987: Determining Thermal Insulating Properties, Part 3: Tests for Thermal Transmittance and Conductance, Section 3.1 Guarded Hot Box Method, London, British Standards Institution.

British Standards Institution (BSI). (1996). BS EN ISO 8990:1996: Determination of Steady State Thermal Transmission Properties - Calibrated and Guarded Hot Box, London, British Standards Institution.

British Standards Institution (BSI). (1999). BS 874-3.2:1990: Determining Thermal Insulating Properties, Part 3: Tests for Thermal Transmittance and Conductance, Section 3.2 Calibrated Hot Box Method, London, British Standards Institution.

Brown P., Burke, M. E., Morris, G., & Webster, P. J. (2011). The SALFORD Low Energy House: Learning from Our Past. Salford: University of Salford.

Building Research Establishment (BRE). (2005). Energy Use in Homes. A Series of Reports on Domestic Energy Use in England - Space and Water Heating. BRE. Watford.

Building Research Establishment (BRE). (2008). Energy Analysis Focus Report. A Study of Hard to Treat Homes Using the English House Condition Survey - Part 1: Dwelling and Household Characteristics of Hard to Treat Homes. DEFRA. London.

Building Research Establishment (BRE). (2013). BREDEM 2012 - A Technical Description of the BRE Domestic Energy Model Version 1.0. BRE. Watford.

Building Standards Institute (BSI). (2003). BS EN ISO 12831:2003 Heating Systems in Buildings. Method for Calculation of the Design Heat Load. BSI. London. In B. E. 12831:2003 & d (Eds.).

Building Standards Institute (BSI). (2008a). BS EN ISO 6946:2007 Building Components and Building Elements. Thermal Resistance and Thermal Transmittance. Calculation Method. BSI.London.

Building Standards Institute (BSI). (2008b). BS EN ISO 13790:2008 Energy Performance of Buildings. Calculation of Energy Use for Space Heating and Cooling. BSI.London.

Bull R., Chang, N., & Fleming, P. (2012). The Use of Building Energy Certificates to Reduce Energy Consumption in European Public Buildings. *Energy and Buildings, 50*(0), 103-110.

Burch J. D. K., Subbarao, C. E., Hancock, C. E., & Balcomb, J. D. (1989). Repeatability and Predictive accuracy of the PSTAR Short-Term Building Monitoring Method', Report SERI/TR-3606,. In Solar Energy Research Institution (Ed.). Colorado.

Carbon Trust. (2012). Closing the Gap: Lessons Learned on Realising the Potential of Low Carbon Building Design. Carbon Trust. London.

Carrillo A., Dominguez, F., & Cejudo, J. (2009). *Calibration of an ENERGYPLUS Simulation Model by the STEM P-STAR Method, Eleventh International IBPSA Conference Glasgow, Scotland, July 27-30 2009*.

Chartered Institution of Building Services Engineers (CIBSE). (2006). Guide A: Environmental Design. CIBSE. London.

Chia-Yu S. (1981). [A Correlation Between Air Infiltration and Air Tightness for Houses in a Developed Residential Area. ASHRAE Transactions. Vol. 87. Pt. 2. 1981. p. 333 - 341.].

Chun W. G., Jeon, M. S., Yoon, H. K., Jeon, H. S., & Auh, P. C. (1997). APPLICATION OF THE PSTAR METHOD TO A MASSIVE TEST CELL FOR THERMAL PERFORMANCE EVALUATION. *International Journal of Energy Research, 21*(2), 129-138. doi: 10.1002/(sici)1099-114x(199702)21:2<129::aid-er220>3.0.co;2-m

Claesson J., & Hagentoft, C. (1991). Heat Loss to the Ground from a Building - 1. General Theory. *Building and Environment, 26*(2), 195-208.

Colmer M. (2013). Early Findings from the Building Performance Evaluation Programme. 20th September 2013, from http://www.goodhomes.org.uk/downloads/events/Mat%20Colmer.pdf

Crilly M., Lemon, M., Wright, A., Cook, M., & Shaw, D. (2012). Retrofitting Homes for Energy Efficiency: An Integrated Approach to Innovation in the Low Carbon Overhaul of UK Social Housing. *Energy & Environment, 23*(6-7), 1027-1056.

d'Ambrosio Alfano F., Dell'Isola, M., Ficco, G., & Tassini, F. (2012). Experimental Analysis of Air Tightness in Mediterranean Buildings Using the Fan Pressurization Method. *Building and Environment, 53*(0), 16-25. doi:

Datataker Inc. (2010). DT500 and DT 600 Range Specifications. Retrieved 22nd July 2013, from http://www.dataloggerinc.com/datasheets/datataker-dt500_dt600.pdf

De Meulenaer V., Van Der Veken, J., Verbreek, G., & Hens, H. (2005). *Comparison of Measurements and Simulations of a Passive House.* Paper presented at the Ninth International IBPSA Conference, , Montréal. Canada. 15th-18th August 2005.

de Wita S., & Augenbroec, G. (2002). Analysis of Uncertainty in Building Design Evaluations and its Implications. *Energy and Buildings, 34*, 951-958.

Demanuele C., Tweddell, T., & Davies, M. (2010). *Bridging The Gap Between Predicted And Actual Energy Performance In Schools*. Paper presented at the World Renewable Energy Congress XI, Abu Dhabi, UAE.

Dengel A., & Swainson, M. (2013). Assessment of MVHR Systems and Air Quality in Zero Carbon Homes. NHBC/BRE Press. Milton Keynes.

Department for Communities and Local Government (DCLG). (2006a). *Approved Document Part L1A – Conservation of Fuel and Power in New Dwellings* London.

Department for Communities and Local Government (DCLG). (2006b). Code for Sustainable Homes: A Step Change in Sustainable Business Practise. DCLG. London.

Department for Communities and Local Government (DCLG). (2007). Building a Greener Future: Policy Statement. DCLG. London.

Department for Communities and Local Government (DCLG). (2008). Code for Sustainable Homes: Setting the Standard in Sustainability for New Homes. DCLG. London.

Department for Communities and Local Government (DCLG). (2010a). *Approved Document Part F – Ventilation*. London.

Department for Communities and Local Government (DCLG). (2010b). *Approved Document Part L1A – Conservation of Fuel and Power in New Dwellings* London.

Department for Communities and Local Government (DCLG). (2010c). *Approved Document Part L1B – Conservation of Fuel and Power in Existing Dwellings* London.

Department for Communities and Local Government (DCLG). (2010d). Code for Sustainable Homes: Technical Guide. DCLG. London.

Department for Communities and Local Government (DCLG). (2011a). Comparing Primary and Secondary Terms Analysis And Re-Normalisation (PStar) Test and Co-Heating Test Results. In DCLG (Ed.). London.

Department for Communities and Local Government (DCLG). (2011b). Domestic Building Services Compliance Guide. DCLG. London.

Department for Communities and Local Government (DCLG). (2011c). Domestic Ventilation Compliance Guide. DCLG. London.

Department for Communities and Local Government (DCLG). (2011d). Zero Carbon Non-Domestic Buildings - Phase 3 Final Report. DCLG. London.

Department for Communities and Local Government (DCLG). (2012a). *2012 Consultation on Changes to the Building Regulations in England Section Two – Part L (Conservation of Fuel and Power) - Proposed Changes to Technical Guidance. DCLG. London*.

Department for Communities and Local Government (DCLG). (2012b). *2012 Consultation on Changes to the Building Regulations in England: Summary of Responses. DCLG. London*.

Department for Communities and Local Government (DCLG). (2013a). DCLG Live Tables on Dwelling Stock (Including Vacants). Retrieved 1st September 2013, from https://www.gov.uk/government/statistical-data-sets/live-tables-on-dwelling-stock-including-vacants

Department for Communities and Local Government (DCLG). (2013b). English Housing Survey Headline Report 2011-2012. DCLG. London.

Department for Environment Food and Rural Affairs (DEFRA). (2001). Limiting Thermal Bridging and Air Leakage: Robust Construction Details for Dwellings and Similar Buildings. TSO. London

Department for Environment Transport & the Regions (DETR). (2005). Energy Efficient Ventilation in Housing: A Guide for Specifiers on the Requirements and Options for Ventilation. Good Practice Guide 268. DETR. London.

Department of Energy & Climate Change (DECC). (2011). The Government's Standard Assessment Procedure for Energy Rating of Dwellings 2009 Edition. BRE. Watford.

Department of Energy & Climate Change (DECC). (2013). UK Renewable Energy Roadmap Update 2013. DECC. London.

Department of Energy and Climate Change (DECC). (2005). Guide to the Government's Standard Assessment Procedure for Energy Rating of Dwellings (SAP). BRE. Watford.
The Climate Change Act 2008, HMSO, London (2008).

Department of Energy and Climate Change (DECC). (2009). *The UK Low Carbon Transition Plan: National Strategy for Climate and Energy, HMSO, London*.

Department of Energy and Climate Change (DECC). (2010a). The Green Deal – A Summary of the Government’s Proposals, HMSO, London.

Department of Energy and Climate Change (DECC). (2010b). UK Greenhouse Gas Emissions - Final Figure Statistical Release. Retrieved 10th April 2013, from http://www.decc.gov.uk/en/content/cms/statistics/climate_stats/gg_emissions/uk_emissions/uk_emissions.

Department of Energy and Climate Change (DECC). (2011a). *The Energy Act 2011, HMSO, London*.

Department of Energy and Climate Change (DECC). (2011b). *Extra Help Where It Is Needed: A New Energy Company Obligation. DECC. London*.

Department of Energy and Climate Change (DECC). (2011c). The Government's Standard Assessment Procedure for Energy Rating of Dwellings 2009 Edition. Building Research Establishment. Watford.

Department of Energy and Climate Change (DECC). (2011d). The Government's Standard Assessment Procedure for Energy Rating of Dwellings Draft 2012 Edition. Building Research Establishment. Watford.

Department Of Energy And Climate Change (DECC). (2011e). Renewable Heat Incentive, DECC, London.

Department of Energy and Climate Change (DECC). (2012a). UK Energy in Brief 2012. DECC. London.

Department of Energy and Climate Change (DECC). (2012b). UK Renewable Energy Roadmap Update 2012. DECC. London.

Department of Energy and Climate Change (DECC). (2013a). Energy Consumption in the UK. Chapter 1: Overall Energy Consumption in the UK Since 1970. DECC. London.

Department of Energy and Climate Change (DECC). (2013b). Energy Consumption in the UK. Chapter 3: Domestic Energy Consumption in the UK Between 1970 and 2012. DECC. London.

Department of Energy and Climate Change (DECC). (2013c). The Standard Assessment Procedure (SAP): Summary of Consultation Responses and Technical Changes -23rd October 2013, DECC, London.

Department of Energy and Climate Change (DECC). (2013d). Statistical Release - 2012 UK Greenhouse Gas Emissions, Provisional Figures and UK 2011 Greenhouse Gas Emissions, Final Figures by Fuel Type and End-Use. DECC. London.

Department of Energy and Climate Change (DECC). (2013e). Statistical Release - Average Annual Domestic Electricity Bills by Home and Non-Home Supplier (QEP 2.2.1). Retrieved 5th January 2014, from https://www.gov.uk/government/statistical-data-sets/annual-domestic-energy-price-statistics

Doran S. (2000). DETR Framework Project Report : Field Investigations of the Thermal Performance of Construction Elements as Built. BRE. Glasgow.

Dorer V., & Breer, D. (1998). Residential mechanical ventilation systems: performance criteria and evaluations. *Energy and Buildings, 27*(3), 247-255.

Dowson M., Poole, A., Harrison, D., & Susman, G. (2012). Domestic UK Retrofit Challenge: Barriers, Incentives and Current Performance Leading into the Green Deal. *Energy Policy, 50*(0), 294-305.

Durbul C. (1988). Inhabitants behaviour with respect to ventilation. Technical note 23. Air Infiltration and Ventilation Centre (AIVC); 1988.

Efficiency Meets Sustainability. (2011). MVHR (Wednesday 26th October 2011). Retrieved 23rd July 2013, from http://efficiencymeetssustainability.blogspot.co.uk/2011_10_01_archive.html

Egan J. (1998). Rethinking Construction: The Report of the Construction Task Force. DETR. London.

Energy & Climate Change Committee. (2011). UK Energy Supply: Security or Independence? HMSO. London.

Energy Saving Experts. (2011). Thermal Bridging Part L1A - A Practical Guide. Retrieved 14th May 2013, from http://www.energy-saving-experts.com/wp-content/uploads/2011/07/Thermal-Bridging-Part-L1A-landscape-version-.pdf

Energy Saving Trust (EST). (2004). The Effect of Building Regulations (Part L1 2002) on Existing Dwellings, EST, London.

Energy Saving Trust (EST). (2005). Post-Construction Testing - A Professional's Guide to Testing Housing for Energy Efficiency. EST. London.

Energy Saving Trust (EST). (2007a). Achieving Airtightness in New Dwellings: Case Studies. In Energy Saving Trust (Ed.). London.

Energy Saving Trust (EST). (2007b). Energy-Efficient Refurbishment of Existing Housing (CE83). In EST (Ed.). London.

Energy Saving Trust (EST). (2008a). Energy Efficiency and the Code for Sustainable Homes - Level 4. EST. London.
Energy Saving Trust (EST). (2008b). Enhanced Construction Details: Introduction and use. 2008 Edition. EST. London.

Energy Saving Trust (EST). (2008c). Monitoring Energy and Carbon Performance in New Homes. EST. London.

Energy Saving Trust (EST). (2010). Report CE320: Fabric First: Focus on Fabric and Services Improvements to Increase Energy Performance in New Homes, EST, London.

Energy Saving Trust (EST). (2013). Green Deal and ECO. Retrieved 16th August 2013, from http://www.energysavingtrust.org.uk/Take-action/Find-a-grant/Green-Deal-and-ECO

Energy Saving Trust (EST). (2014). Our Calculations. Retrieved 21st February 2014, from http://www.energysavingtrust.org.uk/Energy-Saving-Trust/Our-calculations

English Heritage. (2012a). Energy Efficiency and Historic Buildings - Insulating Solid Ground Floors. English Heritage. London.

English Heritage. (2012b). Energy Efficiency and Historic Buildings - Insulation of Suspended Timber Floors. English Heritage. London.

English Housing Survey (EHS). (2012). EHS Bulletin. Issue 7: English Housing Survey Bulletin. Retrieved 17th September 2013, from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/6148/2173722.pdf

EU Observer. (2013). Croatia Becomes 28th EU Member State. Retrieved 15th September 2013, from http://euobserver.com/enlargement/120688

Directive 2009/29/EC of the European Parliament and of the the Council of 23rd April 2009, European Commission, Brussels (2009).

Proposal for a Directive of the European Parliament and of the Council on Energy Efficiency and Repealing Directives 2004/8/EC and 2006/32/EC, European Commission, Brussels (2011).

European Commission. (2012). Commission Staff Working Paper - Analysis of Options Beyond 20% GHG Emission Reductions: Member State Results. Brussels.

European Commission. (2013a). The EU and Climate Change Package. Retrieved 16th October 2013, from http://ec.europa.eu/clima/policies/package/index_en.htm

European Commission. (2013b). EU Energy In Figures: Statistical Pocket Book 2013. European Union. Luxembourg.

European Commission. (2013c). *Green Paper: A 2030 Framework for Climate and Energy Policies*. Brussels.

European Committee for Standardization. (2007a). BS EN ISO 10211 Thermal Bridges in Building Construction – Heat Flows and Surface Temperatures – Detailed Calculations.

European Committee for Standardization. (2007b). EN 13289 Thermal Performance of Buildings – Determination of Air Permeability of Buildings – Fan Pressurization Method. CEN. Brussels.

European Environment Agency. (2012). Final Electrical Consumption by Sector (Ener 018) - Assessment Published April 2012. Retrieved 16th September 2013, from http://www.eea.europa.eu/data-and-maps/indicators/final-electricity-consumption-by-sector/final-electricity-consumption-by-sector-3

European Environment Agency. (2013a). Final Energy Consumption by Sector (CSI 027/ENER 016) - Assessment Published February 2013. Retrieved 16th September 2013, from http://www.eea.europa.eu/data-and-maps/indicators/final-energy-consumption-by-sector-5/assessment

European Environment Agency. (2013b). Greenhouse Gas Emission Trends (CSI 010/CLIM 050) - Assessment Published May 2013. Retrieved 16th September 2013, from:http://www.eea.europa.eu/data-and-maps/indicators/greenhouse-gas-emission-trends/greenhouse-gas-emission-trends-assessment-5

European Union (EU). (2003). *Directive 2002/91/EC Of The European Parliament and of The Council of 16 December 2002 on the Energy Performance of Buildings*. Brussels.

European Union (EU). (2009). *Directive 2009/28/EC of The European Parliament and of The Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC*. Brussels.

European Union (EU). (2010). *Directive 2010/31/EU of The European Parliament and of The Council of 19 May 2010 on the Energy Performance of Buildings (Recast)*. Brussels.

European Union (EU). (2012). *Directive 2012/27/EU of The European Parliament and of The Council of 25 October 2012 on Energy Efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC*. Brussels.

Everett R., Horton, A., & Doggart, J. (1985). Linford Low Energy Houses. In Energy Research Group Open University (Ed.). Milton Keynes.

Expedition Samoyeds. (2012). Hypothermia - General Info and Body Heat Loss. Retrieved 18th August 2013, from http://www.expeditionsamoyeds.org/Hypothermia.html

Feed In Tariffs Ltd. (2013). Feed-In Tariffs. Retrieved 16th August 2013, from http://www.fitariffs.co.uk/

Feist W. (2006). Using Energy Balances to Meet Energy Efficiency. Retrieved 13th June 2013, from http://www.passivhaustagung.de/Passive_House_E/energybalance.html

Feist W., Pfluger, R., Kaufmann, B., Schnieders, J., & Kah, O. (2007). Passive House Planning Package 2007 - Requirements for Quality Approved Passive Houses. The Passivhaus Institut, Darmstadt.

Firth S., Lomas, K., & Wright, A. (2010). Targeting Household Energy-Efficiency Measures Using Sensitivity Analysis. *Building Research & Information, 38*(1), 25-41.

Firth S., Lomas, K., Wright, A., & Wall, R. (2007). Identifying Trends In The Use Of Domestic Appliances From Household Electricity Consumption Measurements. Energy and Buildings 40 (2008) pp 926–936.

FLIR Systems Co. Ltd. (2008). Flir T400 infra-Red Camera Technical Specifications. Retrieved 22nd July 2013, from http://www.flir.com/uploadedFiles/Thermography_APAC/Products/Product_Literture/T400_Datasheet%20APAC(1).pdf

Frei C., Haldi, P., & Sarlos, G. (2003). Dynamic Formulation of a Top-Down and Bottom-Up Merging Energy Policy Model. *Energy Policy, 31*(10), 1017-1031. doi:

Frey C., Mokhtari, A., & Danish, T. (2003). Evaluation of Selected Sensitivity Analysis Methods Based Upon Applications to Two Food Safety Process Risk Models. US Department of Agriculture. Washington DC.

Future Homes Commission. (2012). Building The Homes and Communities Britain Needs. RIBA. London.

George M., Geens, A., & Graham, M. (2006). Stimulating Simulations. Building For A Future Magazine. Spring 2006.

Gillott M., Loveday, D., & Vadodaria, K. (2013a). Airtightness Improvements and Ventilation Systems in Domestic Retrofit - Findings from Project CALEBRE - Briefing Note 1. Project CALEBRE - A Summary of the Project and Its Findings.Loughborough University. Loughborough.

Gillott M., Loveday, D., White, J., Wood, C. J., K., C., & Vadodaria, K. (2013b). Improving the Airtightness in an Existing Dwelling: The Case of the E.ON Retrofit Research House, the Challenges, the Measures and their Effectiveness - PAPER IN REVIEW.

Gillott M., Rodrigues, L., & Spataru, C. (2010). Low-Carbon Housing Design Informed by Research. *Proceedings of the Institution of Civil Engineers – Engineering Sustainability 163*(ES2), 77-87.

Good Homes Alliance (GHA). (2011a). GHA Monitoring Programme 2009-11: Technical Report Results from Phase 1: Post-Construction Testing of a Sample of Highly Sustainable New Homes. In GHA (Ed.). London.

Good Homes Alliance (GHA). (2011b). Ventilation and Good Indoor Air Quality in Low Energy Homes. In GHA (Ed.). London.

Good Homes Alliance (GHA). (2012). Policy. Retrieved 13th July 2013, from http://www.goodhomes.org.uk/what-we-do/policy

Grigg P. (2004). Assessment of Energy Efficiency Impact of Building Regulations Compliance, in: BRE Client Report No. 219683. BRE, Watford.

Grun Eco Design. (2013). How to Avoid Air Leakage and Thermal Bridges. Retrieved 18th August 2013, from http://gruenecodesign.com.au/?p=445

Guerra-Santin O., Tweed, C., Jenkins, H., & Jiang, S. (2013). Monitoring the Performance of Low Energy Dwellings: Two UK Case Studies. *Energy and Buildings, 64*(0), 32-40.

Guerra Santin O., Itard, L., & Visscher, H. (2009). The Effect of Occupancy and Building Characteristics on Energy Use for Space and Water Heating in Dutch Residential Stock. . *Energy and Buildings, 41*(11), 1223-1232.

Haghighat F. (2012). Thermal Comfort in Housing and Thermal Environments in Sustainable Built Environment Vol.1 edited by Haghitat, F. & Kim, J., in Encyclopedia of Life Support Systems (EOLSS), Developed under the Auspices of the UNESCO, EOLSS Publishers, Paris, France.

Harrje D. T., Dutt, G. S., & Gadsby, K. J. (1985). Convective Loop Losses in Buildings in Proceedings of Thermal Performance of the Exterior Envelopes of Buildings III, Clearwater Beach, Florida, 1985, ASHRAE, pp 751-760.

Haynes D. (2013). The Interaction Between Domestic Occupants and Mechanical Ventilation and Heat Recovery System Performance. MSc Thesis. University of East London.

Heffernan E., Pan, W., Liang, X., & De Wilde, P. (2013). *Redefining Zero? A Critical Review of Definitions of Zero Energy Buildings and Zero Carbon Homes. .* Paper presented at the CIBSE Technical Symposium. Liverpool John Moores University, Liverpool, UK. 11-12 April 2013.

Hens H., Janssens, A., Depraetere, W., Carmeliet, J., & Lecompte, J. (2007). Brick Cavity Walls: A Performance Analysis Based on Measurements and Simulations. *Journal of Building Physics, 31*(2), 95-124.

Hillyard R. (2009). Zero Carbon Targets on the Construction Industry. Retrieved 13th September 2013, from https://www.bsria.co.uk/news/article/clean-home/

Holladay M. (2012). Energy Modelling Isn't Very Accurate. Retrieved 10th September 2013, from http://www.greenbuildingadvisor.com/blogs/dept/musings/energy-modeling-isn-t-very-accurate

Homes and Communities Agency (HCA). (2010). Monitoring Guide for Carbon Emissions, Energy and Water Use - The Carbon Challenge: Developing an Environmental Evaluation of Housing Performance in New Communities. HCA. Warrington.

Hughes D. (2009). 10 Ways That SAP 2009 Will Affect You. Retrieved 22nd July 2012, from http://www.building.co.uk/Story.aspx?storyCode=3140858

Hukseflux. (2008). HFP01 & HFP03 Heat Flux Plate/Heat Flux Sensor – User Manual Version 0612. In Hukseflux Thermal Sensors (Ed.). Netherlands.

Ibstock. (2011). Technical Information Sheet - Understanding K Values (Design Thermal Conductivity) and U Values. Retrieved 15th October 2013, from http://www.ibstock.com/pdfs/technical-support/A/Ibstock%20TIS%20A9%20UNDERSTANDING%20THERMAL%20CONDUCTIVITY%20(k)%20VALUES%20.pdf

Ingram V., Banfill, P., & Kennedy, C. (2011, 8 -11th May 2011). *Towards an Objective Assessment of Energy Efficiency in Heritage Buildings.* Paper presented at the Proceedings of the World Renewable Energy Congress 8th - 11th May 2011, Linkoping, Sweden.

International Energy Agency. (2013). Key World Energy Statistics 2013. IEA. Paris.

International Energy Agency (IEA). (1998). Mapping the Energy Future: Energy Modelling and Climate Change Policy. In: Energy and Environment Policy Analysis Series. IEA/Organisation for Economic Co-operation and Development. Paris.

International Organisation for Standardisation. (2006). EN ISO 9972 Thermal Performance of Buildings – Determination of Air Permeability of Buildings – Fan Pressurization Method. ISO. Geneva.

International Organisation for Standardisation. (2007). EN ISO 13370 Thermal Performance of Buildings. Heat Transfer Via the Ground. Calculation Method. ISO. Geneva.

Iorwerth H., Lannon, S., Waldron, D., Bassett, T., & Jones, P. (2013). *A SAP Sensitivity Tool and GIS-Based Urban Scale Domestic Energy-Use Model.* Paper presented at the 13th Conference of International Building Performance Simulation Association, Chambéry, France. August 26-28 2013.

Janda K. (2009). *Buildings Don't Use Energy - People Do.* Paper presented at the PLEA2009 - 26th Conference on Passive and Low Energy Architecture, Quebec City, Canada, 22-24 June 2009.

Jenkins H., & Alexander, D. (2013). Coheating and Other Building Performance Testing. Retrieved 30th September 2013, from http://www.lcri.org.uk/sites/default/files/Co-heating%20and%20other%20building%20performance%20testing%20-%20Huw%20Jenkins_0.pdf

Johnston D. (2013). Bridging the Fabric Performance Gap. Retrieved 13th September 2013, from

http://www.leedsmet.ac.uk/as/cebe/projects/bridging_fabric_performance_gap.pdf

Johnston D., Lowe, R., & Bell, M. (2005). An Exploration of the Technical Feasibility of Achieving CO_2 Emission Reductions in Excess of 60% within the UK Housing Stock by the Year 2050. *Energy Policy, 33*(13), 1643-1659.

Johnston D., Miles-Shenton, D., & Bell, M. (2006). Airtightness of Buildings - Towards Higher Performance. . Retrieved 14th August 2013, from http://www.leedsmet.ac.uk/as/cebe/projects/airtight/airtight9.pdf

Johnston D., Miles-Shenton, D., Farmer, D., & Wingfield, J. (2013). Whole House Heat Loss Test Method (Coheating), Centre for the Built Environment, Leeds Metropolitan University, Leeds.

Johnston D., Miles-Shenton, D., Wingfield, J., & Bell, M. (2004). *Airtightness of UK Dwellings: Some Recent Measurements*. Paper presented at the RICS COBRA Conference Leeds Metropolitan University. 7-8 September 2004.

Jones B., Das, P., Chalabi, Z., Davies, M., Hamilton, I., Lowe, R., . . . Wilkinson, P. (2012). *The Relationship Between Permeability and Infiltration in Conjoined Dwellings*. Paper presented at the 33nd AIVC Conference " Optimising Ventilative Cooling and Airtightness for [Nearly] Zero-Energy Buildings, IAQ and Comfort", Copenhagen. Denmark. 10-11 October 2012.

Judkoff R., Balcomb, J. D., Subbarao, K., Barker, G., & Hancock, E. (2001). *Buildings in a Test Tube: Validation of the Short-Term Energy Monitoring (STEM) Method*. Paper presented at the American Solar Energy Society (ASES) National Solar Conferences Forum 2001, April 21-25 2001, Washington D.C.

Kalousek M., Nemeček, M., & Chuchma, L. (2013). Analysis of the Influence of Geometrical Thermal Bridges and their Elimination by Using a Composite Material Based on Secondary Raw Materials. *Advanced Materials Research, 649*, 45-48.

Kavgic M., Mavrogianni, A., Mumovic, D., Summerfield, A., Stevanovic, Z., & Djurovic-Petrovic, M. (2010). A Review of Bottom-Up Building Stock Models for Energy Consumption in the Residential Sector. *Building and Environment, 45*(7), 1683-1697.

Keeting D. (2012). Member States No Longer on Track for 2020 Targets. Retrieved 3rd April 2013, from http://www.europeanvoice.com/article/imported/member-states-no-longer-on-track-for-2020-targets/75249.aspx

Kelly M. (2010). Energy Efficiency Resilience to Future Climates and Long-Term Sustainability: The Role of the Built Environment. Philosophical Transactions of the Royal Society. 368, 1083–1089.

Kelly S., Crawford-Brown, D., & Pollitt, M. (2012). Building Performance Evaluation and Certification in the UK: Is SAP Fit for Purpose? *Renewable and Sustainable Energy Reviews, 16*(9), 6861-6878.

Kelly S., Pollitt, M., & Crawford-Brown, D. (2011). Building Performance Evaluation and Certification in the UK: A Critical Review of SAP? A Working Paper. University of Cambridge. Cambridge.

Killip G. (2011). *Beyond the Green Deal: Market Transformation for Low-Carbon Housing Refurbishment in the UK.* In Proceedings of Retrofit 2012, 24-26 January, Lowry Theatre, Salford Quays, Salford, Manchester, UK: University of Salford. .

Koopmans C., & te Velde, D. (2001). Bridging the Energy Efficiency Gap: Using Bottom-Up Information in a Top-Down Energy Demand Model. *Energy Economics, 23*(1), 57-75.

LaRusso L. (2013). Winter Warning: Tips for Preventing Frostbite and Hypothermia. Retrieved 16th August 2013, from http://health.cvs.com/GetContent.aspx?token=f75979d3-9c7c-4b16-af56-3e122a3f19e3&chunkiid=13847

Lash D. (2011). Airtightness in Buildings. http://emps.exeter.ac.uk/media/universityofexeter/emps/research/cee/lchsmodule1notes/Air_Leakage_Testing.pdf

Latham M. (1994). Constructing the Team. HMSO. London.

Laustsen J. (2008). Energy Efficiency Requirements in Building Codes, Energy Efficiency Policies for New Building. Organisation for Economic Co-operation and Development/International Energy Agency. Paris.

Leach M., & Deshmukh, S. (2012). Sustainable Energy Law and Policy. In K. Makuch, Pereira, R. (Ed.), *Environmental and Energy Law* (pp. 119-140). Chichester: Wiley-Blackwell.

Leaman A., Stevenson, F., & Bordass, B. (2010). Building Evaluation: Practice and Principles. *Building Research & Information, 38*(5), 564-577.

Ley A. J. (2000). *A History of Building Control in England and Wales 1840 -1990*. London: RICS.

Lomas K., & Eppel, H. (1992). Sensitivity Analysis Techniques for Building Thermal Simulation Programs. *Energy and Buildings, 19*(1), 21-44.

Loughborough University. (2014). Project CALEBRE. Retrieved 11th July 2012, from www.calebre.org.uk/

Loveday D., Vadodaria, K., Haines, V., Hewitt, N., T., H., Griffiths, P., . . . Edman, T. (2011). *Refurbishing the UK's 'Hard to Treat' Dwelling Stock: Understanding Challenges and Constraints – The Work of Project CALEBRE. CIBSE Technical Symposium. DeMontfort University, Leicester. 6th - 7th September 2011.*

Lowe R. (2007). Technical Options and Strategies for Decarbonising UK Housing. *Building Research and Information, 35*(4), 412-425.

Lowe R., & Johnston, D. (1997). A Field Trial of Mechanical Ventilation with Heat Recovery in Local Authority Low-Rise Housing. Leeds Metropolitan University, Leeds.

Lowe R., & Oreszczyn, T. (2008). Regulatory Standards and Barriers to Improved Performance for Housing. *Energy Policy, 36*(12), 4475-4481.

Lowe R., Wingfield, J., Bell, M., & Bell, J. M. (2007). Evidence for Significant Heat Loss through Party Wall Cavities in Load-Bearing Masonry Construction. *Building Services Engineering Research and Technology, 28*(2), 161-181.

MacDonald I. (2002). Quantifying the Effects of Uncertainty in Building Simulation. PhD Thesis. University of Strathclyde.

MacKenzie F., Pout, C., Shorrock, L., Matthews, A., & Henderson, J. (2010). Energy Efficiency in New and Existing Buildings – Comparative Costs and CO2 Savings, BRE Trust, Watford.

Makuch K., Makuch, Z., Pereira, R., & Jourdain, C. (2012). UK Climate Change Law and Policy. In K. Makuch, Pereira, R. (Ed.), *Environmental and Energy Law* (pp. 172-192). Chichester: Wiley-Blackwell.

McLeod R., Hopfe, C., & Rezgui, Y. (2012). An Investigation Into Recent Proposals for a Revised Definition of Zero Carbon Homes in the UK. *Energy Policy, 46*(0), 25-35.

McLeod R. S., Hopfe, C. J., & Rezgui, Y. (2012). A proposed method for generating high resolution current and future climate data for Passivhaus design. *Energy and Buildings, 55*(0), 481-493.

Menezes A., Cripps, A., Bouchlaghem, D., & Buswell, R. (2012). Predicted vs. Actual Energy Performance of Non-Domestic Buildings: Using Post-Occupancy Evaluation Data to Reduce the Performance Gap. *Applied Energy, 97*(0), 355-364. doi:

Mhalas A., Kassem, M., Crosbie, T., & Dawood, N. (2013). A Visual Energy Performance Assessment and Decision Support Tool for Dwellings. *Visualization in Engineering, 1*(7), 1-13.

Miles Shenton D., Wingfield, J., & Bell, M. (2007). Evaluating the Impact of an Enhanced Energy Performance Standard on Load-Bearing Masonry Domestic Construction – Interim Report Number 6: Air Tightness Monitoring, Qualitative Design and Construction Assessments. In C. f. t. B. Environment (Ed.), *Leeds Metropolitan University*. Leeds.

Miles Shenton D., Wingfield, J., Sutton, R., & Bell, M. (2010). Report to Joseph Rowntree Housing Trust. Project Title: Temple Avenue Project Part 1. Temple Avenue Field Trial – Evaluation of Design & Construction Process and Measurement of Fabric Performance of New Build Dwellings. In C. f. t. B. Environment (Ed.), *Leeds Metropolitan University*. Leeds.

Minch A. (2011). Energy Efficient Buildings Heat Gain/Loss through Infiltration, Lecture Briefing.

Moutzouri E. (2011). *Comparison Between PHPP And SAP & Elaboration Of Monitored Data For Two Dwellings With Different Insulation Levels, Masters Level Thesis, Department of Mechanical Engineering, University of Strathclyde.*

Murphy G., Allison, J., & Counsell, J. (2013a). *Benchmarking the Effect of Weather Data Upon Energy Estimations of UK Homes.* Paper presented at the CIBSE Technical Symposium, Liverpool John Moores University. Liverpool.11-12 April 2013.

Murphy G., Allison, J., & Monari, F. (2013b). *Determining the Effect of Weather Data Upon Building Simulations in Regulatory Processes.* Paper presented at the 13th Conference of International Building Performance Simulation Association. Chambéry. France. August 26 -28 2013.

Natarajan S., & Levermore, G. (2007). Domestic Futures—Which Way to a Low-Carbon Housing Stock? *Energy Policy, 35*(11), 5728-5736.

Natarajan S., Padget, J., & Elliott, L. (2011). Modelling UK Domestic Energy and Carbon Emissions: An Agent-Based Approach. *Energy and Buildings, 43*(10), 2602-2612.

Nathaniel Lichfield & Partners. (2012). Laugh Out Loud: A Pocket Book of 50 Cartoons and Jokes about Planning and Development. Retrieved 6th November 2013, from http://nlpplanning.com/lol

National Energy Services (NES). (2012). SAP 2012 in a Nutshell. Retrieved 14th August 2013, from http://www.housebuilder.co.uk/documents/SAP%202012%20in%20a%20Nutshell%20v2.0.pdf

National House Building Council (NHBC). (2009). Indoor Air Quality in Highly Energy Efficient Homes - A Review. NHBC. Milton Keynes.

National House Building Council (NHBC). (2011a). Energy and Air Tightness - How Dwelling Air Permeability Changes Over Time. NHBC. Milton Keynes.
National House Building Council (NHBC). (2011b). Technical Extra – Issue 3 - Special Edition: Approved Document Part L In NHBC (Ed.). Milton Keynes.

National House Building Council (NHBC). (2012). Low And Zero Carbon Homes: Understanding The Performance Challenge *NHBC*. Milton Keynes.

National House Building Council (NHBC). (2013). Technical Extra - Issue 12 - October 2013. NHBC. Milton Keynes.

National House Building Council (NHBC) Foundation. (2013). Review of Coheating Test Methodologies. IHS BRE. Watford.

National Instruments Corporation. (2010). Thermocouple Accuracy Table by Type and Temperature. Retrieved 22nd July 2013, from http://digital.ni.com/public.nsf/allkb/776AB03E065228408625727B00034E20

National Physical Laboratory (NPL). (2012). The Building Performance Gap - Closing it Through Better Measurement. National Measurement Network Event Report. ARUP Offices. 5th December 2012. Retrieved 15th September 2013, from http://www.npl.co.uk/upload/pdf/the-building-performance-gap.pdf

Nicholls R. (2008). The Green Building Bible Volume 2. 4th Edition. Green Building Press. Llandysul.

Northern Ireland Statistics and Research Agency. (2013). Northern Ireland Housing Statistics 2011-2012. Retrieved 1st September 2013, from http://www.dsdni.gov.uk/northern_ireland_housing_statistics_2011-13.pdf

Nuaire. (2009). MRXbox90Mand L Mechanical Ventilation with Heat Recovery Installation and Maintenance. Nuaire. Caerphilly.

Odyssee Mure. (2012). Energy Efficiency Profile: EU Energy Efficiency Trends. Odyssee. France.

OFGEM. (2013). Energy Companies Obligation (ECO): Guidance for Suppliers (Version 1.1). Retrieved 16th August 2013, from https://www.ofgem.gov.uk/ofgem-publications/75775/energycompaniesobligationecoguidanceforsuppliers-version11.pdf

Ormandy D. (2011). Health and Thermal Comfort: From WHO Guidance to Housing Strategies. University of Warwick, Warwick.

Osmani M., & O'Reilly, A. (2009). Feasibility of Zero Carbon Homes in England by 2016: A House Builder's Perspective. *Building and Environment, 44*(9), 1917-1924.

Palmer J., & Cooper, L. (2012). United Kingdom Energy Fact File 2012. DECC. London.

Palmer J., Pane, G., Bell, M., & Wingfield, J. (2011). Comparing Primary and Secondary Terms Analysis and Re-Normalisation (PStar) Test and Co-Heating Test Results Final report – BD2702. DCLG. London.

Passivhaus Institute. (2009). Certification as ‘Quality Approved Passive House’ Criteris for Residential-Use Passive Houses. Certification Documents. W.Feist. Darmstadt. PassivHaus Institute: 7.

Passivhaus Trust. (2011). Passivhaus and Zero Carbon Technical Briefing Document 5th July 2011. Retrieved 29th July 2012, from http://www.passivhaustrust.org.uk/UserFiles/File/Technical%20Papers/110705%20Final%20PH%20ZC%20Brief.pdf.

PassivHaus Trust. (2014a). Outline Specification. Retrieved 18th May 2014, from http://www.passivhaus.org.uk/standard.jsp?id=18

PassivHaus Trust. (2014b). The PassivHaus Standard Retrieved 18th May 2014, from http://www.passivhaus.org.uk/standard.jsp?id=122

Pearson P., & Watson, J. (2012). UK Energy Policy 1980-2010 - A History and Lessons to be Learnt. The Parliamentary Group for Energy Studies. London.

Pereira R., & Jourdain, C. (2012). International and EU Climate Change Law. In K. Makuch, Pereira, R. (Ed.), *Environmental and Energy Law* (pp. 141-172). Chichester: Wiley-Blackwell.

Pérez-Lombard L., Ortiz, J., & Pout, C. (2008). A Review on Buildings Energy Consumption Information. *Energy and Buildings, 40*(3), 394-398.

Persily A. (2013). Repeatability and Accuracy of Pressurisation Testing. Retrieved 13th January 2014, from http://web.ornl.gov/sci/buildings/2012/1982%20B2%20papers/021.pdf

Pohl J. (2011). Building Science Concepts and Application. Wiley-Blackwell. Chichester.

Pollet I., Laverge, J., Vens, A., Losfeld, F., Reeves, M., & Janssens, A. (2013). Performance of a Demand Controlled Mechanical Extract Ventilation System for Dwellings. *Journal of Sustainable Engineering Design, 1*(3), Article 5.

Power A. (2008). Does Demolition or Refurbishment of Old And Inefficient Homes Help To Increase Our Environmental, Social and Economic Viability? *Energy Policy, 36*(12), 4487-4501.

Power A. (2010). Housing & Sustainability: Demolition or Refurbishment? *Proceedings of the Institution of Civil Engineers – Engineering Sustainability 163*(December 2010. DP4), 205-216.

Preiser W. (1995). Post-Occupancy Evaluation: How to Make Buildings Work Better. *Facilities, 13*(11), 19-28.

Preiser W., & Vischer, J. (2004). Assessing Building Performance. Butterworth Heinemann. Oxford.

Quigley E. (2010). *Sensitivity and Uncertainty in BREDEM-8 Predictions.* (MSc), Loughborough University.

Randall J., & Hoyle, J. (1979). Low Energy Housing – Salford’s Answer. *Building Services and Environmental Engineer, June 1979*.

Raslan R., & Davies, M. (2009). Results Variability in Accredited Building Energy Performance Compliance Demonstration Software in the UK: an Inter-Model Comparative Study. *Journal of Building Performance Simulation, 3*(1), 63-85.

Reardon C. (2008). Technical Manual 4.5: Passive Solar Heating. Retrieved 13th August 2013, from http://www.yourhome.gov.au/technical/fs45.html

Renewable Heat Incentive Ltd. (2013). Renewable Heat Incentive. Retrieved 16th August 2013, from http://www.rhincentive.co.uk/

Roaf S., Baker, K., & Peacock, A. (2008). Evidence on Tackling Hard to Treat Properties. The Scottish Government Housing and Regeneration Department. Edinburgh.

Roulet C. (2008). Ventilation and Airflow In Buildings - Methods for Diagnosis and Evaluation. Earthscan. London.

Royal Institute of British Architects (RIBA). (2009). Carbon Literacy Briefing - Executive Summary. RIBA. London.

Rye C., & Scott, C. (2012). The SPAB Research Report 1. U-Value Report. 2012 Revision. SPAB. London.

Ryghaug M., & Sørensen, K. (2009). How Energy Efficiency Fails in the Building Industry. *Energy Policy, 37*(3), 984-991.

Saltelli A., Annoni, P., & D’Hombres, B. (2010). How to Avoid a Perfunctory Sensitivity Analysis. *Procedia - Social and Behavioral Sciences, 2*(6), 7592-7594.

Saltelli A., Chan, K., & Scott, M. (2000). Sensitivity Analysis. Wiley & Sons. Chichester.

Scottish Building Standards Division (SBSA). (2009). Benchmarking Scottish Energy Standards: Passive House And Carbonlite Standards: A Comparison Of Space Heating Energy Demand Using SAP, SBEM, And PHPP Methodologies, SBSA, Livingstone.

Seacoast Inspections LLC. (2013). Blower Door Testing? Retrieved 31st October 2013, from http://www.seacoastinspections.com/BlowerDoor.html

Sherman M. (1998). The Use of Blower-Door Data. Energy Performance of Buildings Group. University of California.

Sherman M., Wilson, D., & Kiel, D. (1986). Variability in Residential Air Leakage. In H. Trechsel, Lagus, P., (Ed.), *Measured Air Leakage of Buildings* (pp. 348-364): ASTM, USA.

Sherman M. H. (1987). Estimation of infiltration from leakage and climate indicators. *Energy and Buildings, 10*(1), 81-86.

Sinnott D., & Dyer , M. (2011). *Airtightness of Dwellings in Ireland: Design, Workmanship and Control.* Paper presented at the COBRA 2011 Proceedings of the RICS Foundation Construction and Building Research Conference, 12 – 13 September. Salford, Manchester.

Sinnott D., Dyer, M. (2012). Air-tightness field data for dwellings in Ireland. *Building and Environment, 51*(0), 269-275.

Siviour J. (1981). *BIBINF Proceedings International Colloquium "Comparative Experimentation of Low Energy Houses" Liege, 6-8 May 1981*.

Siviour J. B. (1994). Experimental U-Values of Some House Walls. Building Services, Engineering, Research and Technology: 15 (1) 35-36.

Smith K. (2013). The Difficult Road to Code 4. *Construction Research and Innovation, 4*(1), 28-29.

Sonderegger R. (1978). Movers and Stayers: The Resident's Contribution to Variation Across Houses in Energy Consumption for Space Heating. *Energy and Buildings, 1*(3), 313-324.

Sonderegger R., Condon, P., & Modera, M. (1980). In Situ Measurement of Residential Energy Performance Using Electric Coheating. *American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) Transactions,, 86 (1) pp 394*.

Sovacool B. (2009). The importance of comprehensiveness in renewable electricity and energy-efficiency policy. *Energy Policy, 37*(4), 1529-1541.

Stafford A. (2012). The Retrofit Challenge: Delivering Low Carbon Buildings. Centre for Low Carbon Futures. Leeds.

Stafford A., Bell, M., & Gorse, C. (2012). Building Confidence - A Working Paper. Retrieved 15th September 2013, from
http://www.leedsmet.ac.uk/as/cebe/projects/building-confidence.pdf

Stamp S. (2013). W2UP3 - Co-heating Tests in the Field and Laboratory [Samuel Stamp, UCL]. Retrieved 12th June 2013, from http://www.lolo.ac.uk/project/view/project/26

Stephen R. (1998). Airtightness in UK Dwellings: BRE Test Results and their Significance - Report No. 359. BRE. London.

Stephen R. (2000). Airtightness in UK Dwellings - BRE Report IP1/00. BRE. Watford.

Stevenson F., & Rijal, H. (2008). Paper No 595: The Sigma Home: Towards an Authentic Evaluation of Prototype Building. 25th Conference on Passive and Low Energy Architecture. 22-24 October 2008. Dublin, Ireland.

Subbarao K. (1998). PSTAR–Primary and Secondary Terms Analysis and Renormalization: A Unified Approach to Building Energy Simulations and Short-Term Monitoring SERI/TR-254-3175. In Solar Energy Research Institute (Ed.). Colorado.

Subbarao K., Burch, J., Balcomb, J., Hancock, C., & Lekov, A. (1989). Short-Term Energy Monitoring: STEM-1.1, User Manual, Report SERI/TR-254-3613. . In Solar Energy Research Institute (Ed.). Colorado.

Subbarao K., Burch, J. D., Hancock, C. E., Lekov, A., & Balcomb, J. D. (1998). Short-Term Energy Monitoring (STEM): Application of the PSTAR Method to a Residence in Fredericksburg, Virginia', Report SERI/TR-254-3356. . In Solar Energy Research Institute (Ed.). Colorado.

Sutton R., Stafford, A., & Gorse, C. (2012). *The Coheating Test - The Value of a Number. International Energy Agency Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements.* Paper presented at the Subtask 2: Full Scale Dynamic Testing: IEA Annex 58 2nd Meeting., Bilbao, Spain, April 2nd - 4th 2012.

Swan L., & Ugursal, V. (2009). Modeling of End-Use Energy Consumption in the Residential Sector: A Review of Modeling Techniques. *Renewable and Sustainable Energy Reviews, 13*(8), 1819-1835.

Swan W., Ruddock, L., Smith, L., & Fitton, R. (2013). Adoption of Sustainable Retrofit in UK Social Housing. *Structural Survey, 31*(3), 181-193.

Technology Strategy Board. (2011). Building Performance Evaluation Competition for Funding May 2010 – 2012 3rd Edition *Technology Strategy Board*. Swindon.

Technology Strategy Board (TSB). (2013). Building Performance Evaluation Project. Retrieved 15th September 2013, from https://connect.innovateuk.org/web/building-performance-evaluation/outputs

Testo Inc. (2011). Vane Anemometer With Built In Vane, Testo, Flanders.

The Guardian. (2013). Actively Cutting Energy Bills in Oldham - Welcome to the Passivhauses. 1st November 2013. Retrieved 8th November 2013, from http://www.theguardian.com/environment/2013/nov/01/cutting-energy-bills-oldham-passivhaus

The Scottish Government Housing and Regeneration Department. (2013). Housing Statistics for Scotland - Key Information and Summary Tables. Retrieved 1st September 2013, fromhttp://www.scotland.gov.uk/Topics/Statistics/Browse/Housing-Regeneration/HSfS/KeyInfoTables

Thermo Fisher Scientific Inc. (2011). DT85 Series 3 Datalogger. Retrieved 22nd July 2013, from http://www.dataloggerinc.com/datasheets/dt85-intelligent-universal-input-data-logger.pdf

Titman D. J. (2001). Applications of Thermography in Non-Destructive Testing of Structures. *NDT & E International, 34*(2), 149-154.
Titon. (2009). Titon HRV1 Q Plus HRV1.5 Q Plus HRV2 Q Plus Heat Recovery Ventilation Units Product Manual. Retrieved 13th November 2010, from http://www.titon.co.uk/media/product/ventilator-systems/download/BM838_iss02_HRV_1_1-5_2_Q_Plus_Product_Manual.pdf

Todd S. (2001). A Review of the Proposals for Amending the Energy Efficiency Provisions in the Building Regulations for Dwellings. *Structural Survey, 19*(2), 89-98.

Trinick J., Elliott, E., M., G., Shepherd, J., & Orme, M. (2009). EEPH / CLG Research into Compliance with Part L of the Building Regulations for New Homes – Phase 2 Main Report. Energy Efficiency Partnership for Homes, CLG. London.

UK Parliament. (1966). Building Control Act 1966 Chapter 27. HMSO. London.

Utley J. I., & Shurrock, L. D. (2008). Domestic Energy Fact File, BRE Trust, Watford.

Utley J. I., & Shurrock, L. D. (2012). Ninety Years of Housing, 1021-2011 - Trends Relating to Living Standards, Energy Use and Carbon Emissions, BRE Trust, Watford.

Vent-Axia. (2010). Domestic Ventilation and The Building Regulations: Part F and L. Vent-Axia. Crawley.

Wallace H. (2012). The UK: 40 Years of EU Membership. *Journal of Contemporary European Research, 8*(4), 531-546.
Warren P., & Webb, B. (1980). *Ventilation Measurements in Housing.* Paper presented at the Proceedings of the CIBS Symposium on Natural Ventilation by Design. December, 1980, London, CIBS, pp.22-34.

Watson J., & Pearson, P. (2012). UK Energy Policy 1980 - 2010: A History and Lessons To Be Learned. IET. London.

Webster P. J. (1987). The SALFORD Low-Energy House, DoE Energy Efficiency Demonstration Scheme (Vol. BRESCU Report No. ED 179/59).

Welsh Assembly Government. (2013). Dwelling Stock Estimates for Wales 2011-12. Statistics for Wales First Release SDR 67/2013. Retrieved 1st September 2013, from http://wales.gov.uk/docs/statistics/2013/130425-dwelling-stock-estimates-2011-12-en.pdf

White J., Gillott, M., & Wood, C. (2013). *The Impact of MVHR Systems on Space Heating Levels in Dwellings*. Paper presented at the 12th International Conference on Sustainable Energy technologies (SET-2013). , 26-29th August 2013. Hong Kong.

Wingfield J. (2011). Fabric Testing: Whole House Heat Loss. In Centre for Built Environment (Ed.). Leeds Metropolitan University, Leeds.

Wingfield J., Bell, M., Bell, J., & Lowe, B. (2006). Evaluating the Impact of an Enhanced Energy Performance Standard on Load-Bearing Masonry Domestic Construction – Interim Report Number 5: Post Construction Testing and Envelope Performance, Centre for the Built Environment, Leeds Metropolitan University, Leeds.

Wingfield J., Bell, M., & Miles-Shenton, D. (2010). Report to EURISOL: Investigations of the Party Wall Thermal Bypass in Timber Frame Dwellings, Centre for the Built Environment, Leeds Metropolitan University, Leeds.

Wingfield J., Bell, M., Miles-Shenton, D., & Seavers, J. (2011a). Elm Tree Mews Field Trial – Evaluation and Monitoring of Dwellings Performance – Final Technical Report. In Centre for Built Environment (Ed.), *Leeds Metropolitan University*. Leeds.

Wingfield J., Bell, M., Miles-Shenton, D., South, T., & Lowe, R. (2011b). Evaluating the Impact of an Enhanced Energy Performance Standard on Load-Bearing Masonry Domestic Construction - Understanding the Gap Between Designed and Real Performance: Lessons from Stamford Brook. DCLG. London.

Wingfield J., Bell, M., Miles Shenton, D., Lowe, B., & South, T. (2007). Evaluating the Impact of an Enhanced Energy Performance Standard on Load-Bearing Masonry Domestic Construction – Interim Report Number 7: Co Heating Tests and Investigation of Party Wall Thermal Bypass In C. f. t. B. Environment (Ed.), *Leeds Metropolitan University*. Leeds.

Wingfield J., Bell, M., Miles Shenton, D., South, T., & Lowe, B. (2008). Evaluating the Impact of an Enhanced Energy Performance Standard on Load-Bearing Masonry Domestic Construction - Report Number 8: Final Report Lessons from Stamford Brook - Understanding the Gap between Designed & Real Performance. In C. f. t. B. Environment (Ed.), *Leeds Metropolitan University*. Leeds.

Wingfield J., Miles-Shenton, D., & Bell, M. (2009). Evaluation of the Party Wall Thermal Bypass in Masonry Dwellings, Centre for the Built Environment, Leeds Metropolitan University, Leeds.

Winzer C. (2012). Conceptualizing energy security. *Energy Policy, 46*(0), 36-48.

Wood C. (2013). E.On Research House Performance Report - Phase 3.1. CONFIDENTIAL REPORT.

Wood G., Ong, R., & McMurray, C. (2012). Housing Tenure, Energy Consumption and the Split-Incentive Issue in Australia. *International Journal of Housing Policy, 12*(4), 439-469.

Woodford C. (2014). Heat Insulation. Retrieved 19th May 2014, from http://www.explainthatstuff.com/heatinsulation.html

World Commission on Environment and Development (WCED). (1987). Our Common Future. Oxford University Press. Oxford.

World Health Organisation. (2007). Housing, Energy and Thermal Comfort - A Review of 10 COuntries within the European Region. Retrieved 20th May 2014, from http://www.euro.who.int/__data/assets/pdf_file/0008/97091/E89887.pdf?ua=1

World Health Organisation. (2010). WHO Guidelines for Indoor Air Quality: Selected Pollutants. Retrieved 20th August 2011, from http://www.euro.who.int/en/what-we-publish/abstracts/who-guidelines-for-indoor-air-quality-selected-pollutants

Wouters P., & Loncour, X. (2005). Review of Selected Theoretical and Experimental Techniques for Energy Characterisation of Buildings. In M. Sanatamouris (Ed.), *Energy Performance of Residential Buildings - A Practical Guide For Energy Rating and Efficiency*. London: James & James/Earthscan.

Yohanis Y. G., Mondol, J. D., Wright, A., & Norton, B. (2008). Real-Life Energy Use In The UK: How Occupancy And Dwelling Characteristics Affect Domestic Electricity Use. Energy and Buildings 40 (2008) pp. 1053–1059.

Zero Carbon Hub. (2010). Carbon Compliance for Tomorrow’s New Homes – A Review of the Modelling Tool and Assumptions – Topic 4: Closing the Gap Between Designed and Built Performance. Zero Carbon Hub. London.

Zero Carbon Hub. (2011a). Carbon Compliance - Setting an Appropriate Limit for Zero Carbon New Homes. Zero Carbon Hub. London.

Zero Carbon Hub. (2011b). Carbon Compliance: Setting an Appropriate Limit for Zero Carbon New Homes - National or Regional Weather: Implications for Carbon Compliance. Zero Carbon Hub. London.

Zero Carbon Hub. (2011c). Greenwatt Way by SSE. LZ Carbon Profile: 029. January 2011. Retrieved 8th November 2013, from http://www.zerocarbonhub.org/sites/default/files/resources/examples/profiles/25_GreenwattWay.pdf

Zero Carbon Hub. (2011d). Shine ZC. LZ Carbon Profile: 020. March 2011. Retrieved 8th November 2013, from:http://www.zerocarbonhub.org/sites/default/files/resources/examples/profiles/17_ShineZC.pdf

Zero Carbon Hub. (2012a). Allowable Solutions for Tomorrow's New Homes - Evaluating Opportunites and Priorities. Zero Carbon Hub. London.

Zero Carbon Hub. (2012b). Fabric Energy Efficiency for Zero Carbon Homes: A Flexible Performance Standard for 2016. Zero Carbon Hub. London.

Zero Carbon Hub. (2012c). Mechanical Ventilation with Heat Recovery in New Homes. Interim Report of the VIAQ Taskgroup. Zero Carbon Hub. London.

Zero Carbon Hub. (2013a). Closing the Gap Between Design and As-Built Performance - New Homes - Interim Progress Report July 2013. Zero Carbon Hub. London.

Zero Carbon Hub. (2013b). Closing the Gap Between Design and As-Built Performance - New Homes - Interim Progress Report. Appendices. July 2013. ZCH. London.

Zero Carbon Hub. (2013c). Minister Launches Hub-Led Project to Tackle the Performance Challenge. Retrieved 11th June 2013, from http://www.zerocarbonhub.org/news_details.aspx?article=37

Zero Carbon Hub. (2013d). The Performance Challenge - A Programme to Close the Gap Between Designed and As-Built Performance. Zero Carbon Hub. London.

Zero Carbon Hub. (2013e). Zero Carbon Strategies for Tomorrow's New Homes. Zero Carbon Hub. London.

Zero Carbon Hub & NHBC Foundation. (2013). Mechanical Ventilation With Heat Recovery in New Homes : Interim Report. In Ventilation and Indoor Air Quality Task Group (Ed.). Zero Carbon Hub, London.

Appendix 1 – Baseline SAP Worksheet

Appendix 2 - SAP Worksheets for E.On and Tarmac House

SAP Worksheet: Design - Final

This Design submission has been carried out by an Authorised SAP Assessor. It has been prepared from plans and specifications and may not reflect the property as constructed.

Assessor Name	Mr James Bonell	**Assessor Number**	2608
Client	University of Nottingham		
Date Last Modified	26/08/2009		
Address	Phase 1a EOn House, Phase 1a University Park, University of Nottingham, NG7 2RD		

1. Overall dwelling dimensions

	Area (m²)			Average storey height (m)		Volume (m³)	
Ground Floor	52.80	(1a)	×	2.40	=	126.72	(1)
First Floor	55.28	(2a)	×	2.50	=	138.20	(2)
Total floor area (1a)+(2a)+(3a)+(4a)+(4b)+(4d)+(4f)+(4h) =	108.08	(5)					
Dwelling volume				(1)+(2)+(3)+(4)+(4c)+(4e)+(4g)+(4i)	=	264.92	(6)

2. Ventilation rate

			m³ per hour	
Number of chimneys	4	× 40 =	160	(7)
Number of open flues	0	× 20 =	0	(8)
Number of intermittent fans or passive vents	0	× 10 =	0	(9)
Number of flueless gas fires	0	× 40 =	0	(9a)

			Air changes per hour	
Infiltration due to chimneys, flues and fans = (7)+(8)+(9)+(9a) =	160	÷ box (6) =	0.60	(10)

If a pressurisation test has been carried out, proceed to box (19)

Number of storeys in the dwelling	2 (11)			
Additional infiltration		[(11) - 1] × 0.1 =	0.10	(12)
Structural infiltration: *0.25 for steel or timber frame or 0.35 for masonry construction*			0.35	(13)
If suspended wooden floor, *enter 0.2 (unsealed) or 0.1 (sealed)*, else enter 0			0.20	(14)
If no draught lobby, enter 0.05, else enter 0			0.05	(15)
Percentage of windows and doors draught stripped	0.00 (16)			

Enter 100 in box (16) for new dwellings which are to comply with Building Regulations

Window infiltration	0.25 - [0.2 × (16) ÷ 100] =	0.25	(17)
Infiltration rate	(10)+(12)+(13)+(14)+(15)+(17) =	1.55	(18)
If based on air permeability value, then [q $_{50}$ ÷ 20] + (10) in box (19), otherwise (19) = (18)		1.55	(19)
Number of sides on which sheltered		1	(20)

Air permeability value applies if a pressurisation test has been done or the design air permeability is being used

(Enter 2 in box (20) for new dwellings where location is not shown)

Shelter factor	1 - [0.075 × (20)] =	0.93	(21)
Adjusted infiltration rate	(19) × (21) =	1.44	(22)

Calculate effective air change rate for the applicable case

If balanced whole house mechanical ventilation system	air throughput (ach) =	N/A	(22a)
If balanced with heat recovery	efficiency in % allowing for in-use factor =	N/A	(22b)
a) If balanced whole house mechanical ventilation with heat recovery	(22) + (22a) × [1 – (22b) / 100] =	N/A	(23)
b) If balanced whole house mechanical ventilation without heat recovery	(22) + (22a) =	N/A	(23a)
c) If whole house extract ventilation or positive input ventilation from outside ***if (22) < 0.25, then (23b) = 0.5; otherwise (23b) = 0.25 + (22)***		N/A	(23b)
d) If natural ventilation or whole house positive input ventilation from loft ***if (22) ≥ 1, then (24) = (22); otherwise (24) = 0.5 +[(22)² × 0.5]***		1.44	(24)
Effective air change rate - enter (23) or (23a) or (23b) or (24) in box (25)		1.44	(25)

3. Heat losses and heat loss parameter

ELEMENT	Area (m²)		U - value		AXU (W/K)	
Windows *	24.47	×	4.03	=	98.54	(27)
Doors	6.65	×	3.00	=	19.95	(26)
Ground Floor	9.46	×	1.00	=	9.47	(28)
Ground Floor	43.34	×	0.68	=	29.51	(28)
Upper Floor	2.48	×	0.81	=	2.00	(31)
Walls	129.53	×	1.39	=	180.44	(29)
Walls	8.56	×	0.69	=	5.91	(29)
Roof	71.55	×	2.10	=	150.33	(30)
Roof	2.49	×	3.15	=	7.83	(30)
Total area of elements ΣA, m²	298.53	(32)				

** for windows and rooflights, use effective window U-value calculated as given in paragraph 3.2*

Fabric heat loss, W/K	(26)+(27)+(27a)+(27b)+(28)+(29)+(29a)+(30)+(30a)+(31) =	503.97	(33)
Thermal bridges - Σ (lxΨ) calculated using Appendix K *if details of thermal bridging are not known calculate y× (32) [see Appendix K] and enter in box (34)*		149.27	(34)
Total fabric heat loss	(33)+(34) =	653.23	(35)
Ventilation heat loss	(25) × 0.33 × (6) =	125.66	(36)
Heat loss coefficient, W/K	(35)+(36) =	778.90	(37)
Heat loss parameter (HLP), W/m²K	(37) ÷ (5) =	7.21	(38)

4. Water heating energy requirement

	kWh/year	
Energy content of hot water used from Table 1 column (b)	2201.59	(39)
Distribution loss from Table 1 column (c) *If instantaneous water heating at point of use, enter "0" in boxes (40) to (45)* *For community heating use Table 1 (c) whether or not hot water tank is present*	388.52	(40)

Water storage loss:

a) If manufacturer's declared loss factor is known (kWh/day):		N/A	(41)
Temperature factor from Table 2b		N/A	(41a)
Energy lost from water storage, kWh/year	(41)×(41a)×365 =	N/A	(42)

b) If manufacturer's declared cylinder loss factor is not known:

Cylinder volume (litres) including any solar storage within same cylinder *If community heating and no tank in dwelling, enter 110 litres in box (43)* *Otherwise, if no stored hot water (this includes instantaneous combi boilers), enter '0' in box (43)*		100.00	(43)
Hot water storage loss factor from Table 2 (kWh/litre/day) *If community heating and no tank in dwelling, use cylinder loss from Table 2 for 50 mm factory insulation in box (44)*		0.14	(44)
Volume factor from Table 2a		1.06	(44a)
Temperature factor from Table 2b		0.78	(44b)
Energy lost from water storage, kWh/year	(43)×(44)×(44a)×(44b)×365 =	4311.18	(45)
Enter (42) or (45) in box (46)		4311.18	(46)
If cylinder contains dedicated solar storage, box (47) = (46) × [(43) - (H11)] / (43), else (47) = (46)		4311.18	(47)
Primary circuit loss from Table 3		1220.00	(48)
Combi loss from Table 3a (enter "0" if no combi boiler)		0.00	(49)
Solar DHW input calculated using Appendix H (enter "0" if no solar collector)		0.00	(50)
Output from water heater, kWh/year	(39)+(40)+(47)+(48)+(49)-(50) =	8121.28	(51)
Heat gains from water heating *include (47) in calculation of (52) only if cylinder is in the dwelling or hot water is from community heating*	0.25 × [(39)+(49)]+0.8×[(40)+(47)+(48)] =	5286.15	(52)

5. Internal gains

		Watts	
Lights, appliances, cooking and metabolic (Table 5)		613.58	(53)
Reduction of internal gains due to low energy lighting (calculated in Appendix L)		22.27	(53a)
Additional gains from Table 5a		0.00	(53b)
Water heating	(52) ÷ 8.76 =	603.44	(54)
Total internal gains	(53) + (53b) + (54) - (53a) =	1194.75	(55)

6. Solar gains

	Access factor Table 6d		Area m²		Flux Table 6a		g Table 6b		FF Table 6c		Gains (W)	
North West	1.00	×	4.00	×	34.00	x 0.9 x	0.85	×	0.70	=	72.83	(56)
North East	1.00	×	10.81	×	34.00	x 0.9 x	0.85	×	0.70	=	196.82	(61)
South West	1.00	×	9.66	×	64.00	x 0.9 x	0.85	×	0.70	=	331.07	(63)

Total solar gains:	[(56) + ... + (64)] =	600.71	(65)

Note: for new dwellings where overshading is not known, the solar access factor is '0.77'

Total gains, W	(55) + (65) =	1795.47	(66)
Gain/loss ratio (GLR)	(66) ÷ (37) =	2.31	(67)
Utilisation factor (Table 7, using GLR in box (67))		1.00	(68)
Useful gains, W	(66) × (68) =	1794.74	(69)

7. Mean internal temperature

		°C	
Mean internal temperature of the living area (Table 8)		17.78	(70)
Temperature adjustment from Table 4e, where appropriate		0.60	(71)
Adjustment for gains *R is obtained from the 'responsiveness' column of Table 4a or Table 4d*	{[(69) ÷ (37)] - 4.0} × 0.2 ×R =	-0.34	(72)
Adjusted living room temperature	(70) + (71) + (72) =	18.04	(73)
Temperature difference between zones (Table 9)		2.00	(74)
Living area fraction (0 to 1.0)	living room area ÷ (5) =	0.14	(75)
Rest-of-house fraction	1 - (75) =	0.86	(76)
Mean internal temperature	(73) - [(74) × (76)] =	16.31	(77)

8. Degree days

Temperature rise from gains	(69) ÷ (37) =	2.30	(78)
Base temperature	(77) - (78) =	14.01	(79)
Degree-days, *use box (79) and Table 10*		1782.03	(80)

9. Space heating requirements

Space heating requirement (useful), kWh/year	0.024 × (80) × (37) =	33312.52	(81)

For range cooker boilers where efficiency is obtained from the Boiler Efficiency Database or manufacturer's declared value, multiply the result in box (81) by (1 - Φ_{case}/Φ_{water}) where Φ_{case} is the heat emission from the case of the range cooker at fullload (in kW); and Φ_{water} is the heat transferred to water at full load (in kW).Φ_{case} and Φ_{water} are obtained from the database record for the range cooker boiler or manufacturer's declared value.

9a. Energy requirements - individual heating systems, including micro-CHP

Note: when space and water heating is provided by community heating use the alternative worksheet 9b

Space heating:

Fraction of heat from secondary/supplementary system (*use value from Table 11, Table 12a or Appendix F)*		0.00	(82)
Efficiency of main heating system, %		50.00	(83)

(SEDBUK or from Table 4a or 4b, adjusted where appropriate by the amount shown in the 'efficiency adjustment' column of Table 4c)

Efficiency of secondary/supplementary heating system, % (use value from Table 4a or Appendix E)		0.00	(84)
Space heating fuel (main) requirement, kWh/year	[1- (82)] × (81) ×100 ÷ (83) =	66625.03	(85)

Space heating fuel (secondary), kWh/year (82) × (81) ×100 ÷ (84) = N/A (85a)

Water heating:

Efficiency of water heater, % 50.00 (86)

(SEDBUK or from Table 4a or 4b, adjusted where appropriate by the amount shown in the 'efficiency adjustment' column of Table 4c)

Energy required for water heating, kWh/year (51) × 100 ÷ (86) = 16242.56 (86a)

Electricity for pumps and fans:	**kWh/year**	
each central heating pump, (Table 4f)	169.00	(87a)
each boiler with a fan-assisted flue (Table 4f)	0.00	(87b)
warm air heating system fans (Table 4f)	0.00	(87c)
mechanical ventilation -balanced, extract or positive input from outside (Table 4f)	0.00	(87d)
maintaining keep-hot facility for gas combi boiler (Table 4f)	0.00	(87e)
pump for solar water heating (Table 4f)	0.00	(87f)

Total electricity for the above equipment, kWh/year (87a)+(87b)+(87c)+(87d)+(87e)+(87f) = 169.00 (87)

10a. Fuel costs - individual heating systems

	Fuel kWh/year		**Fuel price** (Table 12)		**Fuel cost** £/year	
Space heating - main system	(85)	×	1.63	×0.01 =	1085.99	(88)
Space heating - secondary	(85a)	×	N/A	× 0.01 =	0.00	(89)

Water heating

Water heating cost (electric, off-peak tariff)

On-peak fraction (Table 13, or Appendix F for electric CPSUs) 0.00 (90)

Off-peak fraction 1.0 - (90) = 1.00 (90a)

			Fuel price			
On-peak cost	(86a) × (90)	×	N/A	× 0.01 =	0.00	(91)
Off-peak cost	(86a) × (90a)	×	N/A	× 0.01 =	0.00	(91a)
Water heating cost (other fuel)	(86a)	×	1.63	× 0.01 =	264.75	(91b)
Pump and fan energy cost	(87)	×	7.12	× 0.01 =	12.03	(92)
Energy for lighting (calculated in Appendix L)	816.49	×	7.12	× 0.01 =	58.13	(93)
Additional standing charges (Table 12)					34.00	(94)

Renewable and energy-saving technologies (Appendices M and N)

PV

Energy produced or saved, kWh/year	0.00 (95)					
Cost of energy produced or saved, £/year	(95)	×	0.00	× 0.01 =	N/A	(95a)

Wind

Energy produced or saved, kWh/year	0.00 (95b1)					
Cost of energy produced or saved, £/year	(95b1)	×	0.00	× 0.01 =	N/A	(95b)

Micro CHP

Energy produced or saved, kWh/year	N/A	(95c1)					
Cost of energy produced or saved, £/year	(95c1)	×	N/A	× 0.01 =	N/A	(95c)
Energy consumed by the technology, kWh/year	N/A	(96)					
Cost of energy consumed, £/year	(96)	×	N/A	×0.01 =	N/A	(96a)

Special features (Appendix Q)

Energy produced or saved, kWh/year	N/A	(s1)				
Cost of energy produced or saved, £/year	(s1)	×	N/A	× 0.01 =	N/A	(s1a)
Energy consumed by the technology, kWh/year	N/A	(s2)				
Cost of energy consumed, £/year	(s2)	×	N/A	×0.01 =	N/A	(s2a)

Total energy cost (88)+(89)+(91)+(91a)+(91b)+(92)+(93)+(94)-(95a)-(95b)-(95c)+(96a)-(s1a)+(s2a) = 1454.91 (97)

11a. SAP rating - individual heating systems

Energy cost deflator (SAP 2005)		0.91	(98)
Energy cost factor (ECF)	{[(97) × (98)] - 30.0} ÷ {(5) + 45.0} =	8.45	(99)
SAP rating (Table 14)		9	(100)
SAP band		G	

12a. Carbon dioxide emissions rate for individual heating systems (including micro-CHP) and community heating without CHP

Individual heating system:		**Energy** kWh/year		**Emission factor** kg CO2/kWh		**Emissions** kgCO2/year	
Space heating main from box (85)		66625.03	×	0.194	=	12925.26	(101)
Space heating secondary from box (85a)		N/A	×	N/A	=	0.00	(102)
Energy for water heating from box (86a)		16242.56	×	0.194	=	3151.06	(103)
Energy for water heating	(51) or [(87b*) × 100 ÷ (104)] =	N/A	×	N/A	=	N/A	(106)
Space and water heating	[(101) + (102) + (103)] or [(105) + (106)] =					16076.31	(107)
Energy for water heating	(Type 1 fraction) × (87*) × 100 ÷ (104a) =	N/A	×	N/A	=	N/A	(106a)
Energy for water heating	(Type 2 fraction) × (87*) × 100 ÷ (104b) =	N/A	×	0.000	=	N/A	(106b)
Space and water heating	[(105a) + (106a) + (105b) + (106b)] =					16076.31	(107)
Electricity for pumps and fans from box (87) or (88*)		169.00	×	0.422	=	71.32	(108)
Energy for lighting from Appendix L		816.49	×	0.422	=	344.56	(109)
Energy produced or saved in dwelling (Appendices M and N)							
PV energy produced or saved	(95) or (95*)		×	N/A	=	N/A	(110)
Wind energy produced or saved	(95b1) or (95b1*)		×	N/A	=	N/A	(110b)
Micro-CHP energy produced or saved	(95c1) or (95c1*)		×	N/A	=	N/A	(110c)
Micro-CHP energy consumed	(96) or (96*)		×	N/A	=	0.00	(111)

Energy produced or saved in dwelling (Appendix Q)	(s1) or (s1*)	×	N/A	=	0.00	(s1a)
Energy consumed by the technology (Appendix Q)	(s2) or (s2*)	×	N/A	=	0.00	(s2a)
Total CO₂ kg/year	(107) + (108) + (109) - (110) + (111) - (s1a) + (s2a)			=	16492.19	(112)
Carbon dioxide emissions rate	(112) ÷ (5)			=	152.59	(113)
EI rating					7	
EI band					G	

13a. Primary energy, for individual heating systems (including micro-CHP) and community heating without CHP

Individual heating system:		**Energy** kWh/year		**Primary energy factor**		**Primary energy** (kWh/year)
Space heating main from box (85)		66625.03	×	1.150	=	76618.79
Space heating secondary from box (85a)		N/A	×	N/A	=	0.00
Energy for water heating from box (86a)		16242.56	×	1.150	=	18678.94
Energy for water heating	(87b*) × 100 ÷ (104) =	N/A	×	N/A	=	N/A
Space and water heating						95297.73
Energy for water heating	(Type 1 fraction) × (87*) × 100 ÷ (104a) =	N/A	×	N/A	=	N/A
Energy for water heating	(Type 2 fraction) × (87*) × 100 ÷ (104b) =	N/A	×	N/A	=	N/A
Space and water heating					=	95297.73
Electricity for pumps and fans from box (87) or (88*)		169.00	×	2.800	=	473.20
Energy for lighting from Appendix L		816.49	×	2.800	=	2286.16
Energy produced or saved in dwelling (Appendices M and N)						
PV energy produced or saved		(95) or (95*)	×	N/A	=	N/A
Wind energy produced or saved		(95b1) or (95b1*)	×	N/A	=	N/A
Micro-CHP energy produced or saved		(95c1) or (95c1*)	×	N/A	=	N/A
Micro-CHP energy consumed		(96) or (96*)	×	N/A	=	0.00
Energy produced or saved in dwelling (Appendix Q)		(s1) or (s1*)	×	N/A	=	0.00
Energy consumed by the above technology (Appendix Q)		(s2) or (s2*)	×	N/A	=	0.00
Primary energy kWh/year						98057.09
Primary energy kWh/m²/year						907.26

Space heating from CHP or recovered/geothermal heat, box (86*)		N/A	×	N/A	box (107*) =	N/A
Space heating from boilers	(87*) × 100 ÷ (109*) =	N/A	×	N/A	Table 12 =	-1.00
Electricity for pumps and fans, box (88*)		N/A	×	N/A	Table 12 =	N/A
Total PE associated with boilers, CHP or recovered/geothermal heat *If negative, enter "0" in box (115*)*					[(108*) + (110*) + ... + (114*)] =	-1.00
Energy for lighting from Appendix L		816.49	×	2.80	Table 12 =	2286.16
Energy produced or saved in dwelling (Appendix M)						
PV energy produced or saved	(95*)		×	N/A	Table 12 =	N/A
Wind energy produced or saved	(95b1*)		×	N/A	Table 12 =	N/A

NHER

SAP Worksheet: Design - Final

This Design submission has been carried out by an Authorised SAP Assessor. It has been prepared from plans and specifications and may not reflect the property as constructed.

Assessor Name	Mr James Bonell	**Assessor Number**	2608
Client	University of Nottingham		
Date Last Modified	26/08/2009		
Address	Phase 2a EOn House, Phase 2a University Park, University of Nottingham, NG7 2RD		

1. Overall dwelling dimensions

	Area (m²)			Average storey height (m)		Volume (m³)	
Ground Floor	52.80	(1a)	×	2.40	=	126.72	(1)
First Floor	55.28	(2a)	×	2.50	=	138.20	(2)

Total floor area (1a)+(2a)+(3a)+(4a)+(4b)+(4d)+(4f)+(4h) = 108.08 (5)

Dwelling volume (1)+(2)+(3)+(4)+(4c)+(4e)+(4g)+(4i) = 264.92 (6)

2. Ventilation rate

			m³ per hour	
Number of chimneys	0	× 40 =	0	(7)
Number of open flues	0	× 20 =	0	(8)
Number of intermittent fans or passive vents	0	× 10 =	0	(9)
Number of flueless gas fires	0	× 40 =	0	(9a)

Air changes per hour

Infiltration due to chimneys, flues and fans = (7)+(8)+(9)+(9a) = 0 ÷ box (6) = 0.00 (10)

If a pressurisation test has been carried out, proceed to box (19)

Number of storeys in the dwelling 2 (11)

Additional infiltration [(11) - 1] × 0.1 = 0.10 (12)

Structural infiltration: *0.25 for steel or timber frame or 0.35 for masonry construction* 0.35 (13)

If suspended wooden floor, *enter 0.2 (unsealed) or 0.1 (sealed)*, else enter 0 0.20 (14)

If no draught lobby, enter 0.05, else enter 0 0.05 (15)

Percentage of windows and doors draught stripped 79.00 (16)

Enter 100 in box (16) for new dwellings which are to comply with Building Regulations

Window infiltration 0.25 - [0.2 × (16) ÷ 100] = 0.09 (17)

Infiltration rate (10)+(12)+(13)+(14)+(15)+(17) = 0.79 (18)

If based on air permeability value, then [q_{50} ÷ 20] + (10) in box (19), otherwise (19) = (18) 0.79 (19)

Air permeability value applies if a pressurisation test has been done or the design air permeability is being used

Number of sides on which sheltered 1 (20)

(Enter 2 in box (20) for new dwellings where location is not shown)

BSI UKAS QUALITY MANAGEMENT 003

FS 25719

Submission Reference Number:

ND-NES-00002608-09082615235486

SAP © Crown copyright 2005

URN: EOn 002a rev B V: 1
Plan Assessor V: 4.2.28
SAP Worksheet (Version - 9.81)

Shelter factor	1 - [0.075 × (20)] =	0.93	(21)
Adjusted infiltration rate	(19) × (21) =	0.73	(22)
Calculate effective air change rate for the applicable case			
If balanced whole house mechanical ventilation system	air throughput (ach) =	N/A	(22a)
If balanced with heat recovery	efficiency in % allowing for in-use factor =	N/A	(22b)
a) If balanced whole house mechanical ventilation with heat recovery	(22) + (22a) × [1 – (22b) / 100] =	N/A	(23)
b) If balanced whole house mechanical ventilation without heat recovery	(22) + (22a) =	N/A	(23a)
c) If whole house extract ventilation or positive input ventilation from outside *if (22) < 0.25, then (23b) = 0.5; otherwise (23b) = 0.25 + (22)*		N/A	(23b)
d) If natural ventilation or whole house positive input ventilation from loft *if (22) ≥ 1, then (24) = (22); otherwise (24) = 0.5 + [$(22)^2$ × 0.5]*		0.77	(24)
Effective air change rate - enter (23) or (23a) or (23b) or (24) in box (25)		0.77	(25)

3. Heat losses and heat loss parameter

ELEMENT	Area (m²)		U - value		AXU (W/K)	
Windows *	24.47	×	1.59	=	38.95	(27)
Doors	6.65	×	3.00	=	19.95	(26)
Ground Floor	9.46	×	1.00	=	9.47	(28)
Ground Floor	43.34	×	0.68	=	29.51	(28)
Upper Floor	2.48	×	0.81	=	2.00	(31)
Walls	129.53	×	0.54	=	69.43	(29)
Walls	8.56	×	0.69	=	5.91	(29)
Roof	71.55	×	0.15	=	10.73	(30)
Roof	2.49	×	3.15	=	7.83	(30)
Total area of elements ΣA, m²	298.53	(32)				

* *for windows and rooflights, use effective window U-value calculated as given in paragraph 3.2*

Fabric heat loss, W/K	(26)+(27)+(27a)+(27b)+(28)+(29)+(29a)+(30)+(30a)+(31) =	193.78	(33)
Thermal bridges - Σ (lxΨ) calculated using Appendix K *if details of thermal bridging are not known calculate y× (32) [see Appendix K] and enter in box (34)*		149.27	(34)
Total fabric heat loss	(33)+(34) =	343.05	(35)
Ventilation heat loss	(25) × 0.33 × (6) =	67.17	(36)
Heat loss coefficient, W/K	(35)+(36) =	410.22	(37)
Heat loss parameter (HLP), W/m²K	(37) ÷ (5) =	3.80	(38)

4. Water heating energy requirement

	kWh/year	
Energy content of hot water used from Table 1 column (b)	2201.59	(39)
Distribution loss from Table 1 column (c) *If instantaneous water heating at point of use, enter "0" in boxes (40) to (45)* *For community heating use Table 1 (c) whether or not hot water tank is present*	388.52	(40)

Water storage loss:

a) If manufacturer's declared loss factor is known (kWh/day):		N/A	(41)
Temperature factor from Table 2b		N/A	(41a)
Energy lost from water storage, kWh/year	(41)×(41a)×365 =	N/A	(42)
b) If manufacturer's declared cylinder loss factor is not known:			
Cylinder volume (litres) including any solar storage within same cylinder *If community heating and no tank in dwelling, enter 110 litres in box (43)* *Otherwise, if no stored hot water (this includes instantaneous combi boilers), enter '0' in box (43)*		100.00	(43)
Hot water storage loss factor from Table 2 (kWh/litre/day) *If community heating and no tank in dwelling, use cylinder loss from Table 2 for 50 mm factory insulation in box (44)*		0.14	(44)
Volume factor from Table 2a		1.06	(44a)
Temperature factor from Table 2b		0.78	(44b)
Energy lost from water storage, kWh/year	(43)×(44)×(44a)×(44b)×365 =	4311.18	(45)
Enter (42) or (45) in box (46)		4311.18	(46)
If cylinder contains dedicated solar storage, box (47) = (46) × [(43) - (H11)] / (43), else (47) = (46)		4311.18	(47)
Primary circuit loss from Table 3		1220.00	(48)
Combi loss from Table 3a (enter "0" if no combi boiler)		0.00	(49)
Solar DHW input calculated using Appendix H (enter "0" if no solar collector)		0.00	(50)
Output from water heater, kWh/year	(39)+(40)+(47)+(48)+(49)-(50) =	8121.28	(51)
Heat gains from water heating *include (47) in calculation of (52) only if cylinder is in the dwelling or hot water is from community heating*	0.25 × [(39)+(49)]+0.8×[(40)+(47)+(48)] =	5286.15	(52)

5. Internal gains

		Watts	
Lights, appliances, cooking and metabolic (Table 5)		613.58	(53)
Reduction of internal gains due to low energy lighting (calculated in Appendix L)		22.27	(53a)
Additional gains from Table 5a		0.00	(53b)
Water heating	(52) ÷ 8.76 =	603.44	(54)
Total internal gains	(53) + (53b) + (54) - (53a) =	1194.75	(55)

6. Solar gains

	Access factor Table 6d		Area m²		Flux Table 6a		g Table 6b		FF Table 6c		Gains (W)	
North West	1.00	×	4.00	×	34.00	x 0.9 x	0.63	×	0.70	=	53.98	(56)
North East	1.00	×	10.81	×	34.00	x 0.9 x	0.63	×	0.70	=	145.88	(61)
South West	1.00	×	9.66	×	64.00	x 0.9 x	0.63	×	0.70	=	245.38	(63)

Total solar gains:	[(56) + ... + (64)] =	445.23	(65)

Note: for new dwellings where overshading is not known, the solar access factor is '0.77'

Total gains, W	(55) + (65) =	1639.99	(66)
Gain/loss ratio (GLR)	(66) ÷ (37) =	4.00	(67)
Utilisation factor (Table 7, using GLR in box (67))		0.99	(68)
Useful gains, W	(66) × (68) =	1621.81	(69)

7. Mean internal temperature

		° C	
Mean internal temperature of the living area (Table 8)		18.54	(70)
Temperature adjustment from Table 4e, where appropriate		0.60	(71)
Adjustment for gains *R is obtained from the 'responsiveness' column of Table 4a or Table 4d*	{[(69) ÷ (37)] - 4.0} × 0.2 ×R =	-0.01	(72)
Adjusted living room temperature	(70) + (71) + (72) =	19.13	(73)
Temperature difference between zones (Table 9)		1.41	(74)
Living area fraction (0 to 1.0)	living room area ÷ (5) =	0.14	(75)
Rest-of-house fraction	1 - (75) =	0.86	(76)
Mean internal temperature	(73) - [(74) × (76)] =	17.91	(77)

8. Degree days

Temperature rise from gains	(69) ÷ (37) =	3.95	(78)
Base temperature	(77) - (78) =	13.95	(79)
Degree-days, *use box (79) and Table 10*		1769.47	(80)

9. Space heating requirements

Space heating requirement (useful), kWh/year	0.024 × (80) × (37) =	17420.84	(81)

For range cooker boilers where efficiency is obtained from the Boiler Efficiency Database or manufacturer's declared value, multiply the result in box (81) by (1 - Φ_{case}/Φ_{water}) where Φ_{case} is the heat emission from the case of the range cooker at fullload (in kW); and Φ_{water} is the heat transferred to water at full load (in kW).Φ_{case} and Φ_{water} are obtained from the database record for the range cooker boiler or manufacturer's declared value.

9a. Energy requirements - individual heating systems, including micro-CHP

Note: when space and water heating is provided by community heating use the alternative worksheet 9b

Space heating:

Fraction of heat from secondary/supplementary system (*use value from Table 11, Table 12a or Appendix F)*		0.00	(82)
Efficiency of main heating system, %		50.00	(83)

(SEDBUK or from Table 4a or 4b, adjusted where appropriate by the amount shown in the 'efficiency adjustment' column of Table 4c)

Efficiency of secondary/supplementary heating system, % (use value from Table 4a or Appendix E)		0.00	(84)
Space heating fuel (main) requirement, kWh/year	[1- (82)] × (81) ×100 ÷ (83) =	34841.68	(85)

Space heating fuel (secondary), kWh/year	(82) × (81) ×100 ÷ (84) =	N/A	(85a)

Water heating:

Efficiency of water heater, %		50.00	(86)
(SEDBUK or from Table 4a or 4b, adjusted where appropriate by the amount shown in the 'efficiency adjustment' column of Table 4c)			
Energy required for water heating, kWh/year	(51) × 100 ÷ (86) =	16242.56	(86a)

Electricity for pumps and fans:	**kWh/year**	
each central heating pump, (Table 4f)	169.00	(87a)
each boiler with a fan-assisted flue (Table 4f)	0.00	(87b)
warm air heating system fans (Table 4f)	0.00	(87c)
mechanical ventilation -balanced, extract or positive input from outside (Table 4f)	0.00	(87d)
maintaining keep-hot facility for gas combi boiler (Table 4f)	0.00	(87e)
pump for solar water heating (Table 4f)	0.00	(87f)

Total electricity for the above equipment, kWh/year	(87a)+(87b)+(87c)+(87d)+(87e)+(87f) =	169.00	(87)

10a. Fuel costs - individual heating systems

	Fuel kWh/year		**Fuel price** (Table 12)		**Fuel cost** £/year	
Space heating - main system	(85)	×	1.63	×0.01 =	567.92	(88)
Space heating - secondary	(85a)	×	N/A	× 0.01 =	0.00	(89)

Water heating

Water heating cost (electric, off-peak tariff)

On-peak fraction (Table 13, or Appendix F for electric CPSUs)		0.00	(90)
Off-peak fraction	1.0 - (90) =	1.00	(90a)

			Fuel price			
On-peak cost	(86a) × (90)	×	N/A	× 0.01 =	0.00	(91)
Off-peak cost	(86a) × (90a)	×	N/A	× 0.01 =	0.00	(91a)
Water heating cost (other fuel)	(86a)	×	1.63	× 0.01 =	264.75	(91b)
Pump and fan energy cost	(87)	×	7.12	× 0.01 =	12.03	(92)
Energy for lighting (calculated in Appendix L)	816.49	×	7.12	× 0.01 =	58.13	(93)
Additional standing charges (Table 12)					34.00	(94)

Renewable and energy-saving technologies (Appendices M and N)

PV

Energy produced or saved, kWh/year	0.00	(95)				
Cost of energy produced or saved, £/year	(95)	×	0.00	× 0.01 =	N/A	(95a)

Wind

Energy produced or saved, kWh/year	0.00	(95b1)				
Cost of energy produced or saved, £/year	(95b1)	×	0.00	× 0.01 =	N/A	(95b)

Micro CHP

Energy produced or saved, kWh/year	N/A	(95c1)					
Cost of energy produced or saved, £/year	(95c1)	×	N/A	× 0.01 =	N/A	(95c)	
Energy consumed by the technology, kWh/year	N/A	(96)					
Cost of energy consumed, £/year	(96)	×	N/A	×0.01 =	N/A	(96a)	

Special features (Appendix Q)

Energy produced or saved, kWh/year	N/A	(s1)				
Cost of energy produced or saved, £/year	(s1)	×	N/A	× 0.01 =	N/A	(s1a)
Energy consumed by the technology, kWh/year	N/A	(s2)				
Cost of energy consumed, £/year	(s2)	×	N/A	×0.01 =	N/A	(s2a)

Total energy cost (88)+(89)+(91)+(91a)+(91b)+(92)+(93)+(94)-(95a)-(95b)-(95c)+(96a)-(s1a)+(s2a) = 936.84 (97)

11a. SAP rating - individual heating systems

Energy cost deflator (SAP 2005)		0.91	(98)
Energy cost factor (ECF)	{[(97) × (98)] - 30.0} ÷ {(5) + 45.0} =	5.37	(99)
SAP rating (Table 14)		31	(100)
SAP band		F	

12a. Carbon dioxide emissions rate for individual heating systems (including micro-CHP) and community heating without CHP

Individual heating system:		**Energy** kWh/year		**Emission factor** kg CO2/kWh		**Emissions** kgCO2/year	
Space heating main from box (85)		34841.68	×	0.194	=	6759.29	(101)
Space heating secondary from box (85a)		N/A	×	N/A	=	0.00	(102)
Energy for water heating from box (86a)		16242.56	×	0.194	=	3151.06	(103)
Energy for water heating	(51) or [(87b*) × 100 ÷ (104)] =	N/A	×	N/A	=	N/A	(106)
Space and water heating	[(101) + (102) + (103)] or [(105) + (106)] =					9910.34	(107)
Energy for water heating	(Type 1 fraction) × (87*) × 100 ÷ (104a) =	N/A	×	N/A	=	N/A	(106a)
Energy for water heating	(Type 2 fraction) × (87*) × 100 ÷ (104b) =	N/A	×	0.000	=	N/A	(106b)
Space and water heating	[(105a) + (106a) + (105b) + (106b)] =					9910.34	(107)
Electricity for pumps and fans from box (87) or (88*)		169.00	×	0.422	=	71.32	(108)
Energy for lighting from Appendix L		816.49	×	0.422	=	344.56	(109)
Energy produced or saved in dwelling (Appendices M and N)							
PV energy produced or saved	(95) or (95*)		×	N/A	=	N/A	(110)
Wind energy produced or saved	(95b1) or (95b1*)		×	N/A	=	N/A	(110b)
Micro-CHP energy produced or saved	(95c1) or (95c1*)		×	N/A	=	N/A	(110c)
Micro-CHP energy consumed	(96) or (96*)		×	N/A	=	0.00	(111)

Energy produced or saved in dwelling (Appendix Q)	(s1) or (s1*)	×	N/A	=	0.00	(s1a)
Energy consumed by the technology (Appendix Q)	(s2) or (s2*)	×	N/A	=	0.00	(s2a)
Total CO_2 kg/year	(107) + (108) + (109) - (110) + (111) - (s1a) + (s2a)			=	10326.22	(112)
Carbon dioxide emissions rate	(112) ÷ (5)			=	95.54	(113)
EI rating					26	
EI band					F	

13a. Primary energy, for individual heating systems (including micro-CHP) and community heating without CHP

Individual heating system:		**Energy** kWh/year		**Primary energy factor**		**Primary energy** (kWh/year)
Space heating main from box (85)		34841.68	×	1.150	=	40067.93
Space heating secondary from box (85a)		N/A	×	N/A	=	0.00
Energy for water heating from box (86a)		16242.56	×	1.150	=	18678.94
Energy for water heating	(87b*) × 100 ÷ (104) =	N/A	×	N/A	=	N/A
Space and water heating						58746.87
Energy for water heating	(Type 1 fraction) × (87*) × 100 ÷ (104a) =	N/A	×	N/A	=	N/A
Energy for water heating	(Type 2 fraction) × (87*) × 100 ÷ (104b) =	N/A	×	N/A	=	N/A
Space and water heating					=	58746.87
Electricity for pumps and fans from box	(87) or (88*)	169.00	×	2.800	=	473.20
Energy for lighting from Appendix L		816.49	×	2.800	=	2286.16
Energy produced or saved in dwelling (Appendices M and N)						
PV energy produced or saved	(95) or (95*)		×	N/A	=	N/A
Wind energy produced or saved	(95b1) or (95b1*)		×	N/A	=	N/A
Micro-CHP energy produced or saved	(95c1) or (95c1*)		×	N/A	=	N/A
Micro-CHP energy consumed	(96) or (96*)		×	N/A	=	0.00
Energy produced or saved in dwelling (Appendix Q)	(s1) or (s1*)		×	N/A	=	0.00
Energy consumed by the above technology (Appendix Q)	(s2) or (s2*)		×	N/A	=	0.00
Primary energy kWh/year						61506.23
Primary energy kWh/m^2/year						569.08

Space heating from CHP or recovered/geothermal heat, box (86*)	N/A	×	N/A	box (107*) =	N/A
Space heating from boilers (87*) × 100 ÷ (109*) =	N/A	×	N/A	Table 12 =	-1.00
Electricity for pumps and fans, box (88*)	N/A	×	N/A	Table 12 =	N/A
Total PE associated with boilers, CHP or recovered/geothermal heat *If negative, enter "0" in box (115*)*				[(108*) + (110*) + ... + (114*)] =	-1.00
Energy for lighting from Appendix L	816.49	×	2.80	Table 12 =	2286.16
Energy produced or saved in dwelling (Appendix M)					
PV energy produced or saved (95*)		×	N/A	Table 12 =	N/A
Wind energy produced or saved (95b1*)		×	N/A	Table 12 =	N/A

Appendix 3 - Excel Worksheets used for HLC Investigation

E.On House HLC Calculations Removing Natural Ventilation Infiltration - Coheating Test 23rd November 2010 - 2nd December 2011

Without MVHR	**SAP Calc. Ref**	**23/11/2010**	**24/11/2010**	**25/11/2010**	**26/11/2010**	**27/11/2010**	**28/11/2010**	**Mean**
Adjusted Infiltration Rate	(21)	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Wind Speed m/s	(22)	1.462	1.207	2.977	0.447	2.870	0.541	1.58
Wind Factor	(22a)	0.37	0.30	0.74	0.11	0.72	0.14	0.40
Effective Infiltration Rate	(22b)	0.13	0.11	0.27	0.04	0.26	0.05	0.14
Fabric Heat Loss W/K	(33)	158.23	158.23	158.23	158.23	158.23	158.23	158.23
Thermal Bridges W/K	(36)	34.39	34.39	34.39	34.39	34.39	34.39	34.39
Total Fabric Heat Loss W/K	(37)	192.62	192.62	192.62	192.62	192.62	192.62	192.62
Total Fabric Heat Loss (W/K)/m^2		1.79	1.79	1.79	1.79	1.79	1.79	1.79
Ventilation Heat Loss W/K	(38)	11.67	9.63	23.76	3.57	22.90	4.32	12.64
Ventilation Heat Loss (W/K)/m^2		0.11	0.09	0.22	0.03	0.21	0.04	0.12
HTL (HLC) W/K	(39)	206.07	204.04	218.17	197.97	217.31	198.72	205.26
HLP W/K m^2	(40)	1.91	1.89	2.02	1.84	2.02	1.84	1.92

With MVHR Measured Efficiency 81%	**SAP Calc. Ref**	**30/11 AM**	**30/11 PM**	**01/12 AM**	**01/12 PM**	**02/12 AM**	**02/12 PM**	**Mean**
Adjusted Infiltration Rate	(21)	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Wind Speed m/s	(22)	2.65	2.42	2.18	3.19	3.08	1.43	2.49
Wind Factor	(22a)	0.66	0.60	0.55	0.80	0.77	0.36	0.62
Effective Infiltration Rate	(22b)	0.24	0.22	0.20	0.29	0.28	0.13	0.23
MVHR Ventilation Rate	(24a)	0.40	0.38	0.36	0.45	0.44	0.29	0.38
Fabric Heat Loss W/K	(33)	158.23	158.23	158.23	158.23	158.23	158.23	158.23
Thermal Bridges W/K	(36)	34.39	34.39	34.39	34.39	34.39	34.39	34.39
Total Fabric Heat Loss W/K	(37)	192.62	192.62	192.62	192.62	192.62	192.62	192.62
Total Fabric Heat Loss (W/K)/m^2		1.79	1.79	1.79	1.79	1.79	1.79	1.79
Ventilation Heat Loss W/K	(38)	34.74	32.89	31.00	39.02	38.17	24.97	33.46
Ventilation Heat Loss (W/K)/m^2		0.32	0.31	0.29	0.36	0.35	0.23	0.31
HTL (HLC) W/K	(39)	229.15	227.29	225.40	233.43	232.57	219.37	226.08
HLP W/K m^2	(40)	2.13	2.11	2.09	2.17	2.16	2.03	2.11

With MVHR Optimum 90%	**SAP Calc. Ref**	**30/11 AM**	**30/11 PM**	**01/12 AM**	**01/12 PM**	**02/12 AM**	**02/12 PM**	**Mean**
Adjusted Infiltration Rate	(21)	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Wind Speed m/s	(22)	2.65	2.42	2.18	3.19	3.08	1.43	2.49
Wind Factor	(22a)	0.66	0.60	0.55	0.80	0.77	0.36	0.62
Effective Infiltration Rate	(22b)	0.24	0.22	0.20	0.29	0.28	0.13	0.23
MVHR Ventilation Rate	(24a)	0.36	0.34	0.32	0.41	0.40	0.25	0.34
Fabric Heat Loss W/K	(33)	158.23	158.23	158.23	158.23	158.23	158.23	158.23
Thermal Bridges W/K	(36)	34.39	34.39	34.39	34.39	34.39	34.39	34.39
Total Fabric Heat Loss W/K	(37)	192.62	192.62	192.62	192.62	192.62	192.62	192.62
Total Fabric Heat Loss (W/K)/m^2		1.79	1.79	1.79	1.79	1.79	1.79	1.79
Ventilation Heat Loss W/K	(38)	31.34	29.49	27.59	35.62	34.77	21.56	30.06
Ventilation Heat Loss (W/K)/m^2		0.29	0.27	0.26	0.33	0.32	0.20	0.28
HTL (HLC) W/K	(39)	225.75	223.89	222.00	230.03	229.17	215.97	222.68
HLP W/K m^2	(40)	2.09	2.08	2.06	2.13	2.13	2.00	2.08
HTL (HLC) W/K	(39)	225.75	223.89	222.00	230.03	229.17	215.97	222.68
HLP W/K m2	(40)	2.09	2.08	2.06	2.13	2.13	2.00	2.08

E.On House HLC Calculations Removing Natural Ventilation Infiltration - Coheating Test 26th March 2011 - 31st March 2011

Without MVHR	**SAP Calc. Ref**	**26/03/2011**	**27/03/2011**	**28/03/2011**	**Mean**
Adjusted Infiltration Rate	(21)	0.20	0.20	0.20	0.20
Wind Speed m/s	(22)	2.503	1.064	0.465	1.34
Wind Factor	(22a)	0.63	0.27	0.12	0.34
Effective Infiltration Rate	(22b)	0.13	0.05	0.02	0.07
Fabric Heat Loss W/K	(33)	132.77	132.77	132.77	132.77
Thermal Bridges W/K	(36)	34.39	34.39	34.39	34.39
Total Fabric Heat Loss W/K	(37)	167.16	167.16	167.16	167.16
Total Fabric Heat Loss (W/K)/m^2		1.55	1.55	1.55	1.55
Ventilation Heat Loss W/K	(38)	11.00	4.67	2.04	5.91
Ventilation Heat Loss (W/K)/m^2		0.10	0.04	0.02	0.05
HTL (HLC) W/K	(39)	179.71	173.39	170.75	173.07
HLP W/K m^2	(40)	1.67	1.61	1.58	1.62

With MVHR Measured Efficiency 76%	**SAP Calc. Ref**	**29/03/2011**	**30/03/2011**	**31/03/2011**	**Mean**
Adjusted Infiltration Rate	(21)	0.20	0.20	0.20	0.20
Wind Speed m/s	(22)	0.28	0.70	2.17	1.05
Wind Factor	(22a)	0.07	0.18	0.54	0.26
Effective Infiltration Rate	(22b)	0.01	0.04	0.11	0.05
MVHR Ventilation Rate	(24a)	0.19	0.21	0.29	0.23
Fabric Heat Loss W/K	(33)	132.77	132.77	132.77	132.77
Thermal Bridges W/K	(36)	34.39	34.39	34.39	34.39
Total Fabric Heat Loss W/K	(37)	167.16	167.16	167.16	167.16
Total Fabric Heat Loss (W/K)/m^2		1.55	1.55	1.55	1.55
Ventilation Heat Loss W/K	(38)	16.68	18.52	24.97	20.06
Ventilation Heat Loss (W/K)/m^2		0.15	0.17	0.23	0.19
HTL (HLC) W/K	(39)	185.39	187.23	193.68	187.22
HLP W/K m^2	(40)	1.72	1.74	1.80	1.75

With MVHR Optimum Efficiency 90%	**SAP Calc. Ref**	**03/04/2011**	**04/04/2011**	**05/04/2011**	**Mean**
Adjusted Infiltration Rate	(21)	0.20	0.20	0.20	0.20
Wind Speed m/s	(22)	0.69	1.67	2.19	1.52
Wind Factor	(22a)	0.17	0.42	0.55	0.38
Effective Infiltration Rate	(22b)	0.03	0.08	0.11	0.08
MVHR Ventilation Rate	(24a)	0.15	0.20	0.23	0.19
Fabric Heat Loss W/K	(33)	132.77	132.77	132.77	132.77
Thermal Bridges W/K	(36)	34.39	34.39	34.39	34.39
Total Fabric Heat Loss W/K	(37)	167.16	167.16	167.16	167.16
Total Fabric Heat Loss (W/K)/m^2		1.55	1.55	1.55	1.55
Ventilation Heat Loss W/K	(38)	13.21	17.51	19.81	16.84
Ventilation Heat Loss (W/K)/m^2		0.12	0.16	0.18	0.16
HTL (HLC) W/K	(39)	181.92	186.22	188.52	184.00
HLP W/K m^2	(40)	1.69	1.73	1.75	1.72

E.On House HLC Calculations Removing Natural Ventilation Infiltration - Coheating Test 22nd February 2011 - 27th February 2011

Without MVHR - 25°C ΔT	SAP Calc. Ref	16/02/2011	17/02/2011	18/02/2011	19/02/2011	20/02/2011	21/02/2011	Mean
Adjusted Infiltration Rate	(21)	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Wind Speed m/s	(22)	1.322	1.768	2.544	2.496	4.812	2.918	2.64
Wind Factor	(22a)	0.33	0.44	0.64	0.62	1.20	0.73	0.66
Effective Infiltration Rate	(22b)	0.07	0.09	0.13	0.13	0.24	0.15	0.13
Fabric Heat Loss W/K	(33)	158.23	158.23	158.23	158.23	158.23	158.23	158.23
Thermal Bridges W/K	(36)	34.39	34.39	34.39	34.39	34.39	34.39	34.39
Total Fabric Heat Loss W/K	(37)	192.62	192.62	192.62	192.62	192.62	192.62	192.62
Total Fabric Heat Loss (W/K)/m^2		1.79	1.79	1.79	1.79	1.79	1.79	1.79
Ventilation Heat Loss W/K	(38)	5.81	7.77	11.18	10.97	21.14	12.82	11.61
Ventilation Heat Loss (W/K)/m^2		0.05	0.07	0.10	0.10	0.20	0.12	0.11
HTL (HLC) W/K	(39)	200.21	202.18	205.58	205.37	215.55	207.23	204.23
HLP W/K m^2	(40)	1.86	1.88	1.91	1.90	2.00	1.92	1.91

Without MVHR - 35°C ΔT	SAP Calc. Ref	22/02/2011	23/02/2011	24/02/2011	25/02/2011	26/02/2011	27/02/2011	Mean
Adjusted Infiltration Rate	(21)	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Wind Speed m/s	(22)	0.240	5.740	1.669	1.721	3.253	3.165	2.63
Wind Factor	(22a)	0.06	1.43	0.42	0.43	0.81	0.79	0.66
Effective Infiltration Rate	(22b)	0.01	0.29	0.08	0.09	0.16	0.16	0.13
Fabric Heat Loss W/K	(33)	158.23	158.23	158.23	158.23	158.23	158.23	158.23
Thermal Bridges W/K	(36)	34.39	34.39	34.39	34.39	34.39	34.39	34.39
Total Fabric Heat Loss W/K	(37)	192.62	192.62	192.62	192.62	192.62	192.62	192.62
Total Fabric Heat Loss (W/K)/m^2		1.79	1.79	1.79	1.79	1.79	1.79	1.79
Ventilation Heat Loss W/K	(38)	1.06	25.22	7.33	7.56	14.29	13.91	11.56
Ventilation Heat Loss (W/K)/m^2		0.01	0.23	0.07	0.07	0.13	0.13	0.11
HTL (HLC) W/K	(39)	195.46	219.63	201.74	201.97	208.70	208.32	204.18
HLP W/K m^2	(40)	1.81	2.04	1.87	1.87	1.94	1.93	1.91

E.On House HLC Calculations Removing Natural Ventilation Infiltration - Coheating Test 23rd March 2012 - 5th April 2012

Without MVHR	SAP Calc. Ref	23/03/2012	24/03/2012	25/03/2012	26/03/2012	27/03/2012	28/03/2012	29/03/2012	30/03/2012	31/03/2012	01/04/2012	02/04/2012	03/04/2012	04/04/2012	05/04/2012	Mean
Adjusted Infiltration Rate	(21)	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Wind Speed m/s	(22)	1.837	1.791	1.872	1.238	0.849	0.888	1.269	1.088	3.693	1.234	0.607	2.231	4.273	4.494	3.67
Wind Factor	(22a)	0.46	0.45	0.47	0.31	0.21	0.22	0.32	0.27	0.92	0.31	0.15	0.56	1.07	1.12	0.92
Effective Infiltration Rate	(22b)	0.09	0.09	0.09	0.06	0.04	0.04	0.06	0.05	0.19	0.06	0.03	0.11	0.22	0.23	0.18
Fabric Heat Loss W/K	(33)	132.77	132.77	132.77	132.77	132.77	132.77	132.77	132.77	132.77	132.77	132.77	132.77	132.77	132.77	132.77
Thermal Bridges W/K	(36)	34.39	34.39	34.39	34.39	34.39	34.39	34.39	34.39	34.39	34.39	34.39	34.39	34.39	34.39	34.39
Total Fabric Heat Loss W/K	(37)	167.16	167.16	167.16	167.16	167.16	167.16	167.16	167.16	167.16	167.16	167.16	167.16	167.16	167.16	167.16
Total Fabric Heat Loss (W/K)/m^2		1.55	1.55	1.55	1.55	1.55	1.55	1.55	1.55	1.55	1.55	1.55	1.55	1.55	1.55	1.55
Ventilation Heat Loss W/K	(38)	8.07	7.87	8.23	5.44	3.73	3.90	5.57	4.78	16.23	5.42	2.67	9.80	18.78	19.75	16.11
Ventilation Heat Loss (W/K)/m^2		0.07	0.07	0.08	0.05	0.03	0.04	0.05	0.04	0.15	0.05	0.02	0.09	0.17	0.18	0.15
HTL (HLC) W/K	(39)	176.78	176.58	176.94	174.15	172.44	172.61	174.28	173.49	184.94	174.13	171.38	178.51	187.49	188.46	177.30
HLP W/K m^2	(40)	1.64	1.64	1.64	1.62	1.60	1.60	1.62	1.61	1.72	1.62	1.59	1.66	1.74	1.75	1.71

Tarmac House HLC Calculations Removing Natural Ventilation Infiltration - Coheating Test 9th December 2010 - 22nd December 2010

Without MVHR	**SAP Calc. Ref**	**09/12/2010**	**10/12/2010**	**11/12/2010**	**12/12/2010**	**13/12/2010**	**14/12/2010**	**15/12/2010**	**Mean**
Adjusted Infiltration Rate	(21)	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Wind Speed m/s	(22)	1.24	1.01	1.28	1.96	1.40	1.80	0.62	1.35
Wind Factor	(22a)	0.31	0.25	0.32	0.49	0.35	0.45	0.15	0.34
Effective Infiltration Rate	(22b)	0.03	0.02	0.03	0.04	0.03	0.04	0.01	0.03
Fabric Heat Loss W/K	(33)	53.14	53.14	53.14	53.14	53.14	53.14	53.14	53.14
Thermal Bridges W/K	(36)	14.90	14.90	14.90	14.90	14.90	14.90	14.90	14.90
Total Fabric Heat Loss W/K	(37)	68.04	68.04	68.04	68.04	68.04	68.04	68.04	68.04
Total Fabric Heat Loss (W/K)/m^2		0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
Ventilation Heat Loss W/K	(38)	1.88	1.53	1.94	2.97	2.13	2.73	0.93	2.04
Ventilation Heat Loss (W/K)/m^2		0.02	0.02	0.02	0.03	0.02	0.03	0.01	0.02
HTL (HLC) W/K	(39)	70.67	70.32	70.72	71.76	70.91	71.51	69.72	70.08
HLP W/K m^2	(40)	0.77	0.77	0.77	0.79	0.78	0.78	0.76	0.78

With MVHR	**SAP Calc. Ref**	**18/12/2010**	**19/12/2010**	**20/12/2010**	**21/12/2010**	**22/12/2010**	**Mean**
Adjusted Infiltration Rate	(21)	0.09	0.09	0.09	0.09	0.09	0.09
Wind Speed m/s	(22)	2.46	1.49	1.11	1.08	3.02	1.83
Wind Factor	(22a)	0.62	0.37	0.28	0.27	0.75	0.46
Effective Infiltration Rate	(22b)	0.06	0.03	0.02	0.02	0.07	0.04
MVHR Ventilation Rate	(24a)	0.17	0.15	0.14	0.14	0.19	0.16
Fabric Heat Loss W/K	(33)	53.14	53.14	53.14	53.14	53.14	53.14
Thermal Bridges W/K	(36)	14.90	14.90	14.90	14.90	14.90	14.90
Total Fabric Heat Loss W/K	(37)	68.04	68.04	68.04	68.04	68.04	68.04
Total Fabric Heat Loss (W/K)/m^2		0.74	0.74	0.74	0.74	0.74	0.74
Ventilation Heat Loss W/K	(38)	12.33	10.77	10.16	10.11	13.22	11.32
Ventilation Heat Loss (W/K)/m^2		0.13	0.12	0.11	0.11	0.14	0.12
HTL (HLC) W/K	(39)	81.11	79.56	78.94	78.89	82.00	79.36

SAP Worksheet

House :

Engineer :

1. Overall dwelling dimensions

	Area m2	Av Room height m	=	Volume m3	SAP Calc Ref
Ground floor					1
First floor					2
Second floor					3
Third and others					4
Total floor area					5
Dwelling Volume					6

2. Ventilation Rate

					m3/hr	
No of chimneys		x	40	=		7
No of open flues		x	20	=		8
No of intermittent fans or passive vents		x	10	=		9
Number of flueless fires		x	10	=		9a
					ACH	
infiltration due to above				=		10

if pressurization test done then go to #

Addition infiltration from above			12
Percentage of doors and windows draught-stripped			16
Window infiltration			17
Infiltration rate			18
# Pressurisation test	L50 =		19
Number of sides on which dwelling is sheltered			20
Shelter factor			21
Adjusted Infiltration Rate			22
Wind Factor			
Effective Infiltration Rate			

Calculate effective air change rate for the applicable case

If balanced whole house mechanical ventilation system			22a
If balanced with heat recovery	Efficiency in % allowing for in-use factor		22b
a) If balanced mechanical ventilation with heat recovery (MVHR)			23
b) If balanced mechanical ventilation without heat recovery (MV)			23a
c) If whole house extract ventilation or positive input ventilation from outside			23b
d) If natural ventilation or whole house positive ventilation from loft			24

Effective air change rate **Background Infiltration**

3 Heat losses and Heat parameter

ELEMENT		AREA m2	U-value W/m2/K	AU W/K	
Doors (glazed)					26
Doors (solid)	x0.9				
Windows double glazed #1					27a
Windows double glazed #2	x0.9				27b
Rooflights	x0.9				27c
Ground floor 1					28a
Ground Floor 2					28b
Upper Floor					31
Walls type 1					29a
Walls type 2					29b
Walls type 3					29c
Walls type 4					
Roof type 1					30a
Roof type2					30b
other					
Total Surface Area					32
Glazing Area					
Glazing/Floor Area Ratio (%)					
Fabric Heat Loss					33
Thermal Bridges					34
Total Fabric Heat Loss					35
Ventilation loss					36
Heat Loss Coefficient					37
Heat loss parameter HLP					38

Appendix 4 - Equipment Specifications

Appendix 5 - Coheating Test Summary Data

E.On House Coheating Test Data - November 2010 - No MVHR in Operation

	Temperature					POWER & ENERGY												
Date	Mean internal Temp (°C)			Mean External Temp (°C)	Temperature Difference (K)	Zone 1 (Lower Floor)					Zone 2 (Upper Floor)					TOTAL (W)	Mean Solar (W/m^2)	Total (W) Solar Corrected (multiple regression)
	Lower Floor	Upper Floor	Combined			Living (Wh)	Dining (Wh)	Kitchen (Wh)	Total (Wh)	Total (W)	B1 (Wh)	B2 (Wh)	B3 (Wh)	Total (Wh)	Total (W)			
23/11/10	22.61	21.75	22.18	4.69	17.49	23677	13103	22780	59560	2482	12249	7157	7078	26484	1104	3585	17.01	3856.41
24/11/10	22.25	21.43	21.84	1.71	20.13	26370	12866	22884	62120	2588	13840	8483	8983	31306	1304	3893	18.42	4186.48
25/11/10	22.06	21.31	21.69	0.32	21.37	28125	13991	23171	65287	2720	14747	9272	9666	33685	1404	4124	16.72	4390.45
26/11/10	22.32	21.40	21.86	-0.49	22.35	29434	13312	25964	68710	2863	15874	9768	10579	36221	1509	4372	13.13	4581.50
27/11/10	22.23	21.20	21.72	-1.56	23.28	30114	17070	28790	75974	3166	16521	9665	10214	36400	1517	4682	13.86	4903.26
28/11/10	21.96	21.90	21.93	-4.04	25.97	32662	19861	31537	84060	3503	18019	11026	11425	40470	1686	5189	15.50	5435.91

E.On House Coheating Test Data - November 2010 - MVHR in Operation

	Temperature					POWER & ENERGY												
Date	Mean internal Temp (°C)			Mean External Temp (°C)	Temperature Difference (K)	Zone 1 (Lower Floor)					Zone 2 (Upper Floor)					TOTAL (W)	Mean Solar (W/m^2)	Total (W) Solar Corrected (multiple regression)
	Lower Floor	Upper Floor	Combined			Living (Wh)	Dining (Wh)	Kitchen (Wh)	Total (Wh)	Total (W)	B1 (Wh)	B2 (Wh)	B3 (Wh)	Total (Wh)	Total (W)			
30/11/10	22.37	21.31	21.84	1.50	20.34	30933	18112	30178	79223	3301	17372	10784	10691	38847	1619	4920	18.0497685	4943.71
01/12/10	22.12	21.25	21.68	0.54	21.14	31778	18625	31238	81641	3402	14345	14564	10841	39750	1656	5058	31.8287037	5100.50
02/12/10	22.33	21.11	21.72	-0.10	21.82	33978	19892	32516	86386	3599	17841	11149	9607	38597	1608	5208	18.8310185	5232.80

E.On House Coheating Test Data - March 2011 - No MVHR in Operation

	Temperature					POWER & ENERGY												
Date	Mean internal Temp (°C)			Mean External Temp (°C)	Temperature Difference (K)	Zone 1 (Lower Floor)					Zone 2 (Upper Floor)					TOTAL (W)	Mean Solar (W/m^2)	Total (W) Solar Corrected (multiple regression)
	Lower Floor	Upper Floor	Combined			Living (Wh)	Dining (Wh)	Kitchen (Wh)	Total (Wh)	Total (W)	B1 (Wh)	B2 (Wh)	B3 (Wh)	Total (Wh)	Total (W)			
25/03/11	24.56	24.65	24.62	8.45	16.17	9788	6207	11861	27856	2321	7075	7208	2415	16698	1392	3713	109.23	3932.25
26/03/11	25.10	25.04	25.07	7.38	17.69	14309	10501	20819	45629	1901	11454	12340	4643	28437	1185	3086	29.26	3144.86
27/03/11	25.21	25.14	25.17	7.75	14.78	12784	9233	18705	40722	1697	10051	10604	3885	24540	1023	2719	68.94	2857.74
28/03/11	25.41	25.30	25.34	9.28	16.06	11495	4682	14936	31113	1296	9146	7392	2592	19130	797	2093	123.07	2340.67

E.On House Coheating Test Data - March 2011 - Unadjusted MVHR in Operation

	Temperature					POWER & ENERGY												
Date	Mean internal Temp (°C)			Mean External Temp (°C)	Temperature Difference (K)	Zone 1 (Lower Floor)					Zone 2 (Upper Floor)					TOTAL (W)	Mean Solar (W/m^2)	Total (W) Solar Corrected (multiple regression)
	Lower Floor	Upper Floor	Combined			Living (Wh)	Dining (Wh)	Kitchen (Wh)	Total (Wh)	Total (W)	B1 (Wh)	B2 (Wh)	B3 (Wh)	Total (Wh)	Total (W)			
29/03/11	25.27	25.30	25.28	11.08	14.20	5177	2883	7504	15564	1297	4440	5177	2269	11886	991	2288	48.09	2789.94
30/03/11	25.23	25.28	25.26	11.36	13.90	10234	6103	15465	31802	1325	8832	11020	4812	24664	1028	2353	41.74	2788.89
31/03/11	25.50	25.51	25.51	14.11	11.40	8153	4126	11366	23645	985	7356	7268	2917	17541	731	1716	101.85	2780.27

E.On House Coheating Test Data - March 2011 - Adjusted MVHR in Operation

	Temperature					POWER & ENERGY												
Date	Mean internal Temp (°C)			Mean External Temp (°C)	Temperature Difference (K)	Zone 1 (Lower Floor)					Zone 2 (Upper Floor)					TOTAL (W)	Mean Solar (W/m^2)	Total (W) Solar Corrected (multiple regression)
	Lower Floor	Upper Floor	Combined			Living (Wh)	Dining (Wh)	Kitchen (Wh)	Total (Wh)	Total (W)	B1 (Wh)	B2 (Wh)	B3 (Wh)	Total (Wh)	Total (W)			
01/04/11	25.45	25.69	25.57	16.01	9.56	3994	2731	5660	12385	1032	3674	4547	1529	9750	813	1845	54.05	2233.26
02/04/11	25.47	25.69	25.58	14.36	11.22	8173	4368	10540	23081	962	7265	7452	2601	17318	722	1683	84.76	2292.77
03/04/11	25.26	25.43	25.34	10.69	14.66	10395	5363	13331	29089	1212	8617	9238	3684	21539	897	2110	96.22	2801.40
04/04/11	25.02	25.25	25.14	9.47	15.67	10847	6921	15149	32917	1372	9288	12141	4842	26271	1095	2466	70.11	2970.33
05/04/11	25.16	25.44	25.30	13.67	11.64	8017	5907	12140	26064	1086	7223	9873	3511	20607	859	1945	48.60	2294.14

E.On House Coheating Test Data - February 2011 - 25°C Internal Temperature

	Temperature					POWER & ENERGY												
Date	Mean internal Temp (°C)			Mean External Temp (°C)	Temperature Difference (K)	Zone 1 (Lower Floor)					Zone 2 (Upper Floor)					TOTAL (W)	Mean Solar (W/m^2)	Total (W) Solar Corrected (multiple regression)
	Lower Floor	Upper Floor	Combined			Living (Wh)	Dining (Wh)	Kitc hen (Wh)	Total (Wh)	Total (W)	B1 (Wh)	B2 (Wh)	B3 (Wh)	Total (Wh)	Total (W)			
16/02/11	20.96	23.19	22.08	6.45	15.63	12922	9369	12112	34403	1433	13334	6239	9425	28998	1208	2641.71	32.24	2686.72
17/02/11	20.73	23.02	21.87	6.02	15.86	11747	10056	13190	34993	1458	13695	6474	9836	30005	1250	2708.25	29.42	2749.32
18/02/11	20.55	22.98	21.77	5.15	16.62	15927	10665	12088	38680	1612	14303	7108	10885	32296	1346	2957.33	12.08	2974.19
19/02/11	20.49	22.80	21.64	4.64	17.00	19595	11179	10339	41113	1713	15114	7711	12074	34899	1454	3167.17	12.88	3185.15
20/02/11	20.49	22.81	21.65	5.01	16.64	19807	11034	10369	41210	1717	14610	7615	11773	33998	1417	3133.67	13.91	3153.08
21/02/11	20.44	22.56	21.50	4.28	17.22	20055	11505	10750	42310	1763	15102	7869	12487	35458	1477	3240.33	15.03	3261.32

E.On House Coheating Test Data - February 2011 - 35°C Internal Temperature

	Temperature					POWER & ENERGY												
Date	Mean internal Temp (°C)			Mean External Temp (°C)	Temperature Difference (K)	Zone 1 (Lower Floor)					Zone 2 (Upper Floor)					TOTAL (W)	Mean Solar (W/m^2)	Total (W) Solar Corrected (multiple regression)
	Lower Floor	Upper Floor	Combined			Living (Wh)	Dining (Wh)	Kitc hen (Wh)	Total (Wh)	Total (W)	B1 (Wh)	B2 (Wh)	B3 (Wh)	Total (Wh)	Total (W)			
24/02/11	29.50	32.84	31.17	11.16	20.02	17901	21976	23941	63818	2659	21156	12802	15931	49889	2079	4738	52.14	4774.71
25/02/11	29.69	32.89	31.29	11.42	19.87	17536	21713	22536	61785	2574	19888	14000	17676	51564	2149	4723	26.59	4741.71
26/02/11	29.66	32.87	31.30	9.08	22.22	18080	21322	22330	61732	2572	19919	13826	18376	52121	2172	4744	36.07	4769.41
27/02/11	29.34	32.51	30.92	5.84	25.09	21722	23330	24615	69667	2903	22340	15800	22219	60359	2515	5418	29.96	5438.97

E.On House Coheating Test Data - March/April 2012

	Temperature					POWER & ENERGY												
Date	Mean internal Temp (°C)			Mean External Temp (°C)	Temperature Difference (K)	Zone 1 (Lower Floor)					Zone 2 (Upper Floor)					TOTAL (W)	Mean Solar (W/m^2)	Total (W) Solar Corrected (multiple regression)
23/03/12	25.45	26.07	25.76	10.38	15.07	14726	7917	15539	38182	1591	13503	5226	4650	23379	974	2565	75.44	3170.11
24/03/12	26.06	26.88	26.47	9.92	16.14	14805	7556	14960	37321	1555	13206	4882	4228	22316	930	2485	82.72	3148.32
25/03/12	26.22	27.13	26.67	9.47	16.75	13882	6051	12809	32742	1364	12586	3698	3384	19668	820	2294	121.57	3269.08
26/03/12	26.31	27.24	26.77	10.71	15.60	14407	5791	12620	32818	1367	12248	3165	2927	18340	764	2187	124.94	3188.95
27/03/12	26.40	27.36	26.88	11.96	14.45	13442	5028	11150	29620	1234	11222	2699	2505	16426	684	2054	121.50	3028.14
28/03/12	26.43	27.35	26.89	13.40	13.03	12552	4611	10515	27678	1153	10426	2380	2348	15154	631	1917	130.43	2963.47
31/03/12	26.03	26.54	26.28	6.66	19.37	14487	8962	14358	37807	1575	13116	6313	4547	23976	999	2574	45.09	2646.89
01/04/12	26.05	26.66	26.35	6.86	19.19	16285	8559	15334	40178	1674	14588	5679	4011	24278	1012	2673	121.19	2868.20
02/04/12	25.94	26.41	26.41	7.17	18.77	15589	10208	15903	41700	1738	13892	7240	4987	26119	1088	2749	60.37	2846.29
03/04/12	25.96	26.37	26.17	7.30	18.66	14965	10925	16195	42085	1754	13516	7860	5502	26878	1120	2765	69.59	2877.17
04/04/12	25.71	26.14	25.92	4.38	21.32	19413	14034	19728	53175	2216	18199	9986	6777	34962	1457	3672	46.87	3747.84
05/04/12	25.73	26.18	25.95	4.56	21.17	19603	13155	19484	52242	2177	18205	9211	6412	33828	1410	3265	78.78	3391.88

Tarmac House Coheating Test Data -December 2010 - No MVHR in Operation

	Temperature					POWER & ENERGY												
Date	Mean internal Temp (°C)			Mean External Temp (°C)	Temperature Difference (K)	Zone 1 (Lower Floor)					Zone 2 (Upper Floor)					TOTAL (W)	Mean Solar (W/m^2)	Total (W) Solar Corrected (multiple regression)
	Lower Floor	Upper Floor	Combined			Living (Wh)	Dining (Wh)	Kitc hen (Wh)	Total (Wh)	Total (W)	B1 (Wh)	B2 (Wh)	B3 (Wh)	Total (Wh)	Total (W)			
09/12/10	23.28	22.14	22.71	1.52	21.19	4008	11113	10388	25509	1063	10580	7310	5700	23590	983	2046	12.84	2045.79
10/12/10	23.37	22.70	23.03	6.41	16.62	3820	9046	9064	21930	914	7999	9163	3646	20808	867	1781	9.19	1780.75
11/12/10	23.36	22.86	23.11	6.30	16.81	3332	8327	7786	19445	810	7259	7547	2781	17587	733	1543	12.7	1543.00
12/12/10	23.36	22.78	23.07	3.40	19.67	3278	8158	7548	18984	791	8345	8717	3280	20342	848	1639	13.34	1638.58
13/12/10	23.21	22.76	22.99	4.47	18.52	10345	8097	4938	23380	974	7925	8368	3045	19338	806	1780	12.62	1779.92
14/12/10	23.21	22.78	22.99	4.54	18.45	12208	7643	1763	21614	901	7614	7943	2770	18327	764	1664	3.63	1664.21
15/12/10	23.31	22.78	23.04	5.40	17.64	11542	7725	2569	21836	910	7586	7937	2800	18323	763	1673	12.22	1673.29

Tarmac House Coheating Test Data -December 2010 - MVHR in Operation

	Temperature					POWER & ENERGY												
Date	Mean internal Temp (°C)			Mean External Temp (°C)	Temperature Difference (K)	Zone 1 (Lower Floor)					Zone 2 (Upper Floor)					TOTAL (W)	Mean Solar (W/m^2)	Total (W) Solar Corrected (multiple regression)
	Lower Floor	Upper Floor	Combined			Living (Wh)	Dining (Wh)	Kitchen (Wh)	Total (Wh)	Total (W)	B1 (Wh)	B2 (Wh)	B3 (Wh)	Total (Wh)	Total (W)			
18/12/10	23.02	22.16	22.59	-2.04	24.63	13848	9179	7131	30158	1257	11412	15688	6032	33132	1381	2637	14.61	2679.57
19/12/10	23.03	22.15	22.59	-2.92	25.51	14480	9645	8215	32340	1348	11692	14881	5962	32535	1356	2703	42.22	2825.88
20/12/10	23.06	22.18	22.62	-4.52	27.14	15115	10503	9817	35435	1476	11869	15242	6037	33148	1381	2858	17.37	2908.13
21/12/10	23.05	22.21	22.63	-2.86	25.49	15154	10023	8801	33978	1416	12010	16276	6336	34622	1443	2858	11.53	2891.86
22/12/10	23.08	22.36	22.72	-0.49	23.21	14495	9004	6910	30409	1267	11190	15130	5826	32146	1339	2606	15.04	2650.19

Appendix 6 - Heat Flux Test Summary Data

Date	Code Level 6 Mean Internal Temperature (°C)	Mean Temperature - Bottom of Cavity (°C)	Mean Temperature - Middle of Cavity (°C)	Mean Temperature - Top of Cavity (°C)	Code Level 6 Mean Heat Flux - Individual Sensors (W/m^2)									Code Level 6 Mean Total Daily Heat Flux (W/m^2)
					Left Upper	Left Centre	Left Lower	Centre Top	Centre Centre	Centre Lower	Right Upper	Right Centre	Right Lower	
10/03/2011	21.99	20.43	21.70	22.44	1.28	0.99	1.38	1.54	3.61	0.80	1.17	0.63	0.89	1.36
11/03/2011	21.76	20.46	21.76	22.54	-0.59	-1.60	-2.63	-0.67	0.39	-0.77	-0.30	-0.52	-0.12	-0.76
12/03/2011	21.62	20.41	21.69	22.52	-0.31	-0.23	-0.29	-0.38	0.48	-0.13	0.10	-0.14	0.50	-0.04
13/03/2011	21.66	20.45	21.70	22.55	-0.17	-0.06	-0.07	-0.20	0.97	-0.10	0.09	-0.46	0.29	0.03
14/03/2011	21.64	20.48	21.70	22.51	-1.02	-0.64	-0.58	-1.52	-2.48	-0.73	-0.98	-1.35	-0.48	-1.09
15/03/2011	20.93	20.26	21.57	22.41	-1.68	-1.85	-2.50	-1.80	-0.68	-3.15	-1.61	-2.15	-2.46	-1.99
16/03/2011	20.89	19.93	21.14	22.07	0.18	0.51	0.83	0.01	1.28	1.01	0.48	0.26	0.68	0.58
17/03/2011	20.90	19.96	21.18	22.03	-1.92	-1.63	-1.28	-2.33	-2.17	-1.08	-1.85	-1.87	-0.94	-1.67
18/03/2011	20.29	19.62	20.64	21.14	-1.43	-1.18	-1.17	-1.53	-0.82	-1.28	-1.21	-1.13	-1.01	-1.20
19/03/2011	19.61	19.04	19.98	20.37	-1.03	-0.80	-0.73	-1.05	-0.66	-0.84	-0.78	-0.87	-0.53	-0.81
20/03/2011	19.15	18.57	19.69	20.33	-1.63	-1.53	-1.46	-1.94	-1.71	-1.33	-1.50	-2.18	-1.63	-1.66
21/03/2011	18.98	18.32	19.50	20.27	-0.70	-0.56	-0.77	-0.87	0.23	-0.88	-0.62	-1.51	-1.45	-0.79
22/03/2011	19.07	18.30	19.48	20.30	-0.62	-0.58	-0.63	-0.75	-0.14	-0.57	-0.62	-1.52	-1.33	-0.75
23/03/2011	19.16	18.36	19.53	20.35	-1.08	-0.87	-0.69	-1.39	-1.16	-0.63	-1.32	-1.87	-1.48	-1.17
24/03/2011	19.17	18.34	19.37	19.99	-0.12	-0.03	-0.07	0.21	0.85	-0.28	0.05	-0.37	-0.65	-0.04
25/03/2011	19.24	18.29	19.17	19.61	0.54	0.37	0.32	0.67	0.60	0.29	0.71	0.27	0.12	0.43
26/03/2011	20.05	18.51	19.27	19.68	2.80	2.43	1.47	3.10	3.99	1.41	3.14	2.74	1.86	2.55
27/03/2011	20.64	18.87	19.56	19.77	2.57	2.54	2.94	2.64	2.77	3.03	3.09	3.30	3.90	2.98
28/03/2011	21.30	19.24	19.82	19.78	2.86	2.60	2.87	3.02	2.73	3.08	3.50	3.97	4.43	3.23
29/03/2011	21.86	19.61	20.10	19.91	3.16	2.89	3.07	3.53	3.31	3.23	3.95	4.49	4.73	3.59
30/03/2011	22.36	20.02	20.43	20.19	2.83	2.50	2.55	3.07	2.94	2.82	3.56	4.13	4.33	3.19
31/03/2011	22.89	20.55	20.87	20.80	3.27	2.89	2.80	4.14	4.59	3.18	4.30	4.40	4.33	3.77
01/04/2011	23.30	21.08	21.62	21.87	2.37	2.34	2.25	2.71	1.95	2.55	3.08	3.30	3.46	2.67
02/04/2011	23.93	21.74	22.66	23.18	0.39	0.43	0.14	0.54	0.33	0.71	0.97	0.67	1.07	0.58
03/04/2011	23.84	22.11	23.17	23.70	-0.77	-0.70	-0.43	-0.48	-0.67	-0.10	-0.30	-0.43	0.27	-0.40
04/04/2011	23.56	22.17	23.04	23.49	0.07	0.10	0.17	0.38	0.14	0.24	0.47	0.22	0.85	0.30
05/04/2011	23.82	22.12	22.94	23.34	2.54	2.48	2.33	2.99	4.36	2.76	3.22	3.04	3.05	2.97
06/04/2011	24.52	22.45	23.33	23.71	2.54	2.31	2.32	2.70	1.96	2.75	2.85	2.96	3.41	2.65
07/04/2011	24.83	22.78	23.80	24.07	0.15	0.13	0.30	0.42	0.09	0.54	0.84	0.81	1.33	0.51

Date	Code Level 6 Mean Internal Temperature (°C)	Mean Temperature - Bottom of Cavity (°C)	Mean Temperature - Middle of Cavity (°C)	Mean Temperature - Top of Cavity (°C)	Code Level 6 Mean Heat Flux - Individual Sensors (W/m^2)									Code Level 6 Mean Total Daily Heat Flux (W/m^2)
					Left Upper	Left Centre	Left Lower	Centre Top	Centre Centre	Centre Lower	Right Upper	Right Centre	Right Lower	
08/04/2011	24.51	22.80	23.77	23.92	-0.04	-0.03	0.11	0.43	0.24	0.24	0.86	0.83	1.29	0.44
09/04/2011	23.88	22.52	23.34	23.42	-0.56	-0.41	-0.24	-0.40	-0.23	-0.10	-0.10	0.12	0.29	-0.18
10/04/2011	22.74	21.93	22.68	22.74	-1.85	-1.84	-1.73	-1.81	-1.88	-1.99	-1.72	-1.69	-1.57	-1.79
11/04/2011	22.62	21.26	22.03	22.15	2.21	1.93	2.18	2.48	2.90	2.42	2.49	2.49	2.20	2.37
12/04/2011	23.10	21.20	22.18	22.30	2.57	2.05	2.29	2.82	2.73	2.47	2.98	2.82	3.03	2.64
13/04/2011	23.70	21.51	22.41	22.47	2.94	2.26	2.66	3.24	2.97	2.89	3.65	3.50	3.92	3.11
14/04/2011	24.27	22.05	22.86	22.98	2.08	1.81	2.35	2.45	2.50	2.46	3.04	2.99	3.61	2.59
15/04/2011	24.54	22.35	23.18	23.21	1.35	1.21	1.60	1.57	1.38	1.70	2.05	2.24	2.62	1.75
16/04/2011	24.24	22.57	23.33	23.40	-1.29	-1.12	-0.63	-1.24	-1.60	-0.61	-0.77	-0.61	-0.04	-0.88
17/04/2011	23.41	22.19	22.92	22.97	-1.16	-1.03	-0.72	-0.95	-1.07	-0.66	-0.67	-0.52	-0.44	-0.80
18/04/2011	22.69	21.69	22.38	22.49	-1.04	-0.91	-0.69	-0.91	-0.88	-0.57	-0.73	-0.65	-0.69	-0.79
19/04/2011	22.04	21.17	21.88	22.08	-1.01	-0.87	-0.72	-0.92	-0.84	-0.68	-0.83	-0.83	-0.96	-0.85
20/04/2011	21.55	20.72	21.44	21.74	-0.80	-0.67	-0.53	-0.73	-0.58	-0.48	-0.65	-0.73	-0.83	-0.67
21/04/2011	21.26	20.40	21.16	21.55	-0.58	-0.43	-0.33	-0.53	-0.30	-0.27	-0.45	-0.60	-0.74	-0.47
22/04/2011	21.21	20.25	21.11	21.65	-0.32	-0.19	-0.05	-0.25	-0.03	0.05	-0.24	-0.52	-0.66	-0.25
23/04/2011	21.32	20.30	21.23	21.90	-0.40	-0.25	-0.04	-0.36	-0.13	0.04	-0.35	-0.66	-0.78	-0.32
24/04/2011	21.49	20.43	21.38	22.03	-0.37	-0.16	-0.01	-0.33	-0.09	0.08	-0.36	-0.58	-0.79	-0.29
25/04/2011	21.56	20.51	21.38	21.87	-0.19	-0.01	0.06	-0.12	0.00	0.07	-0.19	-0.36	-0.55	-0.14
26/04/2011	21.56	20.47	21.22	21.47	0.25	0.33	0.40	0.33	0.45	0.42	0.39	0.30	0.01	0.32
27/04/2011	21.49	20.33	20.93	20.92	0.58	0.49	0.60	0.63	0.65	0.61	0.71	0.80	0.65	0.64
28/04/2011	21.38	20.13	20.62	20.46	0.79	0.67	0.77	0.81	0.84	0.79	1.02	1.21	1.07	0.88
29/04/2011	21.29	19.95	20.40	20.21	0.84	0.68	0.80	0.87	0.89	0.85	1.08	1.32	1.13	0.94
30/04/2011	21.22	19.91	20.43	20.52	0.57	0.55	0.70	0.57	0.68	0.74	0.82	0.84	0.77	0.69
01/05/2011	21.21	19.96	20.64	20.98	0.20	0.27	0.46	0.20	0.32	0.46	0.39	0.30	0.33	0.32
02/05/2011	21.23	19.98	20.73	21.11	0.34	0.33	0.51	0.37	0.53	0.55	0.58	0.45	0.41	0.45
03/05/2011	21.27	20.01	20.81	21.25	0.07	0.10	0.26	0.13	0.17	0.32	0.25	0.03	0.16	0.17
04/05/2011	21.31	20.05	20.87	21.28	0.04	0.08	0.22	0.08	0.18	0.29	0.22	0.12	0.21	0.16
05/05/2011	21.30	20.07	20.88	21.27	-0.17	-0.19	-0.01	-0.16	-0.08	0.16	0.08	-0.02	0.01	-0.04
06/05/2011	21.27	20.10	20.92	21.39	-0.31	-0.27	-0.07	-0.27	-0.19	0.04	-0.12	-0.31	-0.28	-0.20

Date	Code Level 6 Mean Internal Temperature (°C)	Mean Temperature - Bottom of Cavity (°C)	Mean Temperature - Middle of Cavity (°C)	Mean Temperature - Top of Cavity (°C)	Code Level 6 Mean Heat Flux - Individual Sensors (W/m^2)									Code Level 6 Mean Total Daily Heat Flux (W/m^2)
					Left Upper	Left Centre	Left Lower	Centre Top	Centre Centre	Centre Lower	Right Upper	Right Centre	Right Lower	
07/05/2011	21.37	20.16	21.03	21.58	-0.29	-0.26	-0.03	-0.26	-0.12	0.16	-0.16	-0.35	-0.49	-0.20
08/05/2011	21.55	20.32	21.26	21.87	-0.39	-0.26	-0.01	-0.31	-0.14	0.19	-0.34	-0.54	-0.50	-0.26
09/05/2011	21.62	20.47	21.40	22.00	-0.31	-0.23	-0.07	-0.18	-0.08	0.08	-0.13	-0.38	-0.40	-0.19
10/05/2011	21.66	20.55	21.48	22.07	-0.45	-0.34	-0.18	-0.34	-0.07	0.06	-0.22	-0.48	-0.49	-0.28
11/05/2011	21.68	20.62	21.55	22.15	-0.54	-0.44	-0.30	-0.44	-0.12	0.10	-0.33	-0.69	-0.71	-0.38
12/05/2011	21.66	20.65	21.59	22.16	-0.51	-0.42	-0.31	-0.53	-0.46	-0.02	-0.31	-0.64	-0.70	-0.43
13/05/2011	21.64	20.70	21.66	22.23	-0.53	-0.47	-0.30	-0.45	-0.36	0.02	-0.29	-0.67	-0.62	-0.41
14/05/2011	21.57	20.64	21.55	22.01	-0.41	-0.42	-0.33	-0.23	-0.04	-0.06	-0.12	-0.49	-0.41	-0.28
15/05/2011	21.46	20.51	21.38	21.76	-0.45	-0.46	-0.31	-0.51	-0.60	0.01	-0.20	-0.39	-0.31	-0.36
16/05/2011	21.38	20.42	21.31	21.83	-0.59	-0.56	-0.36	-0.56	-0.52	0.00	-0.38	-0.61	-0.49	-0.45
17/05/2011	21.33	20.41	21.34	21.95	-0.71	-0.27	-0.44	-0.69	-0.57	-0.27	-0.54	-0.83	-0.91	-0.58

Date	Code Level 4 Mean Internal Temperature (°C)	Mean Temperature - Bottom of Cavity (°C)	Mean Temperature - Middle of Cavity (°C)	Mean Temperature - Top of Cavity (°C)	Code Level 4 Mean Heat Flux - Individual Sensors (W/m^2)									Code Level 4 Mean Total Daily Heat Flux (W/m^2)
					Left Upper	Left Centre	Left Lower	Centre Upper	Centre Centre	Centre lower	Right Top	Right Centre	Right Lower	
10/03/2011	24.68	20.43	21.70	22.44	1.72	1.84	1.08	1.50	1.40	2.16	1.53	1.58	1.10	1.55
11/03/2011	23.86	20.46	21.76	22.54	0.77	0.91	0.43	0.53	0.43	1.51	0.54	0.62	0.53	0.70
12/03/2011	24.05	20.41	21.69	22.52	0.88	0.94	0.42	0.63	0.36	1.50	0.67	0.69	0.64	0.75
13/03/2011	24.12	20.45	21.70	22.55	0.69	0.84	0.28	0.54	0.49	2.25	0.50	0.78	0.71	0.79
14/03/2011	23.60	20.48	21.70	22.51	0.61	0.63	0.24	0.51	0.23	1.01	0.49	0.60	0.35	0.52
15/03/2011	23.80	20.26	21.57	22.41	0.67	0.85	0.52	0.51	0.58	1.52	0.60	0.76	0.68	0.74
16/03/2011	24.04	19.93	21.14	22.07	1.14	1.28	0.76	0.97	1.10	2.07	0.87	1.24	1.04	1.16
17/03/2011	21.64	19.96	21.18	22.03	-1.98	-1.85	-1.53	-2.51	-2.39	-1.16	-2.53	-2.23	-1.43	-1.96
18/03/2011	19.74	19.62	20.64	21.14	-0.66	-0.66	-0.93	-0.87	-1.13	-0.71	-1.13	-1.14	-0.85	-0.90
19/03/2011	21.45	19.04	19.98	20.37	3.67	3.82	3.03	4.21	3.64	4.32	3.55	3.66	3.20	3.68
20/03/2011	22.45	18.57	19.69	20.33	1.30	1.38	1.53	1.20	0.95	1.93	1.09	1.22	1.32	1.32
21/03/2011	21.81	18.32	19.50	20.27	0.73	0.68	0.71	0.59	0.23	0.95	0.56	0.41	0.33	0.58
22/03/2011	22.48	18.30	19.48	20.30	1.60	1.60	1.75	1.67	1.28	2.62	1.49	1.54	1.34	1.65
23/03/2011	20.98	18.36	19.53	20.35	-1.00	-1.10	-0.34	-1.25	-1.49	-0.70	-1.15	-1.26	-0.88	-1.02
24/03/2011	19.53	18.34	19.37	19.99	-0.92	-1.04	-0.61	-1.08	-1.30	-0.73	-1.03	-1.16	-1.06	-0.99
25/03/2011	18.92	18.29	19.17	19.61	-0.92	-0.96	-0.74	-1.02	-1.16	-0.66	-0.95	-1.03	-1.05	-0.94
26/03/2011	17.92	18.51	19.27	19.68	-2.20	-2.17	-1.91	-2.36	-2.31	-1.77	-2.07	-2.15	-1.84	-2.09
27/03/2011	16.72	18.87	19.56	19.77	-2.87	-2.83	-2.49	-3.02	-2.88	-2.30	-2.68	-2.78	-2.23	-2.68
28/03/2011	16.23	19.24	19.82	19.78	-2.42	-2.36	-2.46	-2.59	-2.44	-1.92	-2.27	-2.41	-2.12	-2.33
29/03/2011	16.22	19.61	20.10	19.91	-2.33	-2.25	-2.54	-2.54	-2.21	-1.72	-2.18	-2.26	-1.94	-2.22
30/03/2011	16.87	20.02	20.43	20.19	-1.17	-1.02	-1.53	-1.04	-0.85	-0.66	-0.66	-0.84	-0.15	-0.88
31/03/2011	18.51	20.55	20.87	20.80	0.53	0.66	0.23	1.03	1.28	1.17	1.51	1.25	1.82	1.05
01/04/2011	20.71	21.08	21.62	21.87	3.79	3.90	3.73	4.78	4.51	4.53	4.99	4.28	6.86	4.59
02/04/2011	22.16	21.74	22.66	23.18	1.71	1.78	2.39	1.98	1.97	2.69	2.04	1.81	3.94	2.26
03/04/2011	21.89	22.11	23.17	23.70	-0.34	-0.30	0.22	-0.61	-0.48	0.50	-0.64	-0.79	-0.70	-0.35
04/04/2011	21.35	22.17	23.04	23.49	0.17	0.19	0.96	0.20	0.14	0.36	-0.10	-0.23	0.20	0.21
05/04/2011	21.38	22.12	22.94	23.34	-1.38	-1.10	-0.39	-1.48	-1.37	-0.94	-1.22	-1.32	-1.02	-1.14
06/04/2011	21.53	22.45	23.33	23.71	-1.58	-1.42	-0.88	-1.77	-1.54	-0.91	-1.56	-1.45	-1.10	-1.36

Date	Code Level 4 Mean Internal Temperature (°C)	Mean Temperature - Bottom of Cavity (°C)	Mean Temperature - Middle of Cavity (°C)	Mean Temperature - Top of Cavity (°C)	Code Level 4 Mean Heat Flux - Individual Sensors (W/m^2)									Code Level 4 Mean Total Daily Heat Flux (W/m^2)
					Left Upper	Left Centre	Left Lower	Centre Upper	Centre Centre	Centre lower	Right Top	Right Centre	Right Lower	
07/04/2011	21.35	22.78	23.80	24.07	-1.14	-1.06	-1.85	-1.14	-1.03	-0.68	-0.86	-0.51	-0.31	-0.95
08/04/2011	21.38	22.80	23.77	23.92	-0.87	-0.89	-1.14	-0.98	-0.92	-0.46	-0.78	-0.80	-0.12	-0.77
09/04/2011	21.94	22.52	23.34	23.42	-0.65	-0.55	-0.26	-0.71	-0.60	0.02	-0.54	-0.60	0.04	-0.43
10/04/2011	21.32	21.93	22.68	22.74	-1.11	-1.27	-1.03	-1.09	-1.10	-0.59	-1.05	-1.19	-0.72	-1.02
11/04/2011	21.40	21.26	22.03	22.15	0.31	0.23	0.35	0.44	0.48	0.63	0.50	0.50	0.88	0.48
12/04/2011	20.42	21.20	22.18	22.30	-1.75	-2.09	-1.65	-1.97	-1.93	-1.54	-1.76	-1.92	-1.41	-1.78
13/04/2011	20.14	21.51	22.41	22.47	0.51	0.22	0.29	0.55	0.37	0.49	0.54	0.41	0.78	0.46
14/04/2011	20.51	22.05	22.86	22.98	-1.35	-1.62	-1.17	-1.70	-1.63	-1.36	-1.52	-1.76	-1.09	-1.47
15/04/2011	20.95	22.35	23.18	23.21	-0.34	-0.32	-0.22	-0.35	-0.30	0.13	-0.35	-0.33	0.20	-0.21
16/04/2011	21.41	22.57	23.33	23.40	-1.26	-1.36	-1.24	-1.44	-1.30	-1.01	-1.11	-0.80	-0.39	-1.10
17/04/2011	21.52	22.19	22.92	22.97	-0.72	-0.80	-0.37	-0.79	-0.65	-0.56	-0.70	-0.62	-0.11	-0.59
18/04/2011	21.61	21.69	22.38	22.49	0.01	-0.11	1.21	0.10	0.14	0.34	0.00	-0.12	0.60	0.24
19/04/2011	21.57	21.17	21.88	22.08	-0.20	-0.43	0.65	-0.12	-0.03	0.23	-0.14	0.10	0.47	0.06
20/04/2011	21.71	20.72	21.44	21.74	0.64	0.48	0.73	0.80	0.75	0.88	0.77	0.74	1.00	0.75
21/04/2011	21.72	20.40	21.16	21.55	0.87	0.78	0.63	1.04	1.00	1.07	1.07	0.97	1.14	0.95
22/04/2011	23.04	20.25	21.11	21.65	1.97	1.89	1.62	2.15	2.09	2.11	1.95	1.94	2.15	1.99
23/04/2011	23.22	20.30	21.23	21.90	1.07	0.92	1.18	1.12	0.99	1.33	0.98	1.06	1.56	1.13
24/04/2011	22.45	20.43	21.38	22.03	-0.71	-0.99	-0.42	-0.82	-0.86	-0.45	-0.96	-0.88	0.10	-0.67
25/04/2011	21.24	20.51	21.38	21.87	-0.65	-1.05	-0.73	-0.60	-0.73	-0.50	-0.72	-0.80	-0.12	-0.65
26/04/2011	19.56	20.47	21.22	21.47	-2.12	-2.31	-2.00	-2.23	-2.14	-1.89	-2.05	-2.14	-1.31	-2.02
27/04/2011	18.40	20.33	20.93	20.92	-1.68	-2.01	-2.03	-1.67	-1.67	-1.62	-1.55	-1.82	-1.14	-1.69
28/04/2011	17.74	20.13	20.62	20.46	-1.70	-1.91	-2.02	-1.70	-1.62	-1.56	-1.52	-1.74	-1.15	-1.66
29/04/2011	18.05	19.95	20.40	20.21	-0.58	-0.73	-1.22	-0.50	-0.44	-0.58	-0.21	-0.38	-0.19	-0.54
30/04/2011	21.49	19.91	20.43	20.52	2.25	2.20	1.00	2.58	2.58	2.40	2.69	2.64	2.36	2.30
01/05/2011	21.55	19.96	20.64	20.98	0.87	0.89	0.69	0.94	1.07	1.46	1.06	1.58	2.00	1.17
02/05/2011	20.88	19.98	20.73	21.11	0.72	0.63	0.39	0.79	0.84	1.00	0.68	0.79	1.25	0.79
03/05/2011	21.64	20.01	20.81	21.25	1.16	1.10	0.79	1.27	1.25	1.37	1.39	1.60	2.89	1.43
04/05/2011	20.60	20.05	20.87	21.28	-0.21	-0.29	-0.07	-0.28	-0.20	0.12	-0.37	-0.43	0.29	-0.16

Date	Code Level 4 Mean Internal Temperature (°C)	Mean Temperature - Bottom of Cavity (°C)	Mean Temperature - Middle of Cavity (°C)	Mean Temperature - Top of Cavity (°C)	Code Level 4 Mean Heat Flux - Individual Sensors (W/m^2)									Code Level 4 Mean Total Daily Heat Flux (W/m^2)
					Left Upper	Left Centre	Left Lower	Centre Upper	Centre Centre	Centre lower	Right Top	Right Centre	Right Lower	
05/05/2011	21.07	20.07	20.88	21.27	0.48	0.38	0.39	0.46	0.45	0.63	0.71	0.77	1.21	0.61
06/05/2011	21.75	20.10	20.92	21.39	0.85	0.78	0.70	0.80	0.71	0.94	0.94	1.03	1.66	0.93
07/05/2011	22.56	20.16	21.03	21.58	0.80	0.71	0.74	0.82	0.70	0.99	0.83	0.98	1.58	0.91
08/05/2011	22.65	20.32	21.26	21.87	0.32	0.24	0.36	0.38	0.26	0.44	0.39	0.56	1.19	0.46
09/05/2011	22.52	20.47	21.40	22.00	0.88	0.80	0.58	0.99	0.93	0.98	0.95	1.01	1.44	0.95
10/05/2011	22.69	20.55	21.48	22.07	1.25	1.17	1.10	1.34	1.19	1.30	1.42	1.56	2.10	1.38
11/05/2011	22.64	20.62	21.55	22.15	0.80	0.83	1.13	0.73	0.59	0.81	0.61	0.57	1.31	0.82
12/05/2011	22.38	20.65	21.59	22.16	1.06	0.97	1.21	1.13	0.84	0.92	1.37	1.41	1.80	1.19
13/05/2011	22.34	20.70	21.66	22.23	0.33	0.25	0.99	0.20	0.04	0.26	0.18	0.23	1.15	0.40
14/05/2011	21.24	20.64	21.55	22.01	-0.26	-0.51	0.60	-0.33	-0.54	-0.41	-0.23	-0.33	0.24	-0.20
15/05/2011	21.43	20.51	21.38	21.76	0.32	0.07	1.27	0.22	0.13	0.20	0.31	0.08	0.60	0.35
16/05/2011	22.65	20.42	21.31	21.83	1.40	1.32	1.93	1.36	1.20	1.18	1.62	1.58	1.86	1.50
17/05/2011	22.97	20.41	21.34	21.95	0.83	0.77	1.52	0.68	0.59	0.93	0.53	0.37	1.05	0.81

Appendix 7 - SAP 2005 Sensitivity Analysis Worksheet

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB
1				1	2	5	6	10	12	19	21	22	22a	22b	25	33	35	36	37	38	39	40	42	45	46	47	48	51
2	SAP Cell Ref	Parameter	Scenario	Ground Floor Volume	First Floor Volume	Total Floor Area	Dwelling Volume	Infiltration Due to Chimneys etc	Additional Infiltration	Infiltration Rate	Shelter Factor	Adjusted Infiltration Rate	Air Throughput	Heat Recovery Efficiency in Use	Effective Air Change Rate	Fabric Heat Loss	Total Fabric Heat Loss	Ventilation Heat Loss	Heat Loss Coefficient	Heat Loss Parameter	Energy Content of Water	Distribution Loss	Energy Lost from Water Storage	Energy Lost from Water Storage	Energy Lost from Water Storage	Energy Lost Adjusted for Solar Storage	Primary Circuit Loss	Output from Water Heater
3		OFFICIAL SAP WORKSHEET VALUES	43.94	101.06	106.77	87.88	207.88	0.00	0.00	0.15	0.93	0.14	0.36	75.65	0.22	55.32	62.38	15.43	77.81	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.29
4		SAPPER 8 BASE CASE	43.94	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
5	1a	Ground Floor Area	43.94	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
6	n/a	Ground Floor Height	2.3	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
7	2a	First Floor Area	43.94	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
8	n/a	First Floor Height	2.43	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
9	7	Number of chimneys	0	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
10	8	Number of open flues	0	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
11	9	Number of intermittent fans/vents	0	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
12	9a	Number of flueless gas fires	0	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
13	11	Number of Storeys in Dwelling	2	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
14	n/a	% Energy Saving Lightbulbs	100%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
15		% Energy Saving Lightbulbs	90%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
16		% Energy Saving Lightbulbs	80%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
17		% Energy Saving Lightbulbs	70%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
18		% Energy Saving Lightbulbs	60%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
19		% Energy Saving Lightbulbs	50%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
20		% Energy Saving Lightbulbs	40%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
21		% Energy Saving Lightbulbs	30%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
22		% Energy Saving Lightbulbs	20%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
23		% Energy Saving Lightbulbs	10%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
24		% Energy Saving Lightbulbs	1%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
25	n/a	Orientation	N	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
26		Orientation	NE	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
27		Orientation	E	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
28		Orientation	SE	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
29		Orientation	S	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
30		Orientation	SW	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
31		Orientation	W	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
32		Orientation	NW	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
33	13	Structural Infiltration	Masonry	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
34		Structural Infiltration	Steel or Timber Frame																									
35	14	Suspended Wooden Floors	n/a	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
36		Suspended Wooden Floors	sealed																									
37		Suspended Wooden Floors	unsealed																									
38	15	Draught Lobby Present?	Yes	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
39		Draught Lobby Present?	No																									
40	16	% Windows/Doors Draughtproofed	100	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
41		% Windows/Doors Draughtproofed	75																									
42		% Windows/Doors Draughtproofed	50																									
43		% Windows/Doors Draughtproofed	25																									
44		% Windows/Doors Draughtproofed	0																									
45	19	Q50	3	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
46		Q50	2.95 As Built	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.22	55.31	62.38	15.42	77.79	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
47		Q50	1.97 2011	101.06	106.77	87.88	207.84	0.00	0.00	0.10	0.93	0.09	0.41	75.70	0.19	55.31	62.38	13.06	75.44	0.86	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
48	20	No.Sides on Which Sheltered	1	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
49	22	Ventilation Type	Balanced whole house ventilation with heat recovery	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
50		Ventilation Type	Natural with passive/intermittent vents 0 vent & positive input from loft	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.00	0.00	0.51	55.31	62.38	34.95	97.33	1.11	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
51		Ventilation Type	Natural with passive/intermittent vents 1 vent & positive input from loft	101.06	106.77	87.88	207.84	0.50	0.00	0.20	0.93	0.18	0.00	0.00	0.52	55.31	62.38	35.44	97.82	1.11	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
52		Ventilation Type	Natural with passive/intermittent vents 2 vent & positive input from loft	101.06	106.77	87.88	207.84	0.10	0.00	0.25	0.93	0.23	0.00	0.00	0.53	55.31	62.38	36.07	98.45	1.12	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
53		Ventilation Type	Natural with passive/intermittent vents 3 vent & positive input from loft	101.06	106.77	87.88	207.84	0.14	0.00	0.29	0.93	0.27	0.00	0.00	0.54	55.31	62.38	36.84	99.21	1.13	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
54		Ventilation Type	Natural with passive/intermittent vents 4 vent & positive input from loft	101.06	106.77	87.88	207.84	0.19	0.00	0.34	0.93	0.32	0.00	0.00	0.55	55.31	62.38	37.73	100.11	1.14	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
55		Ventilation Type	Positive input ventilation from outside 0/1/2 vent	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.50	0.00	0.50	55.31	62.38	34.29	98.67	1.10	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
56		Ventilation Type	Positive input ventilation from outside 3 vent	101.06	106.77	87.88	207.84	0.14	0.00	0.29	0.93	0.27	0.22	0.00	0.52	55.31	62.38	35.82	98.20	1.12	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
57		Ventilation Type	Positive input ventilation from outside 4 vent	101.06	106.77	87.88	207.84	19.00	0.00	0.34	0.93	0.32	0.57	0.00	0.57	55.31	62.38	38.87	101.25	1.15	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
58		Ventilation Type	Whole house centralised mechanical extract ventilation	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.50	0.00	0.50	55.31	62.38	34.29	98.67	1.10	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
59		Ventilation Type	Whole house decentralised mechanical extract ventilation	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.39	0.00	0.39	55.31	62.38	26.66	89.04	1.01	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
60		Ventilation Type	Balanced whole house ventilation no heat recovery	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.50	0.00	0.50	55.31	62.38	34.29	96.67	1.10	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
61	n/a	Ducting Type	Flexible ducting (in use factor 1.7) insulated (in use factor 0.85)	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
62		Ducting Type	Flexible ducting (in use factor 1.7) uninsulated (in use factor 0.70)	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	62.30	0.27	55.31	62.38	18.86	81.23	0.92	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
63		Ducting Type	Rigid ducting (in use factor 1.4) insulated (in use factor 0.85)	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
64		Ducting Type	Rigid ducting (in use factor 1.4) uninsulated (in use factor 0.70)	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	62.30	0.27	55.31	62.38	18.86	81.23	0.92	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
65	n/a	Heat Recovery Efficiency of System	89%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
66		Heat Recovery Efficiency of System	85%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	72.30	0.24	55.31	62.38	16.38	78.76	0.90	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
67		Heat Recovery Efficiency of System	80%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	68.00	0.25	55.31	62.38	17.44	79.82	0.91	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
68		Heat Recovery Efficiency of System	75%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	63.80	0.27	55.31	62.38	18.49	80.86	0.92	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
69		Heat Recovery Efficiency of System	70%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	59.50	0.29	55.31	62.38	19.55	81.93	0.93	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
70		Heat Recovery Efficiency of System	65%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	55.30	0.30	55.31	62.38	20.59	82.97	0.94	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
71		Heat Recovery Efficiency of System	60%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	51.00	0.32	55.31	62.38	21.66	84.03	0.96	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
72		Heat Recovery Efficiency of System	55%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	46.80	0.33	55.31	62.38	22.70	85.07	0.97	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
73		Heat Recovery Efficiency of System	50%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	42.50	0.35	55.31	62.38	23.76	86.14	0.98	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
74	n/a	Specific Fan Power	0.63	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
75		Specific Fan Power	0.50	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
76		Specific Fan Power	1.00	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
77		Specific Fan Power	1.50	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
78		Specific Fan Power	2.00	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
79		Specific Fan Power	2.50	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
80	26-30	U Values	Base Case	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
81		U Values	+1%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.87	62.93	15.54	78.47	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
82		U Values	+2%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	56.41	63.48	15.54	79.01	0.90	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
83		U Values	+5%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	58.01	65.07	15.54	80.61	0.92	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
84		U Values	+8%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	59.25	66.42	15.54	82.16	0.93	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
85		U Values	+10%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	60.67	67.73	15.54	83.27	0.95	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
86		U Values	+15%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	63.32	70.35	15.54	85.92	0.98	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
87		U Values	+20%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	65.96	73.03	15.54	88.56	1.01	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
88		U Values	+21%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	66.49	73.55	15.54	89.09	1.01	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
89		U Values	+22%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	67.01	74.08	15.54	89.62	1.02	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
90		U Values	+23%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	67.54	74.61	15.54	90.15	1.03	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
91		U Values	+24%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	68.08	75.13	15.54	90.67	1.03	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
92		U Values	+25%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	68.90	75.66	15.54	91.20	1.04	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
93		U Values	+30%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	71.22	78.29	15.54	93.82	1.07	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
94		U Values	+40%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	76.45	83.51	15.54	99.05	1.13	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
95		U Values	+45%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	79.05	86.11	15.54	101.65	1.16	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
96		U Values	+50%	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	81.64	88.71	15.54	104.24	1.19	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
97	34	Thermal Bridges	7.07 (y=0.04)	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	62.38	15.54	77.91	0.89	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
98		Thermal Bridges	Default 26.5 (y=0.15)	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	81.81	15.54	97.34	1.11	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
99		Thermal Bridges	User Input 17.67(y=0.10)	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	72.91	15.54	88.51	1.01	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12
100		Thermal Bridges	User Input 35.33 (y=0.2)	101.06	106.77	87.88	207.84	0.00	0.00	0.15	0.93	0.14	0.36	75.70	0.23	55.31	90.64	15.54	106.18	1.21	1948.78	343.90	0.00	702.04	702.04	526.53	360.00	2243.12

	A	B	C	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ
1				52	53	53a	53b	54	55	65	66	67	68	69	70	72	73	74	76	77	78	79	80	81	86	87	87a
2	SAP Cell Ref	Parameter	Scenario	Heat Gains from Water Heating	Gains from Lights etc	Reduction due to low energy lighting	Gains from Fans/Pumps	Gains from Water Heating	Total Internal Gains	Total Solar Gains	Total Gains	Gains/ Loss Ratio	Utilisation Factor	Useful Gains	Mean Internal Temp. of Living Area	Adjustment for Gains	Adjusted Living Room Temp	Temp Diff Between Zones	Rest of House Fraction	Mean Internal Temp	Temp Rise from Gains	Base Temp	Degree Days	Space Heating Req (useful)	Space Heating from CHP etc	Space Heating from Boilers Type 1	Water Heated by CHP etc
3		OFFICIAL SAP WORKSHEET VALUES	43.94	1471.54	517.83	59.76	0.00	167.98	626.05	276.30	902.36	11.60	0.79	711.25	18.88	1.03	19.91	1.75	0.70	18.68	9.14	9.54	867.24	1619.54	0.00	1781.49	0.00
4		SAPPER 8 BASE CASE	43.94	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
5	1a	Ground Floor Area	43.94	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
6	n/a	Ground Floor Height	2.3	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
7	2a	First Floor Area	43.94	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
8	n/a	First Floor Height	2.43	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
9	7	Number of chimneys	0	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
10	8	Number of open flues	0	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
11	9	Number of intermittent fans/vents	0	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
12	9a	Number of flueless gas fires	0	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
13	11	Number of Storeys in Dwelling	2	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
14	n/a	% Energy Saving Lightbulbs	100%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
15		% Energy Saving Lightbulbs	90%	1472.00	518.00	54.00	0.00	168.00	632.00	276.00	908.00	11.66	0.79	714.00	18.88	1.03	19.91	1.75	0.70	18.68	9.17	9.51	862.00	1612.00	0.00	1774.00	0.00
16		% Energy Saving Lightbulbs	80%	1472.00	518.00	48.00	0.00	168.00	638.00	276.00	914.00	11.74	0.78	717.00	18.88	1.04	19.92	1.75	0.70	18.69	9.20	9.48	857.00	1603.00	0.00	1764.00	0.00
17		% Energy Saving Lightbulbs	70%	1472.00	518.00	42.00	0.00	168.00	644.00	276.00	920.00	11.81	0.70	720.00	18.88	1.05	19.93	1.75	0.70	18.70	9.24	9.46	853.00	1594.00	0.00	1754.00	0.00
18		% Energy Saving Lightbulbs	60%	1472.00	518.00	36.00	0.00	168.00	650.00	276.00	926.00	11.89	0.78	722.00	18.88	1.05	19.93	1.75	0.70	18.70	9.27	9.43	848.00	1586.00	0.00	1744.00	0.00
19		% Energy Saving Lightbulbs	50%	1472.00	518.00	30.00	0.00	168.00	656.00	276.00	932.00	11.97	0.78	725.00	18.88	1.06	19.94	1.75	0.70	18.71	9.31	9.40	843.00	1577.00	0.00	1735.00	0.00
20		% Energy Saving Lightbulbs	40%	1472.00	518.00	24.00	0.00	168.00	662.00	276.00	938.00	12.04	0.78	728.00	18.88	1.07	19.95	1.75	0.70	18.72	9.34	9.38	839.00	1568.00	0.00	1725.00	0.00
21		% Energy Saving Lightbulbs	30%	1472.00	518.00	18.00	0.00	168.00	668.00	276.00	944.00	12.12	0.77	730.00	18.88	1.07	19.95	1.75	0.70	18.72	9.37	9.35	834.00	1560.00	0.00	1716.00	0.00
22		% Energy Saving Lightbulbs	20%	1472.00	518.00	2.00	0.00	168.00	674.00	276.00	950.00	12.20	0.77	733.00	18.88	1.08	19.96	1.75	0.70	18.73	9.41	9.32	830.00	1551.00	0.00	1707.00	0.00
23		% Energy Saving Lightbulbs	10%	1472.00	518.00	6.00	0.00	168.00	680.00	276.00	956.00	12.27	0.77	736.00	18.88	1.09	19.97	1.75	0.70	18.74	9.44	9.29	825.00	1543.00	0.00	1697.00	0.00
24		% Energy Saving Lightbulbs	1%	1472.00	518.00	1.00	0.00	168.00	685.00	276.00	961.00	12.34	0.77	738.00	18.88	1.09	19.97	1.75	0.70	18.74	9.47	9.47	821.00	1535.00	0.00	1689.00	0.00
25	n/a	Orientation	N	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
26		Orientation	NE	1472.00	518.00	60.00	0.00	168.00	626.00	284.00	909.00	11.68	0.79	715.00	18.88	1.04	19.92	1.75	0.70	18.68	9.18	9.18	861.00	1610.00	0.00	1771.00	0.00
27		Orientation	E	1472.00	518.00	60.00	0.00	168.00	626.00	272.00	898.00	11.53	0.79	710.00	18.88	1.02	19.90	1.75	0.70	18.67	9.11	9.11	871.00	1629.00	0.00	1791.00	0.00
28		Orientation	SE	1472.00	518.00	60.00	0.00	168.00	626.00	247.00	970.00	11.21	0.80	698.00	18.88	0.99	19.87	1.75	0.70	18.64	8.96	8.96	892.00	1669.00	0.00	1836.00	0.00
29		Orientation	S	1472.00	518.00	60.00	0.00	168.00	626.00	224.00	850.00	10.91	0.81	687.00	18.88	0.96	19.84	1.75	0.70	18.61	8.82	8.82	913.00	1707.00	0.00	1878.00	0.00
30		Orientation	SW	1472.00	518.00	60.00	0.00	168.00	626.00	208.00	834.00	10.71	0.81	679.00	18.88	0.94	19.82	1.75	0.70	18.59	8.72	8.72	928.00	1735.00	0.00	1908.00	0.00
31		Orientation	W	1472.00	518.00	60.00	0.00	168.00	626.00	216.00	842.00	10.81	0.81	683.00	18.88	0.95	19.83	1.75	0.70	18.60	8.77	8.77	920.00	1721.00	0.00	1893.00	0.00
32		Orientation	NW	1472.00	518.00	60.00	0.00	168.00	626.00	245.00	870.00	11.18	0.80	697.00	18.88	0.99	19.87	1.75	0.70	18.64	8.94	8.94	895.00	1673.00	0.00	1841.00	0.00
33	13	Structural Infiltration	Masonry	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	1.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
34		Structural Infiltration	Steel or Timber Frame																						0.00		0.00
35	14	Suspended Wooden Floors	n/a	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
36		Suspended Wooden Floors	sealed																						0.00		0.00
37		Suspended Wooden Floors	unsealed																						0.00		0.00
38	15	Draught Lobby Present?	Yes	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
39		Draught Lobby Present?	No																						0.00		0.00
40	16	% Windows/Doors Draughtproofed	100	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
41		% Windows/Doors Draughtproofed	75																						0.00		0.00
42		% Windows/Doors Draughtproofed	50																						0.00		0.00
43		% Windows/Doors Draughtproofed	25																						0.00		0.00
44		% Windows/Doors Draughtproofed	0																						0.00		0.00
45	19	Q50	3	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
46		Q50	2.95 As Built	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.60	0.79	711.00	18.88	1.03	19.91	1.75	0.70	18.68	9.14	9.53	866.00	1617.00	0.00	1779.00	0.00
47		Q50	1.97 2011	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.96	0.78	702.00	18.88	1.06	19.94	1.75	0.70	18.71	9.31	9.40	844.00	1527.00	0.00	1680.00	0.00
48	20	No.Sides on Which Sheltered	1	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
49	22	Ventilation Type	Balanced whole house ventilation with heat recovery	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
50		Ventilation Type	Natural with passive/intermittent vents 0 vent & positive input from loft	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	9.27	0.86	773.00	18.88	0.79	19.67	1.79	0.70	18.41	7.94	10.47	1039.00	2427.00	0.00	2670.00	0.00
51		Ventilation Type	Natural with passive/intermittent vents 1 vent & positive input from loft	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	9.22	0.86	774.00	18.88	0.78	19.66	1.79	0.70	18.40	7.91	10.49	1043.00	2779.00	0.00	2694.00	0.00
52		Ventilation Type	Natural with passive/intermittent vents 2 vent & positive input from loft	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	9.17	0.86	776.00	18.88	0.78	19.66	1.79	0.70	18.40	7.88	10.52	1048.00	2476.00	0.00	2723.00	0.00
53		Ventilation Type	Natural with passive/intermittent vents 3 vent & positive input from loft	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	9.10	0.86	778.00	18.88	0.77	19.65	1.79	0.70	18.38	7.84	10.55	1054.00	2509.00	0.00	2760.00	0.00
54		Ventilation Type	Natural with passive/intermittent vents 4 vent & positive input from loft	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	9.01	0.86	780.00	18.88	0.76	19.64	1.80	0.70	18.37	7.79	10.58	1061.00	2548.00	0.00	2803.00	0.00
55		Ventilation Type	Positive input ventilation from outside 0/1/2 vent	1472.00	518.00	60.00	27.00	168.00	653.00	276.00	902.00	9.61	0.85	786.00	18.88	0.83	19.71	1.78	0.70	18.45	8.13	10.32	1010.00	2344.00	0.00	2578.00	0.00
56		Ventilation Type	Positive input ventilation from outside 3 vent	1472.00	518.00	60.00	27.00	168.00	653.00	276.00	902.00	9.46	0.85	790.00	18.88	0.81	19.69	1.79	0.70	18.43	8.05	10.38	1022.00	2409.00	0.00	2650.00	0.00
57		Ventilation Type	Positive input ventilation from outside 4 vent	1472.00	518.00	60.00	27.00	168.00	653.00	276.00	902.00	9.18	0.86	798.00	18.88	0.78	19.66	1.80	0.70	19.66	7.89	10.50	1046.00	2541.00	0.00	2795.00	0.00
58		Ventilation Type	Whole house centralised mechanical extract ventilation	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	9.33	0.85	771.00	18.88	0.80	19.68	1.78	0.70	18.42	7.98	10.44	1054.00	2399.00	0.00	2639.00	0.00
59		Ventilation Type	Whole house decentralised mechanical extract ventilation	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	9.13	0.83	750.00	18.88	0.88	19.76	1.75	0.70	18.53	8.42	10.11	971.00	2075.00	0.00	2282.00	0.00
60		Ventilation Type	Balanced whole house ventilation no heat recovery	1472.00	518.00	60.00	13.00	168.00	639.00	276.00	902.00	9.47	0.85	779.00	18.88	0.81	19.69	1.78	0.70	18.44	8.08	10.38	1022.00	2371.00	0.00	2608.00	0.00
61	n/a	Ducting Type	Flexible ducting (in use factor 1.7) insulated (in use factor 0.85)	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
62		Ducting Type	Flexible ducting (in use factor 1.7) uninsulated (in use factor 0.70)	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.11	0.80	724.00	18.88	0.98	19.86	1.75	0.70	18.63	8.91	9.72	899.00	1754.00	0.00	1929.00	0.00
63		Ducting Type	Rigid ducting (in use factor 1.4) insulated (in use factor 0.85)	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.64	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
64		Ducting Type	Rigid ducting (in use factor 1.4) uninsulated (in use factor 0.70)	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.11	0.80	724.00	18.88	0.98	19.86	1.75	0.70	18.63	8.91	9.72	899.00	1754.00	0.00	1929.00	0.00
65	n/a	Heat Recovery Efficiency of System	89%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
66		Heat Recovery Efficiency of System	85%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.46	0.79	715.00	18.88	1.02	19.90	1.75	0.70	18.66	9.08	9.59	876.00	1655.00	0.00	1821.00	0.00
67		Heat Recovery Efficiency of System	80%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.31	0.80	719.00	18.88	1.00	19.88	1.75	0.70	18.65	9.00	9.64	886.00	1697.00	0.00	1867.00	0.00
68		Heat Recovery Efficiency of System	75%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.16	0.80	723.00	18.88	0.99	19.87	1.75	0.70	18.64	8.94	9.70	896.00	1739.00	0.00	1913.00	0.00
69		Heat Recovery Efficiency of System	70%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.01	0.80	726.00	18.88	0.97	19.85	1.75	0.70	18.62	8.87	9.76	906.00	1781.00	0.00	1960.00	0.00
70		Heat Recovery Efficiency of System	65%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	10.88	0.81	730.00	18.88	0.96	19.84	1.75	0.70	18.61	8.80	9.91	916.00	1823.00	0.00	2006.00	0.00
71		Heat Recovery Efficiency of System	60%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	10.74	0.81	734.00	18.88	0.95	19.83	1.75	0.70	18.59	8.73	9.86	926.00	1867.00	0.00	2053.00	0.00
72		Heat Recovery Efficiency of System	55%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	10.61	0.82	737.00	18.88	0.93	19.81	1.75	0.70	18.58	8.66	9.92	935.00	1909.00	0.00	2100.00	0.00
73		Heat Recovery Efficiency of System	50%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	10.48	0.82	741.00	18.88	0.92	19.80	1.75	0.70	18.57	8.60	9.97	945.00	1953.00	0.00	2148.00	0.00
74	n/a	Specific Fan Power	0.63	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
75		Specific Fan Power	0.50	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
76		Specific Fan Power	1.00	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
77		Specific Fan Power	1.50	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
78		Specific Fan Power	2.00	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
79		Specific Fan Power	2.50	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
80	26-30	U Values	Base Case	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
81		U Values	+1%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.50	0.79	714.00	18.88	1.02	19.90	1.75	0.70	18.67	9.10	9.57	873.00	1644.00	0.00	1808.00	0.00
82		U Values	+2%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.42	0.79	716.00	18.88	1.01	19.89	1.75	0.70	18.66	9.06	9.60	878.00	1665.00	0.00	1832.00	0.00
83		U Values	+5%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.19	0.80	722.00	18.88	0.99	19.87	1.75	0.70	18.64	8.95	9.69	894.00	1729.00	0.00	1901.00	0.00
84		U Values	+8%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	10.98	0.81	727.00	18.88	0.97	19.85	1.75	0.70	18.62	8.85	9.77	908.00	1791.00	0.00	1970.00	0.00
85		U Values	+10%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	10.84	0.81	731.00	18.88	0.96	19.84	1.75	0.70	18.60	8.78	9.83	919.00	1836.00	0.00	2019.00	0.00
86		U Values	+15%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	10.50	0.82	740.00	18.88	0.92	19.80	1.75	0.70	18.57	8.61	9.96	943.00	1944.00	0.00	2138.00	0.00
87		U Values	+20%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	10.19	0.83	748.00	18.88	0.89	19.77	1.75	0.70	18.54	8.45	10.09	967.00	2055.00	0.00	2260.00	0.00
88		U Values	+21%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	10.13	0.83	750.00	18.88	0.88	19.76	1.75	0.70	18.53	8.42	10.11	971.00	2077.00	0.00	2284.00	0.00
89		U Values	+22%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	10.07	0.83	751.00	18.88	0.88	19.76	1.76	0.70	18.52	8.38	10.14	976.00	2099.00	0.00	2309.00	0.00
90		U Values	+23%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	10.01	0.83	753.00	18.88	0.87	19.75	1.76	0.70	18.51	8.35	10.16	980.00	2121.00	0.00	2333.00	0.00
91		U Values	+24%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	9.95	0.84	755.00	18.88	0.86	19.74	1.76	0.70	18.50	8.32	10.18	985.00	2143.00	0.00	2357.00	0.00
92		U Values	+25%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	9.89	0.84	756.00	18.88	0.86	19.74	1.76	0.70	18.50	8.29	10.21	989.00	2165.00	0.00	2382.00	0.00
93		U Values	+30%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	9.62	0.85	764.00	18.88	0.83	19.71	1.77	0.70	18.46	8.14	10.32	1011.00	2277.00	0.00	2504.00	0.00
94		U Values	+40%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	9.11	0.86	777.00	18.88	0.77	19.65	1.79	0.70	18.39	7.85	10.54	1053.00	2502.00	0.00	2752.00	0.00
95		U Values	+45%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	8.88	0.87	784.00	18.88	0.74	19.62	1.80	0.70	18.35	7.71	10.64	1072.00	2616.00	0.00	2877.00	0.00
96		U Values	+50%	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	8.66	0.87	790.00	18.88	0.71	19.59	1.81	0.70	18.32	7.57	10.74	1091.00	2730.00	0.00	3003.00	0.00
97	34	Thermal Bridges	7.07 (y=0.04)	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	11.58	0.79	712.00	18.88	1.03	19.91	1.75	0.70	18.67	9.13	9.54	867.00	1622.00	0.00	1784.00	0.00
98		Thermal Bridges	Default 26.5 (y=0.15)	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	9.27	0.86	773.00	18.88	0.79	19.67	1.79	0.70	18.41	7.94	10.47	1039.00	2428.00	0.00	2671.00	0.00
99		Thermal Bridges	User Input 17.67(y=0.10)	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	10.20	0.83	748.00	18.88	0.89	19.77	1.75	0.70	18.54	8.45	10.09	966.00	2053.00	0.00	2258.00	0.00
100		Thermal Bridges	User Input 35.33 (y=0.2)	1472.00	518.00	60.00	0.00	168.00	626.00	276.00	902.00	8.50	0.88	794.00	18.88	0.70	19.58	1.82	0.70	18.29	7.48	10.82	1105.00	2816.00	0.00	3098.00	0.00

	A	B	C	BA	BB	BC	BD	BE	BF	BG	BH	BI	BJ	BK	BL	BM	BN	BO	BP	BQ	BR	BS	BT	BU	BV	BW	BX
1				87b	88	88a	89	90	91	92	93b	93c	94	94a	94b	95	95a	95b1	95b	s1	s1a	s2a	s2a	97	98	99	100
2	SAP Cell Ref	Parameter	Scenario	Water Heated by Boilers Type 1	Electricity for Pumps/ Fans	Electricity for Lighting	Space Heat Cost (CHP etc)	Space Heat Cost (Boiler Type 1)	Water Heat Cost (CHP etc)	Water Heat Cost (Boiler Type 1)	Immersion On Peak Cost	Immersion Off Peak Cost	Pump/ Fan Energy Cost	Lighting Energy Cost	Additional Standing Charges	PV Energy Produced/Saved	PV Total Cost	Wind Energy Produced/ Saved	Wind Total Cost	Other Features Energy Produced/Saved	Other Features Energy Cost Produced/Saved	Other Features Energy Consumed	Other Features Energy Cost Consumed	Total Heating Cost	Energy Cost Deflator	Energy Cost Factor	SAP Rating
3		OFFICIAL SAP WORKSHEET VALUES	43.94	2467.62	271.02	398.38	0.00	35.45	0.00	49.11	0.00	0.00	19.30	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.22	0.91	0.91	87.00
4		SAPPER 8 BASE CASE	43.94	2467.00	271.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.28	0.91	0.91	87.25
5	1a	Ground Floor Area	43.94	2467.00	271.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.28	0.91	0.91	87.25
6	n/a	Ground Floor Height	2.3	2467.00	271.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.28	0.91	0.91	87.25
7	2a	First Floor Area	43.94	2467.00	271.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.28	0.91	0.91	87.25
8	n/a	First Floor Height	2.43	2467.00	271.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.28	0.91	0.91	87.25
9	7	Number of chimneys	0	2467.00	271.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.28	0.91	0.91	87.25
10	8	Number of open flues	0	2467.00	271.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.28	0.91	0.91	87.25
11	9	Number of intermittent fans/vents	0	2467.00	271.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.28	0.91	0.91	87.25
12	9a	Number of flueless gas fires	0	2467.00	271.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.28	0.91	0.91	87.25
13	11	Number of Storeys in Dwelling	2	2467.00	271.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.28	0.91	0.91	87.25
14	n/a	% Energy Saving Lightbulbs	100%	2467.00	271.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.28	0.91	0.91	87.25
15		% Energy Saving Lightbulbs	90%	2467.00	271.00	438.00	0.00	35.30	0.00	49.10	0.00	0.00	19.31	31.20	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	168.91	0.91	0.93	87.00
16		% Energy Saving Lightbulbs	80%	2467.00	271.00	478.00	0.00	35.10	0.00	49.10	0.00	0.00	19.31	34.04	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	171.55	0.91	0.95	87.75
17		% Energy Saving Lightbulbs	70%	2467.00	271.00	518.00	0.00	34.90	0.00	49.10	0.00	0.00	19.31	36.87	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	174.19	0.91	0.97	86.50
18		% Energy Saving Lightbulbs	60%	2467.00	271.00	558.00	0.00	34.71	0.00	49.10	0.00	0.00	19.31	39.71	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	176.83	0.91	0.99	86.25
19		% Energy Saving Lightbulbs	50%	2467.00	271.00	598.00	0.00	34.52	0.00	49.10	0.00	0.00	19.31	42.55	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	179.48	0.91	0.99	86.00
20		% Energy Saving Lightbulbs	40%	2467.00	271.00	637.00	0.00	34.33	0.00	49.10	0.00	0.00	19.31	45.38	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	182.13	0.91	1.02	85.75
21		% Energy Saving Lightbulbs	30%	2467.00	271.00	677.00	0.00	34.15	0.00	49.10	0.00	0.00	19.31	48.22	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	184.78	0.91	1.04	85.48
22		% Energy Saving Lightbulbs	20%	2467.00	271.00	717.00	0.00	33.96	0.00	49.10	0.00	0.00	19.31	51.06	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	187.43	0.91	1.06	85.23
23		% Energy Saving Lightbulbs	10%	2467.00	271.00	757.00	0.00	33.78	0.00	49.10	0.00	0.00	19.31	53.89	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	190.08	0.91	1.08	84.98
24		% Energy Saving Lightbulbs	1%	2467.00	271.00	793.00	0.00	33.61	0.00	49.10	0.00	0.00	19.31	56.54	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	192.47	0.91	1.09	84.76
25	n/a	Orientation	N	2467.00	271.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.28	0.91	0.91	87.25
26		Orientation	NE	2467.00	271.00	398.00	0.00	35.25	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.03	0.91	0.91	87.28
27		Orientation	E	2467.00	271.00	398.00	0.00	36.65	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.42	0.91	0.91	87.24
28		Orientation	SE	2467.00	271.00	398.00	0.00	36.53	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	167.31	0.91	0.92	87.16
29		Orientation	S	2467.00	271.00	398.00	0.00	37.37	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	168.15	0.91	0.93	87.07
30		Orientation	SW	2467.00	271.00	398.00	0.00	37.97	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	168.75	0.91	0.93	87.02
31		Orientation	W	2467.00	271.00	398.00	0.00	37.67	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	168.45	0.91	0.93	87.05
32		Orientation	NW	2467.00	271.00	398.00	0.00	36.63	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	167.40	0.91	0.92	87.14
33	13	Structural Infiltration	Masonry	2467.00	271.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.28	0.91	0.91	87.25
34		Structural Infiltration	Steel or Timber Frame				0.00		0.00		0.00	0.00				0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
35	14	Suspended Wooden Floors	n/a	2467.00	271.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.28	0.91	0.91	87.25
36		Suspended Wooden Floors	sealed				0.00		0.00		0.00	0.00				0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
37		Suspended Wooden Floors	unsealed				0.00		0.00		0.00	0.00				0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
38	15	Draught Lobby Present?	Yes	2467.00	271.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.28	0.91	0.91	87.25
39		Draught Lobby Present?	No				0.00		0.00		0.00	0.00				0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
40	16	% Windows/Doors Draughtproofed	100	2467.00	271.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.28	0.91	0.91	87.25
41		% Windows/Doors Draughtproofed	75				0.00		0.00		0.00	0.00				0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
42		% Windows/Doors Draughtproofed	50				0.00		0.00		0.00	0.00				0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
43		% Windows/Doors Draughtproofed	25				0.00		0.00		0.00	0.00				0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
44		% Windows/Doors Draughtproofed	0				0.00		0.00		0.00	0.00				0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
45	19	Q50	3	2467.00	271.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.28	0.91	0.91	87.25
46		Q50	2.95 As Built	2467.00	272.00	398.00	0.00	35.40	0.00	49.10	0.00	0.00	19.40	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.27	0.91	0.91	87.25
47		Q50	1.97 2011	2467.00	297.00	398.00	0.00	33.43	0.00	49.10	0.00	0.00	21.15	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.05	0.91	0.91	87.28
48	20	No.Sides on Which Sheltered	1	2467.00	271.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.28	0.91	0.91	87.25
49	22	Ventilation Type	Balanced whole house ventilation with heat recovery	2467.00	271.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.28	0.91	0.91	87.25
50		Ventilation Type	Natural with passive/intermittent vents 0 vent & positive input from loft	2467.00	75.00	398.00	0.00	53.14	0.00	49.10	0.00	0.00	5.34	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	169.28	0.91	0.94	86.91
51		Ventilation Type	Natural with passive/intermittent vents 1 vent & positive input from loft	2467.00	75.00	398.00	0.00	53.60	0.00	49.10	0.00	0.00	5.34	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	170.71	0.91	0.94	86.86
52		Ventilation Type	Natural with passive/intermittent vents 2 vent & positive input from loft	2467.00	75.00	398.00	0.00	54.20	0.00	49.10	0.00	0.00	5.34	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	171.00	0.91	0.95	86.81
53		Ventilation Type	Natural with passive/intermittent vents 3 vent & positive input from loft	2467.00	75.00	398.00	0.00	54.93	0.00	49.10	0.00	0.00	5.34	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	171.27	0.91	0.95	86.74
54		Ventilation Type	Natural with passive/intermittent vents 4 vent & positive input from loft	2467.00	75.00	398.00	0.00	55.78	0.00	49.10	0.00	0.00	5.34	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	172.59	0.91	0.96	86.65
55		Ventilation Type	Positive input ventilation from outside 0/1/2 vent	2467.00	347.00	398.00	0.00	51.30	0.00	49.10	0.00	0.00	24.68	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	187.45	0.91	1.06	85.23
56		Ventilation Type	Positive input ventilation from outside 3 vent	2467.00	347.00	398.00	0.00	52.73	0.00	49.10	0.00	0.00	24.68	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	188.88	0.91	1.07	85.09
57		Ventilation Type	Positive input ventilation from outside 4 vent	2467.00	347.00	398.00	0.00	55.62	0.00	49.10	0.00	0.00	24.68	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	191.76	0.91	1.09	84.83
58		Ventilation Type	Whole house centralised mechanical extract ventilation	2467.00	347.00	398.00	0.00	52.51	0.00	49.10	0.00	0.00	24.68	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	188.65	0.91	1.07	85.12
59		Ventilation Type	Whole house decentralised mechanical extract ventilation	2467.00	347.00	398.00	0.00	45.41	0.00	49.10	0.00	0.00	16.71	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	173.59	0.91	0.96	86.56
60		Ventilation Type	Balanced whole house ventilation no heat recovery	2467.00	270.00	398.00	0.00	51.90	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	182.68	0.91	1.03	85.69
61	n/a	Ducting Type	Flexible ducting (in use factor 1.7) insulated (in use factor 0.85)	2467.00	271.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.28	0.91	0.91	87.25
62		Ducting Type	Flexible ducting (in use factor 1.7) uninsulated (in use factor 0.70)	2467.00	271.00	398.00	0.00	38.39	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	169.16	0.91	0.93	86.98
63		Ducting Type	Rigid ducting (in use factor 1.4) insulated (in use factor 0.85)	2467.00	237.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	16.84	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	163.81	0.91	0.90	87.49
64		Ducting Type	Rigid ducting (in use factor 1.4) uninsulated (in use factor 0.70)	2467.00	237.00	398.00	0.00	38.39	0.00	49.10	0.00	0.00	16.84	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.70	0.91	0.92	87.21
65	n/a	Heat Recovery Efficiency of System	89%	2467.00	271.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.28	0.91	0.91	87.25
66		Heat Recovery Efficiency of System	85%	2467.00	271.00	398.00	0.00	36.23	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	167.10	0.91	0.92	87.18
67		Heat Recovery Efficiency of System	80%	2467.00	271.00	398.00	0.00	37.15	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	167.93	0.91	0.92	87.10
68		Heat Recovery Efficiency of System	75%	2467.00	271.00	398.00	0.00	38.06	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	168.84	0.91	0.93	87.02
69		Heat Recovery Efficiency of System	70%	2467.00	271.00	398.00	0.00	39.00	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	169.77	0.91	0.94	86.92
70		Heat Recovery Efficiency of System	65%	2467.00	271.00	398.00	0.00	39.92	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	170.49	0.91	0.94	86.84
71		Heat Recovery Efficiency of System	60%	2467.00	271.00	398.00	0.00	40.86	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	171.64	0.91	0.95	86.74
72		Heat Recovery Efficiency of System	55%	2467.00	271.00	398.00	0.00	41.79	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	172.57	0.91	0.96	86.65
73		Heat Recovery Efficiency of System	50%	2467.00	271.00	398.00	0.00	42.75	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	173.53	0.91	0.96	86.56
74	n/a	Specific Fan Power	0.63	2467.00	271.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.28	0.91	0.91	87.25
75		Specific Fan Power	0.50	2467.00	231.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	16.43	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	163.60	0.91	0.89	87.53
76		Specific Fan Power	1.00	2467.00	386.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	27.51	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	174.48	0.91	0.97	86.47
77		Specific Fan Power	1.50	2467.00	542.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	38.60	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	185.57	0.91	1.05	85.41
78		Specific Fan Power	2.00	2467.00	698.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	49.69	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	196.66	0.91	1.12	84.35
79		Specific Fan Power	2.50	2467.00	854.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	60.78	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	207.75	0.91	1.02	83.29
80	26-30	U Values	Base Case	2467.00	271.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.28	0.91	0.91	87.25
81		U Values	+1%	2467.00	271.00	398.00	0.00	35.98	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.76	0.91	0.92	87.21
82		U Values	+2%	2467.00	271.00	398.00	0.00	36.45	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	167.23	0.91	0.92	87.17
83		U Values	+5%	2467.00	271.00	398.00	0.00	37.84	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	168.62	0.91	0.93	87.03
84		U Values	+8%	2467.00	271.00	398.00	0.00	39.20	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	169.97	0.91	0.94	86.91
85		U Values	+10%	2467.00	271.00	398.00	0.00	40.18	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	170.96	0.91	0.95	86.81
86		U Values	+15%	2467.00	271.00	398.00	0.00	42.56	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	173.33	0.91	0.96	86.58
87		U Values	+20%	2467.00	271.00	398.00	0.00	44.98	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	175.76	0.91	0.98	86.35
88		U Values	+21%	2467.00	271.00	398.00	0.00	45.46	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	176.24	0.91	0.98	86.31
89		U Values	+22%	2467.00	271.00	398.00	0.00	45.94	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	176.72	0.91	0.98	86.26
90		U Values	+23%	2467.00	271.00	398.00	0.00	46.43	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	177.2	0.91	0.99	86.21
91		U Values	+24%	2467.00	271.00	398.00	0.00	46.91	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	177.69	0.91	0.99	86.17
92		U Values	+25%	2467.00	271.00	398.00	0.00	47.40	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	178.17	0.91	0.99	86.12
93		U Values	+30%	2467.00	271.00	398.00	0.00	49.84	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	180.61	0.91	1.01	85.89
94		U Values	+40%	2467.00	271.00	398.00	0.00	54.77	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	185.55	0.91	1.04	85.41
95		U Values	+45%	2467.00	271.00	398.00	0.00	57.26	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	188.04	0.91	1.06	85.17
96		U Values	+50%	2467.00	271.00	398.00	0.00	59.77	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	190.54	0.91	1.08	84.94
97	34	Thermal Bridges	7.07 (y=0.04)	2467.00	271.00	398.00	0.00	35.50	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166.28	0.91	0.91	87.25
98		Thermal Bridges	Default 26.5 (y=0.15)	2467.00	271.00	398.00	0.00	53.15	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	183.93	0.91	1.03	85.57
99		Thermal Bridges	User Input 17.67(y=0.10)	2467.00	271.00	398.00	0.00	44.93	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	175.31	0.91	0.98	86.35
100		Thermal Bridges	User Input 35.33 (y=0.2)	2467.00	271.00	398.00	0.00	61.65	0.00	49.10	0.00	0.00	19.31	28.36	34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	192.43	0.91	1.09	84.76

	A	B	C	BY	BZ	CA	CB	CC	CD	CE	CF	CG	CH	CI	CJ	CK	CL	CM	CN	CO	CP	CQ	CR	CS	CT	CU
1				n/a	105	106	107	108	109	110	110b	110c	111	s1a	s2a	112	113	n/a	n/a							
2	SAP Cell Ref	Parameter	Scenario	SAP Band	Cost of Community Space Heating	Cost of Community Water Heating	Cost of Combined Space/Water	Cost of Community Pumps/Fans	Cost of Community Lighting	Cost of PV Energy Produced/Saved	Cost of Wind Energy Produced/Saved	Cost of Special Feature Produced/Saved	Cost of Special Feature Energy Consumed	Energy Produced/Saved in Dwelling	Energy Consumed by Technology	Total CO2	CO2 Emissions Rate	EI Rating	EI Band	PE for Space Heating	PE for Water Heating	PE Space & Water Heating	PE Pumps/ Fans	PE Lighting	PE PV	PE Wind
3		OFFICIAL SAP WORKSHEET VALUES	43.94	B	52.40	72.58	124.97	114.37	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.46	4.64	96.00	A	2305.46	3193.38	5498.85	758.87	1115.40	0.00	0.00
4		SAPPER 8 BASE CASE	43.94	B	52.47	72.57	125.04	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.61	4.64	95.89	A	2308.81	3193.15	5502.00	759.37	1115.00	0.00	0.00
5	1a	Ground Floor Area	43.94	B	52.47	72.57	125.04	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.61	4.64	95.89	A	2308.81	3193.15	5502.00	759.37	1115.00	0.00	0.00
6	n/a	Ground Floor Height	2.3	B	52.47	72.57	125.04	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.61	4.64	95.89	A	2308.81	3193.15	5502.00	759.37	1115.00	0.00	0.00
7	2a	First Floor Area	43.94	B	52.47	72.57	125.04	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.61	4.64	95.89	A	2308.81	3193.15	5502.00	759.37	1115.00	0.00	0.00
8	n/a	First Floor Height	2.43	B	52.47	72.57	125.04	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.61	4.64	95.89	A	2308.81	3193.15	5502.00	759.37	1115.00	0.00	0.00
9	7	Number of chimneys	0	B	52.47	72.57	125.04	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.61	4.64	95.89	A	2308.81	3193.15	5502.00	759.37	1115.00	0.00	0.00
10	8	Number of open flues	0	B	52.47	72.57	125.04	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.61	4.64	95.89	A	2308.81	3193.15	5502.00	759.37	1115.00	0.00	0.00
11	9	Number of intermittent fans/vents	0	B	52.47	72.57	125.04	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.61	4.64	95.89	A	2308.81	3193.15	5502.00	759.37	1115.00	0.00	0.00
12	9a	Number of flueless gas fires	0	B	52.47	72.57	125.04	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.61	4.64	95.89	A	2308.81	3193.15	5502.00	759.37	1115.00	0.00	0.00
13	11	Number of Storeys in Dwelling	2	B	52.47	72.57	125.04	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.61	4.64	95.89	A	2308.81	3193.15	5502.00	759.37	1115.00	0.00	0.00
14	n/a	% Energy Saving Lightbulbs	100%	B	52.47	72.57	125.04	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.61	4.64	95.89	A	2308.81	3193.15	5502.00	759.37	1115.00	0.00	0.00
15		% Energy Saving Lightbulbs	90%	B	52.17	72.57	124.74	114.45	184.93	0.00	0.00	0.00	0.00	0.00	0.00	424.11	4.83	95.72	A	2295.34	3193.15	5488.00	759.37	1227.00	0.00	0.00
16		% Energy Saving Lightbulbs	80%	B	51.87	72.57	124.44	114.45	201.74	0.00	0.00	0.00	0.00	0.00	0.00	440.63	5.01	95.56	A	222.36	3193.15	5476.00	759.37	1339.00	0.00	0.00
17		% Energy Saving Lightbulbs	70%	B	51.59	72.57	124.16	114.45	218.55	0.00	0.00	0.00	0.00	0.00	0.00	457.16	5.20	95.39	A	269.82	3193.15	5463.00	759.37	1450.00	0.00	0.00
18		% Energy Saving Lightbulbs	60%	B	51.30	72.57	123.87	114.45	235.36	0.00	0.00	0.00	0.00	0.00	0.00	473.69	5.39	95.22	A	2257.37	3193.15	5451.00	759.37	1562.00	0.00	0.00
19		% Energy Saving Lightbulbs	50%	B	51.02	72.57	123.59	114.45	252.17	0.00	0.00	0.00	0.00	0.00	0.00	490.22	5.58	95.06	A	2245.00	3193.15	5438.00	759.37	1673.00	0.00	0.00
20		% Energy Saving Lightbulbs	40%	B	50.74	72.57	123.31	114.45	268.99	0.00	0.00	0.00	0.00	0.00	0.00	506.75	5.77	94.89	A	2232.73	3193.15	5426.00	759.37	1785.00	0.00	0.00
21		% Energy Saving Lightbulbs	30%	B	50.47	72.57	123.04	114.45	285.80	0.00	0.00	0.00	0.00	0.00	0.00	523.29	5.95	94.72	A	2220.55	3193.15	5414.00	759.37	1896.00	0.00	0.00
22		% Energy Saving Lightbulbs	20%	B	50.19	72.57	122.76	114.45	302.61	0.00	0.00	0.00	0.00	0.00	0.00	539.82	6.14	94.56	A	2220.45	3193.15	5402.00	759.37	2008.00	0.00	0.00
23		% Energy Saving Lightbulbs	10%	B	49.92	72.57	122.49	114.45	319.42	0.00	0.00	0.00	0.00	0.00	0.00	555.36	6.33	94.39	A	2196.44	3193.15	5390.00	759.37	2119.00	0.00	0.00
24		% Energy Saving Lightbulbs	1%	B	49.67	72.57	122.24	114.45	344.55	0.00	0.00	0.00	0.00	0.00	0.00	571.25	6.50	94.24	A	2185.70	3193.15	5379.00	759.37	2220.00	0.00	0.00
25	n/a	Orientation	N	B	52.47	72.57	125.04	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.61	4.64	95.89	A	2308.81	3193.15	5502.00	759.37	1115.00	0.00	0.00
26		Orientation	NE	B	52.10	72.57	124.67	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.23	4.63	95.89	A	2292.30	3193.15	5485.00	759.37	1115.00	0.00	0.00
27		Orientation	E	B	53.69	72.57	125.26	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.82	4.64	95.89	A	2318.24	3193.15	5511.00	759.37	1115.00	0.00	0.00
28		Orientation	SE	B	53.99	72.57	126.56	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	409.13	4.66	95.87	A	2375.59	3193.15	5569.00	759.37	1115.00	0.00	0.00
29		Orientation	S	B	55.24	72.57	127.81	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	410.30	4.67	95.86	A	2430.50	3193.15	5624.00	759.37	1115.00	0.00	0.00
30		Orientation	SW	B	56.12	72.57	128.69	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	411.26	4.68	95.85	A	2469.28	3193.15	5662.00	759.37	1115.00	0.00	0.00
31		Orientation	W	B	55.68	72.57	128.25	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	410.81	4.67	95.86	A	2776.82	3193.15	5643.00	759.37	1115.00	0.00	0.00
32		Orientation	NW	B	54.13	72.57	126.70	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	409.81	4.66	95.87	A	2381.85	3193.15	5575.00	759.37	1115.00	0.00	0.00
33	13	Structural Infiltration	Masonry	B	52.47	72.57	125.04	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.61	4.64	95.89	A	2308.81	3193.15	5502.00	759.37	1115.00	0.00	0.00
34		Structural Infiltration	Steel or Timber Frame							0.00	0.00	0.00	0.00	0.00	0.00										0.00	0.00
35	14	Suspended Wooden Floors	n/a	B	52.47	72.57	125.04	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.61	4.64	95.89	A	2308.81	3193.15	5502.00	759.37	1115.00	0.00	0.00
36		Suspended Wooden Floors	sealed							0.00	0.00	0.00	0.00	0.00	0.00										0.00	0.00
37		Suspended Wooden Floors	unsealed							0.00	0.00	0.00	0.00	0.00	0.00										0.00	0.00
38	15	Draught Lobby Present?	Yes	B	52.47	72.57	125.04	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.61	4.64	95.89	A	2308.81	3193.15	5502.00	759.37	1115.00	0.00	0.00
39		Draught Lobby Present?	No							0.00	0.00	0.00	0.00	0.00	0.00										0.00	0.00
40	16	% Windows/Doors Draughtproofed	100	B	52.47	72.57	125.04	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.61	4.64	95.89	A	2308.81	3193.15	5502.00	759.37	1115.00	0.00	0.00
41		% Windows/Doors Draughtproofed	75							0.00	0.00	0.00	0.00	0.00	0.00										0.00	0.00
42		% Windows/Doors Draughtproofed	50							0.00	0.00	0.00	0.00	0.00	0.00										0.00	0.00
43		% Windows/Doors Draughtproofed	25							0.00	0.00	0.00	0.00	0.00	0.00										0.00	0.00
44		% Windows/Doors Draughtproofed	0							0.00	0.00	0.00	0.00	0.00	0.00										0.00	0.00
45	19	Q50	3	B	52.47	72.57	125.04	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.61	4.64	95.89	A	2308.81	3193.15	5502.00	759.37	1115.00	0.00	0.00
46		Q50	2.95 As Built	B	52.32	72.57	124.89	114.98	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.99	4.64	95.89	A	2302.12	3193.15	5495.00	762.88	1115.00	0.00	0.00
47		Q50	1.97 2011	B	49.42	72.57	121.99	125.37	168.12	0.00	0.00	0.00	0.00	0.00	0.00	415.47	4.73	95.81	A	2174.31	3193.15	5367.00	831.82	1115.00	0.00	0.00
48	20	No.Sides on Which Sheltered	1	B	52.47	72.57	125.04	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.61	4.64	95.89	A	2308.81	3193.15	5502.00	759.37	1115.00	0.00	0.00
49	22	Ventilation Type	Balanced whole house ventilation with heat recovery	B	52.47	72.57	125.04	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.61	4.64	95.89	A	2308.81	3193.15	5502.00	759.37	1115.00	0.00	0.00
50		Ventilation Type	Natural with passive/intermittent vents 0 vent & positive input from loft	B	78.53	72.57	151.10	31.65	168.12	0.00	0.00	0.00	0.00	0.00	0.00	350.87	3.99	96.46	A	3455.51	3193.15	6649.00	210.00	1115.00	0.00	0.00
51		Ventilation Type	Natural with passive/intermittent vents 1 vent & positive input from loft	B	79.22	72.57	151.79	31.65	168.12	0.00	0.00	0.00	0.00	0.00	0.00	351.56	4.00	96.45	A	3485.82	3193.15	6679.00	210.00	1115.00	0.00	0.00
52		Ventilation Type	Natural with passive/intermittent vents 2 vent & positive input from loft	B	80.10	72.57	152.67	31.65	168.12	0.00	0.00	0.00	0.00	0.00	0.00	352.44	4.01	96.45	A	3524.52	3193.15	6718.00	210.00	1115.00	0.00	0.00
53		Ventilation Type	Natural with passive/intermittent vents 3 vent & positive input from loft	B	81.18	72.57	153.75	31.65	168.12	0.00	0.00	0.00	0.00	0.00	0.00	353.52	4.02	96.44	A	3571.91	3193.15	6765.00	210.00	1115.00	0.00	0.00
54		Ventilation Type	Natural with passive/intermittent vents 4 vent & positive input from loft	B	82.45	72.57	15.02	31.65	168.12	0.00	0.00	0.00	0.00	0.00	0.00	354.79	4.04	96.42	A	3627.75	3193.15	6821.00	210.00	1115.00	0.00	0.00
55		Ventilation Type	Positive input ventilation from outside 0/1/2 vent	B	75.83	72.57	148.40	146.25	168.12	0.00	0.00	0.00	0.00	0.00	0.00	462.76	5.27	95.33	A	3336.36	3193.15	6530.00	970.38	1115.00	0.00	0.00
56		Ventilation Type	Positive input ventilation from outside 3 vent	B	77.94	72.57	150.51	146.25	168.12	0.00	0.00	0.00	0.00	0.00	0.00	464.88	5.29	95.31	A	3429.32	3193.15	6622.00	970.38	1115.00	0.00	0.00
57		Ventilation Type	Positive input ventilation from outside 4 vent	B	82.20	72.57	154.77	146.25	168.12	0.00	0.00	0.00	0.00	0.00	0.00	469.14	5.34	95.27	A	3616.71	3193.15	6810.00	970.38	1115.00	0.00	0.00
58		Ventilation Type	Whole house centralised mechanical extract ventilation	B	77.61	72.57	150.18	146.25	168.12	0.00	0.00	0.00	0.00	0.00	0.00	434.55	5.29	95.32	A	3414.92	3193.15	6608.00	970.38	1115.00	0.00	0.00
59		Ventilation Type	Whole house decentralised mechanical extract ventilation	B	67.12	72.57	139.69	99.06	168.12	0.00	0.00	0.00	0.00	0.00	0.00	406.87	4.63	95.90	A	2953.29	3193.15	6146.00	657.28	1115.00	0.00	0.00
60		Ventilation Type	Balanced whole house ventilation no heat recovery	B	76.71	72.57	149.28	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	431.85	4.91	95.65	A	3375.37	3193.15	6569.00	759.37	1115.00	0.00	0.00
61	n/a	Ducting Type	Flexible ducting (in use factor 1.7) insulated (in use factor 0.85)	B	52.47	72.57	125.04	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.61	4.64	95.89	A	2308.81	3193.15	5502.00	759.37	1115.00	0.00	0.00
62		Ducting Type	Flexible ducting (in use factor 1.7) uninsulated (in use factor 0.70)	B	56.73	72.57	129.30	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	411.87	4.69	95.85	A	2496.26	3193.15	5689.00	759.37	1115.00	0.00	0.00
63		Ducting Type	Rigid ducting (in use factor 1.4) insulated (in use factor 0.85)	B	52.47	72.57	125.04	99.84	168.12	0.00	0.00	0.00	0.00	0.00	0.00	393.00	4.47	96.04	A	2308.81	3193.15	5502.00	662.42	1115.00	0.00	0.00
64		Ducting Type	Rigid ducting (in use factor 1.4) uninsulated (in use factor 0.70)	B	56.73	72.57	129.30	99.84	168.12	0.00	0.00	0.00	0.00	0.00	0.00	397.26	4.52	95.99	A	2496.26	3193.15	5689.00	662.42	1115.00	0.00	0.00
65	n/a	Heat Recovery Efficiency of System	89%	B	52.47	72.57	125.04	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.61	4.64	95.89	A	2308.81	3193.15	5502.00	759.37	1115.00	0.00	0.00
66		Heat Recovery Efficiency of System	85%	B	53.55	72.57	126.12	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	408.68	4.65	95.88	A	2355.99	3193.15	5549.00	759.37	1115.00	0.00	0.00
67		Heat Recovery Efficiency of System	80%	B	54.91	72.57	127.48	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	410.05	4.67	95.86	A	2416.04	3193.15	5609.00	759.37	1115.00	0.00	0.00
68		Heat Recovery Efficiency of System	75%	B	56.25	72.57	128.82	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	411.39	4.68	95.85	A	2475.91	3193.15	5668.00	759.37	1115.00	0.00	0.00
69		Heat Recovery Efficiency of System	70%	B	57.63	72.57	130.20	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	412.77	4.70	95.84	A	2535.91	3193.15	5729.00	759.37	1115.00	0.00	0.00
70		Heat Recovery Efficiency of System	65%	B	58.99	72.57	131.56	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	414.13	4.71	95.82	A	2595.73	3193.15	5789.00	759.37	1115.00	0.00	0.00
71		Heat Recovery Efficiency of System	60%	B	60.39	72.57	132.96	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	415.55	4.73	95.81	A	2657.33	3193.15	5850.00	759.37	1115.00	0.00	0.00
72		Heat Recovery Efficiency of System	55%	B	61.77	72.57	134.34	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	416.91	4.74	95.80	A	2727.87	3193.15	5911.00	759.37	1115.00	0.00	0.00
73		Heat Recovery Efficiency of System	50%	B	63.19	72.57	135.76	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	418.32	4.76	95.78	A	2780.20	3193.15	5973.00	759.37	1115.00	0.00	0.00
74	n/a	Specific Fan Power	0.63	B	52.47	72.57	125.04	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.61	4.64	95.89	A	2308.81	3193.15	5502.00	759.37	1115.00	0.00	0.00
75		Specific Fan Power	0.50	B	52.47	72.57	125.04	97.36	168.12	0.00	0.00	0.00	0.00	0.00	0.00	408.32	4.44	96.06	A	2308.81	3193.15	5502.00	646.01	1115.00	0.00	0.00
76		Specific Fan Power	1.00	B	52.47	72.57	125.04	163.08	168.12	0.00	0.00	0.00	0.00	0.00	0.00	409.01	5.19	95.40	A	2308.81	3193.15	5502.00	1082.02	1115.00	0.00	0.00
77		Specific Fan Power	1.50	B	52.47	72.57	125.04	228.79	168.12	0.00	0.00	0.00	0.00	0.00	0.00	414.53	5.94	94.74	A	2308.81	3193.15	5502.00	1518.04	1115.00	0.00	0.00
78		Specific Fan Power	2.00	B	52.47	72.57	125.04	294.50	168.12	0.00	0.00	0.00	0.00	0.00	0.00	413.07	6.69	94.07	A	2308.81	3193.15	5502.00	1954.04	1115.00	0.00	0.00
79		Specific Fan Power	2.50	B	52.47	72.57	125.04	360.21	168.12	0.00	0.00	0.00	0.00	0.00	0.00	418.03	7.43	93.41	A	2308.81	3193.15	5502.00	2390.05	1115.00	0.00	0.00
80	26-30	U Values	Base Case	B	52.47	72.57	125.04	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.61	4.64	95.89	A	2308.81	3193.15	5502.00	759.37	1115.00	0.00	0.00
81		U Values	+1%	B	53.18	72.57	125.75	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	408.32	4.55	95.88	A	2339.87	3193.15	5533.00	759.37	1115.00	0.00	0.00
82		U Values	+2%	B	53.87	72.57	126.44	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	409.01	4.65	95.88	A	2370.00	3193.15	5564.00	759.37	1115.00	0.00	0.00
83		U Values	+5%	B	55.93	72.57	128.50	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	411.06	4.68	95.85	A	2460.75	3193.15	5654.00	759.37	1115.00	0.00	0.00
84		U Values	+8%	B	57.93	72.57	130.50	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	413.07	4.70	95.83	A	2549.02	3193.15	5742.00	759.37	1115.00	0.00	0.00
85		U Values	+10%	B	59.39	72.57	131.96	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	414.53	4.72	95.82	A	2613.22	3193.15	5806.00	759.37	1115.00	0.00	0.00
86		U Values	+15%	B	62.90	72.57	135.47	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	418.03	4.76	95.78	A	2767.41	3193.15	5961.00	759.37	1115.00	0.00	0.00
87		U Values	+20%	B	66.48	72.57	139.05	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	421.61	4.80	95.75	A	2925.04	3193.15	6118.00	759.37	1115.00	0.00	0.00
88		U Values	+21%	B	67.19	72.57	139.76	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	422.33	4.81	95.74	A	2956.40	3193.15	6150.00	759.37	1115.00	0.00	0.00
89		U Values	+22%	B	67.90	72.57	140.47	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	423.04	4.81	95.73	A	2987.77	3193.15	6181.00	759.37	1115.00	0.00	0.00
90		U Values	+23%	B	68.62	72.57	141.19	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	423.76	4.82	95.73	A	3019.25	3193.15	6212.00	759.37	1115.00	0.00	0.00
91		U Values	+24%	B	69.33	72.57	141.90	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	424.47	4.83	95.72	A	3050.74	3193.15	6244.00	759.37	1115.00	0.00	0.00
92		U Values	+25%	B	70.05	72.57	142.62	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	425.19	4.84	95.71	A	3082.37	3193.15	6276.00	759.37	1115.00	0.00	0.00
93		U Values	+30%	B	73.66	72.57	146.23	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	428.79	4.88	95.68	A	3240.95	3193.15	6234.00	759.37	1115.00	0.00	0.00
94		U Values	+40%	B	80.95	72.57	153.52	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	436.09	4.96	95.60	A	3561.79	3193.15	6755.00	759.37	1115.00	0.00	0.00
95		U Values	+45%	B	84.63	72.57	157.20	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	439.77	5.00	95.57	A	3723.78	3193.15	6917.00	759.37	1115.00	0.00	0.00
96		U Values	+50%	B	88.33	72.57	160.90	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	443.47	5.05	95.53	A	3886.68	3193.15	7080.00	759.37	1115.00	0.00	0.00
97	34	Thermal Bridges	7.07 (y=0.04)	B	52.47	72.57	125.04	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	407.61	4.64	95.89	A	2308.81	3193.15	5502.00	759.37	1115.00	0.00	0.00
98		Thermal Bridges	Default 26.5 (y=0.15)	B	78.56	72.57	151.13	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	433.69	4.94	95.63	A	3456.45	3193.15	6650.00	759.37	1115.00	0.00	0.00
99		Thermal Bridges	User Input 17.67(y=0.10)	B	66.41	72.57	138.98	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	421.54	4.80	95.75	A	2921.96	3193.15	1115.00	759.37	1115.00	0.00	0.00
100		Thermal Bridges	User Input 35.33 (y=0.2)	B	91.12	72.57	163.69	114.45	168.12	0.00	0.00	0.00	0.00	0.00	0.00	446.25	5.08	95.50	A	4009.10	3193.15	7202.00	759.37	1115.00	0.00	0.00

	A	B	C	CV	CW	CX	CY	CZ	DA
1									
2	SAP Cell Ref	Parameter	Scenario	PE MicroCHP produced	PE MIcroCHP Consume	PE Produced/Saved by	PE Consumed by Technology	PE Total	PE m2
3		OFFICIAL SAP WORKSHEET VALUES	43.94	0.00	0.00	0.00	0.00	7373.17	83.90
4		SAPPER 8 BASE CASE	43.94	0.00	0.00	0.00	0.00	7377.00	84.94
5	1a	Ground Floor Area	43.94	0.00	0.00	0.00	0.00	7377.00	84.94
6	n/a	Ground Floor Height	2.3	0.00	0.00	0.00	0.00	7377.00	84.94
7	2a	First Floor Area	43.94	0.00	0.00	0.00	0.00	7377.00	84.94
8	n/a	First Floor Height	2.43	0.00	0.00	0.00	0.00	7377.00	84.94
9	7	Number of chimneys	0	0.00	0.00	0.00	0.00	7377.00	84.94
10	8	Number of open flues	0	0.00	0.00	0.00	0.00	7377.00	84.94
11	9	Number of intermittent fans/vents	0	0.00	0.00	0.00	0.00	7377.00	84.94
12	9a	Number of flueless gas fires	0	0.00	0.00	0.00	0.00	7377.00	84.94
13	11	Number of Storeys in Dwelling	2	0.00	0.00	0.00	0.00	7377.00	84.94
14	n/a	% Energy Saving Lightbulbs	100%	0.00	0.00	0.00	0.00	7377.00	84.94
15		% Energy Saving Lightbulbs	90%	0.00	0.00	0.00	0.00	7475.00	85.06
16		% Energy Saving Lightbulbs	80%	0.00	0.00	0.00	0.00	7573.00	86.17
17		% Energy Saving Lightbulbs	70%	0.00	0.00	0.00	0.00	7672.00	87.30
18		% Energy Saving Lightbulbs	60%	0.00	0.00	0.00	0.00	7772.00	88.44
19		% Energy Saving Lightbulbs	50%	0.00	0.00	0.00	0.00	7871.00	89.57
20		% Energy Saving Lightbulbs	40%	0.00	0.00	0.00	0.00	7970.00	90.69
21		% Energy Saving Lightbulbs	30%	0.00	0.00	0.00	0.00	8069.00	91.82
22		% Energy Saving Lightbulbs	20%	0.00	0.00	0.00	0.00	8169.00	92.96
23		% Energy Saving Lightbulbs	10%	0.00	0.00	0.00	0.00	8268.00	94.08
24		% Energy Saving Lightbulbs	1%	0.00	0.00	0.00	0.00	8358.00	95.11
25	n/a	Orientation	N	0.00	0.00	0.00	0.00	7377.00	84.94
26		Orientation	NE	0.00	0.00	0.00	0.00	7360.00	83.75
27		Orientation	E	0.00	0.00	0.00	0.00	7386.00	84.05
28		Orientation	SE	0.00	0.00	0.00	0.00	7444.00	84.71
29		Orientation	S	0.00	0.00	0.00	0.00	7498.00	85.32
30		Orientation	SW	0.00	0.00	0.00	0.00	7537.00	85.76
31		Orientation	W	0.00	0.00	0.00	0.00	7518.00	85.55
32		Orientation	NW	0.00	0.00	0.00	0.00	7450.00	84.77
33	13	Structural Infiltration	Masonry	0.00	0.00	0.00	0.00	7377.00	84.94
34		Structural Infiltration	Steel or Timber Frame	0.00	0.00	0.00	0.00		
35	14	Suspended Wooden Floors	n/a	0.00	0.00	0.00	0.00	7377.00	84.94
36		Suspended Wooden Floors	sealed	0.00	0.00	0.00	0.00		
37		Suspended Wooden Floors	unsealed	0.00	0.00	0.00	0.00		
38	15	Draught Lobby Present?	Yes	0.00	0.00	0.00	0.00	7377.00	84.94
39		Draught Lobby Present?	No	0.00	0.00	0.00	0.00		
40	16	% Windows/Doors Draughtproofed	100	0.00	0.00	0.00	0.00	7377.00	84.94
41		% Windows/Doors Draughtproofed	75	0.00	0.00	0.00	0.00		
42		% Windows/Doors Draughtproofed	50	0.00	0.00	0.00	0.00		
43		% Windows/Doors Draughtproofed	25	0.00	0.00	0.00	0.00		
44		% Windows/Doors Draughtproofed	0	0.00	0.00	0.00	0.00		
45	19	Q50	3	0.00	0.00	0.00	0.00	7377.00	84.94
46		Q50	2.95 As Built	0.00	0.00	0.00	0.00	7374.00	83.91
47		Q50	1.97 2011	0.00	0.00	0.00	0.00	7315.00	83.24
48	20	No.Sides on Which Sheltered	1	0.00	0.00	0.00	0.00	7377.00	84.94
49	22	Ventilation Type	Balanced whole house ventilation with heat recovery	0.00	0.00	0.00	0.00	7377.00	84.94
50		Ventilation Type	Natural with passive/intermittent vents 0 vent & positive input from loft	0.00	0.00	0.00	0.00	7974.00	90.74
51		Ventilation Type	Natural with passive/intermittent vents 1 vent & positive input from loft	0.00	0.00	0.00	0.00	8004.00	91.08
52		Ventilation Type	Natural with passive/intermittent vents 2 vent & positive input from loft	0.00	0.00	0.00	0.00	8043.00	91.52
53		Ventilation Type	Natural with passive/intermittent vents 3 vent & positive input from loft	0.00	0.00	0.00	0.00	8091.00	92.07
54		Ventilation Type	Natural with passive/intermittent vents 4 vent & positive input from loft	0.00	0.00	0.00	0.00	8146.00	92.69
55		Ventilation Type	Positive input ventilation from outside 0/1/2 vent	0.00	0.00	0.00	0.00	8615.00	98.03
56		Ventilation Type	Positive input ventilation from outside 3 vent	0.00	0.00	0.00	0.00	8708.00	99.09
57		Ventilation Type	Positive input ventilation from outside 4 vent	0.00	0.00	0.00	0.00	8896.00	101.23
58		Ventilation Type	Whole house centralised mechanical extract ventilation	0.00	0.00	0.00	0.00	8694.00	98.93
59		Ventilation Type	Whole house decentralised mechanical extract ventilation	0.00	0.00	0.00	0.00	7919.00	90.11
60		Ventilation Type	Balanced whole house ventilation no heat recovery	0.00	0.00	0.00	0.00	8443.00	96.07
61	n/a	Ducting Type	Flexible ducting (in use factor 1.7) insulated (in use factor 0.85)	0.00	0.00	0.00	0.00	7377.00	84.94
62		Ducting Type	Flexible ducting (in use factor 1.7) uninsulated (in use factor 0.70)	0.00	0.00	0.00	0.00	7564.00	86.07
63		Ducting Type	Rigid ducting (in use factor 1.4) insulated (in use factor 0.85)	0.00	0.00	0.00	0.00	7280.00	82.84
64		Ducting Type	Rigid ducting (in use factor 1.4) uninsulated (in use factor 0.70)	0.00	0.00	0.00	0.00	7467.00	84.97
65	n/a	Heat Recovery Efficiency of System	89%	0.00	0.00	0.00	0.00	7377.00	84.94
66		Heat Recovery Efficiency of System	85%	0.00	0.00	0.00	0.00	7424.00	84.48
67		Heat Recovery Efficiency of System	80%	0.00	0.00	0.00	0.00	7484.00	85.16
68		Heat Recovery Efficiency of System	75%	0.00	0.00	0.00	0.00	7543.00	85.83
69		Heat Recovery Efficiency of System	70%	0.00	0.00	0.00	0.00	7604.00	86.53
70		Heat Recovery Efficiency of System	65%	0.00	0.00	0.00	0.00	7664.00	87.21
71		Heat Recovery Efficiency of System	60%	0.00	0.00	0.00	0.00	7725.00	87.90
72		Heat Recovery Efficiency of System	55%	0.00	0.00	0.00	0.00	7786.00	88.60
73		Heat Recovery Efficiency of System	50%	0.00	0.00	0.00	0.00	7848.00	89.30
74	n/a	Specific Fan Power	0.63	0.00	0.00	0.00	0.00	7377.00	84.94
75		Specific Fan Power	0.50	0.00	0.00	0.00	0.00	7263.00	82.65
76		Specific Fan Power	1.00	0.00	0.00	0.00	0.00	7699.00	87.61
77		Specific Fan Power	1.50	0.00	0.00	0.00	0.00	8135.00	92.57
78		Specific Fan Power	2.00	0.00	0.00	0.00	0.00	8571.00	97.53
79		Specific Fan Power	2.50	0.00	0.00	0.00	0.00	9007.00	102.49
80	26-30	U Values	Base Case	0.00	0.00	0.00	0.00	7377.00	84.94
81		U Values	+1%	0.00	0.00	0.00	0.00	7408.00	84.30
82		U Values	+2%	0.00	0.00	0.00	0.00	7438.00	84.64
83		U Values	+5%	0.00	0.00	0.00	0.00	7529.00	85.67
84		U Values	+8%	0.00	0.00	0.00	0.00	7617.00	86.68
85		U Values	+10%	0.00	0.00	0.00	0.00	7681.00	87.40
86		U Values	+15%	0.00	0.00	0.00	0.00	7835.00	89.16
87		U Values	+20%	0.00	0.00	0.00	0.00	7993.00	90.95
88		U Values	+21%	0.00	0.00	0.00	0.00	8024.00	91.31
89		U Values	+22%	0.00	0.00	0.00	0.00	8056.00	91.67
90		U Values	+23%	0.00	0.00	0.00	0.00	8087.00	92.02
91		U Values	+24%	0.00	0.00	0.00	0.00	8119.00	92.39
92		U Values	+25%	0.00	0.00	0.00	0.00	8150.00	92.74
93		U Values	+30%	0.00	0.00	0.00	0.00	8309.00	94.55
94		U Values	+40%	0.00	0.00	0.00	0.00	8630.00	98.20
95		U Values	+45%	0.00	0.00	0.00	0.00	8792.00	100.05
96		U Values	+50%	0.00	0.00	0.00	0.00	8955.00	101.90
97	34	Thermal Bridges	7.07 (y=0.04)	0.00	0.00	0.00	0.00	7377.00	84.94
98		Thermal Bridges	Default 26.5 (y=0.15)	0.00	0.00	0.00	0.00	8524.00	97.00
99		Thermal Bridges	User Input 17.67(y=0.10)	0.00	0.00	0.00	0.00	7990.00	90.92
100		Thermal Bridges	User Input 35.33 (y=0.2)	0.00	0.00	0.00	0.00	9077.00	103.29

Appendix 8 - SAP 2009 Sensitivity Analysis Worksheet

SAP 2009 MODEL SENSITIVITY ANALYSIS (NO MVHR VENTILATION STRATEGY)											
			Total Fabric Heat Loss	**Heat Loss Coefficient**	**Space Heating Demand**	**Space Heat Req**	**SAP Rating**		**EI rating**		**Carbon Emissions**	**Primary Energy**
Baseline Data			**121.98**	**170.57**	**5604.87**	**6353.28**	**80**	**C**	**81**	**B**	**2133.43**	**11132.21**
U Values (Wall)	%	Value										
	5.00	0.22	122.89	171.48	5650.63	6405.16	80	C	81	B	2243.60	11184.62
	10.00	0.23	123.80	172.39	5696.36	6456.99	80	C	81	B	2153.77	11237.00
	15.00	0.24	124.71	173.30	5741.99	6508.71	80	C	81	B	2163.92	11289.27
	20.00	0.25	125.62	174.21	5787.58	6560.39	80	C	81	B	2174.06	11341.50
	25.00	0.26	126.53	175.12	5833.06	6611.95	80	C	81	B	2184.17	11393.63
	30.00	0.27	127.44	176.03	5878.59	6663.56	80	C	81	B	2194.30	11445.80
	40.00	0.29	129.26	177.85	5969.36	6766.45	80	C	81	B	2215.50	11549.84
	50.00	0.32	131.07	179.67	6059.93	6869.12	80	C	80	C	2234.65	11653.67
	-5.00	0.20	121.07	169.66	5559.08	6301.39	80	C	81	B	2123.25	11079.77
	-10.00	0.19	120.16	168.75	5513.15	6249.32	80	C	81	B	2113.04	11027.18
	-15.00	0.18	119.25	167.84	5467.27	6197.31	81	B	82	B	2102.84	10974.65
	-20.00	0.17	118.34	166.93	5421.26	6145.16	81	B	82	B	2092.62	10921.98
	-25.00	0.16	117.43	166.02	5375.24	6093.00	81	B	82	B	2082.40	10869.31
	-30.00	0.15	116.52	165.11	5329.17	6040.77	81	B	82	B	2072.16	10816.58
	-40.00	0.13	114.70	163.29	5236.83	5936.10	81	B	82	B	2051.65	10710.92
	-50.00	0.11	112.88	161.47	5144.33	5831.25	81	B	82	B	2031.11	10605.11
U Values (Roof)	%	Value										
	5.00	0.17	122.42	171.01	5627.03	6378.41	80	C	81	B	2138.36	11157.59
	10.00	0.18	122.86	171.45	5649.22	6403.56	80	C	81	B	2143.29	11183.01
	15.00	0.18	123.30	171.89	5671.33	6428.62	80	C	81	B	2148.20	11208.33
	20.00	0.19	123.74	172.33	5693.53	6453.78	80	C	81	B	2153.14	11233.76
	25.00	0.20	124.18	172.78	5715.65	6478.85	80	C	81	B	2158.06	11256.09
	30.00	0.21	124.62	173.22	5737.73	6503.89	80	C	81	B	2162.97	11284.39
	40.00	0.22	125.50	174.10	5781.99	6554.05	80	C	81	B	2172.81	11335.10
	50.00	0.24	126.38	174.98	5826.11	6604.07	80	C	81	B	2182.63	11385.66
	-5.00	0.15	121.53	170.13	5582.66	6328.11	80	C	81	B	2128.49	11106.77
	-10.00	0.14	121.09	169.69	5560.48	6302.97	80	C	81	B	2123.56	11081.38
	-15.00	0.14	120.65	169.25	5538.25	6277.78	80	C	81	B	2118.62	11055.92
	-20.00	0.13	120.21	168.81	5516.03	6252.58	80	C	81	B	2113.68	11030.47
	-25.00	0.12	119.77	168.37	5493.78	6227.36	80	C	82	B	2108.73	11005.00
	-30.00	0.11	119.33	167.93	5471.49	6202.10	81	B	82	B	2103.78	10979.48
	-40.00	0.10	118.45	167.04	5426.97	6151.63	81	B	82	B	2093.89	10928.51
	-50.00	0.08	117.57	166.16	5382.37	6101.08	81	B	82	B	2083.98	10877.46
U Values (Floor)	%	Value										
	5.00	0.22	122.55	171.15	5634.00	6386.31	80	C	81	B	2139.91	11165.57
	10.00	0.23	123.13	171.73	5663.08	6419.27	80	C	81	B	2146.37	11198.88
	15.00	0.24	123.71	172.31	5692.13	6452.20	80	C	81	B	2152.83	11232.16
	20.00	0.25	124.29	172.89	5721.20	6485.15	80	C	81	B	2159.29	11265.46
	25.00	0.26	124.87	173.46	5750.22	6518.04	80	C	81	B	2165.75	11298.70
	30.00	0.27	125.45	174.04	5779.18	6550.87	80	C	81	B	2172.19	11331.89
	40.00	0.29	126.61	175.20	5837.15	6616.58	80	C	81	B	2185.08	11398.31
	50.00	0.32	127.76	176.36	5894.96	6682.12	80	C	81	B	2197.94	11464.56
	-5.00	0.20	121.40	169.99	5575.74	6320.26	80	C	81	B	2126.95	11098.84
	-10.00	0.19	120.82	169.41	5546.57	6287.20	80	C	81	B	2120.47	11065.45
	-15.00	0.18	120.24	168.83	5517.44	6254.18	80	C	81	B	2113.99	11032.09
	-20.00	0.17	119.66	168.26	5488.20	6221.04	80	C	82	B	2107.50	10998.61
	-25.00	0.16	119.08	167.68	5459.01	6187.94	80	C	82	B	2101.01	10965.19
	-30.00	0.15	118.50	167.10	5429.72	6154.75	81	B	82	B	2094.50	10931.66
	-40.00	0.13	117.35	165.94	5371.21	6088.43	81	B	82	B	2081.50	10864.69
	-50.00	0.11	116.19	164.78	5312.53	6021.91	81	B	82	B	2068.46	10797.54
U Values (Windows/Doors)	%	Value										
	5.00	1.68	124.29	172.89	5721.20	6485.15	80	C	81	B	2159.30	11265.46
	10.00	1.76	126.59	175.19	5836.52	6615.87	80	C	81	B	2184.94	11397.58
	15.00	1.84	128.88	177.48	5950.93	6745.56	80	C	81	B	2210.40	11528.71
	20.00	1.92	131.16	179.76	6064.36	6874.13	80	C	80	C	2235.64	11658.75
	25.00	2.00	133.43	182.03	6176.84	7001.63	79	C	80	C	2260.68	11787.73
	30.00	2.08	135.69	184.28	6288.39	7128.08	79	C	80	C	2285.51	11915.67
	40.00	2.24	140.16	188.76	6508.70	7377.80	79	C	80	C	2334.58	12168.44
	50.00	2.40	144.60	193.19	6725.34	7623.38	79	C	79	C	2382.85	12417.12
	-5.00	1.52	119.65	168.24	5487.59	6220.35	80	C	82	B	2107.36	10997.92
	-10.00	1.44	117.31	165.90	5369.33	6086.30	81	B	82	B	2081.08	10862.57
	-15.00	1.36	114.96	163.55	5250.13	5951.17	81	B	82	B	2054.60	10726.13
	-20.00	1.28	112.59	161.19	5129.91	5814.90	81	B	82	B	2027.91	10588.62
	-25.00	1.20	110.22	158.81	5008.75	5677.57	81	B	82	B	2001.02	10450.08
	-30.00	1.12	107.83	156.42	4886.60	5539.11	81	B	83	B	1973.91	10310.47
	-40.00	0.96	103.01	151.61	4639.47	5258.98	82	B	83	B	1919.12	10028.18
	-50.00	0.80	98.14	146.74	4388.47	4974.46	82	B	84	B	1863.52	9741.76
U Values (Party Wall)		Value										
		0.10	125.19	173.78	5766.04	6535.97	80	C	81	B	2169.27	11316.82
		0.50	138.02	186.62	6403.57	7258.63	79	C	80	C	2311.16	12047.81
Thermal Bridging	y value											
	y=0.15		121.98	170.57	5604.87	6353.28	80	C	81	B	2133.43	11132.21
	y=0.08		105.93	154.52	4789.38	5428.90	82	B	83	B	1952.35	10199.38
	y=0.04		96.76	145.36	4317.13	4893.59	82	B	84	B	1847.72	9660.40
	y=0.1		110.51	159.11	5023.91	5694.75	81	B	82	B	2004.38	10467.41
	y=0.2		133.44	182.03	6177.13	7001.96	79	C	80	C	2260.74	11788.07
	y=0.3		156.36	204.96	7293.31	8267.19	78	C	78	C	2509.49	13069.50
	y=0.4		179.28	227.88	8371.04	9488.83	76	C	76	C	2750.06	14306.79
	y=0.5		202.21	250.80	9411.77	10668.52	75	C	76	C	2982.63	15506.87

SAP 2009 MODEL SENSITIVITY ANALYSIS (NO MVHR VENTILATION STRATEGY)

			Total Fabric Heat Loss	Heat Loss Coefficient	Space Heating Demand	Space Heat Req	SAP Rating		EI rating		Carbon Emissions	Primary Energy
Baseline Data			**121.98**	**170.57**	**5604.87**	**6353.28**	**80**	**C**	**81**	**B**	**2133.43**	**11132.21**
Air Pressure Test	q50 Value											
	7.00		121.98	170.57	5604.87	6353.28	80	C	81	B	2133.43	11132.21
	8.00		121.98	172.10	5695.41	6455.91	80	C	81	B	2153.58	11236.01
	9.00		121.98	173.82	5797.67	6571.83	80	C	81	B	2176.34	11353.28
	10.00		121.98	175.76	5911.64	6701.02	80	C	81	B	2201.72	11484.00
	11.00		121.98	177.89	6037.37	6843.54	80	C	80	C	2229.65	11627.91
	12.00		121.98	180.23	6137.81	6957.39	79	C	80	C	2260.11	11784.82
	13.00		121.98	182.77	6321.81	7165.96	79	C	80	C	2296.09	11954.69
	14.00		121.98	185.51	6480.83	7346.21	79	C	80	C	2328.53	12137.27
	15.00		121.98	188.46	6650.66	7538.72	79	C	79	C	2366.39	12332.30
	6.00		121.98	169.25	5526.19	6264.10	80	B	81	B	2115.92	11042.01
	5.00		121.98	168.13	5459.48	6188.48	81	B	82	B	2101.08	10965.55
	4.00		121.98	167.22	5404.80	6126.50	81	B	82	B	2088.92	10902.90
	3.00		121.98	166.50	5362.19	6078.20	81	B	82	B	2079.44	10854.07
Divide by 20 Rule	Division Factor	q50 Eqivalent										
	20.00	7.00	121.98	170.57	5604.87	6353.28	80	C	81	B	2133.43	11132.21
	15.00	9.20	121.98	174.19	5819.54	6596.62	80	C	81	B	2181.21	11378.36
	10.00	14.00	121.98	185.51	6480.83	7346.21	79	C	80	C	2328.53	12137.27
	5.00	28.00	121.98	238.97	9312.67	10556.19	75	C	74	C	2960.73	15394.07
	25.00	5.50	121.98	168.66	5491.33	6224.59	80	C	82	B	2108.17	11002.07
	30.00	4.70	121.98	167.84	5441.81	6168.46	81	B	82	B	2097.15	10945.31
0.5 ACH	ACH	q50 Equivalent										
	0.50	7.00	121.98	170.57	5604.87	6353.28	80	C	81	B	2133.43	11132.21
	0.60	11.45	121.98	178.95	6097.20	6911.36	80	C	80	C	2243.04	11696.90
	0.70	15.00	121.98	188.45	6650.66	7538.72	79	C	79	C	2366.39	12332.30
	0.80	17.80	121.98	197.94	7182.12	8141.14	78	C	78	C	2484.92	12942.94
	0.90	20.40	121.98	207.43	7726.69	8758.44	77	C	77	C	2606.46	13569.02
	1.00	22.70	121.98	216.93	8213.99	9310.81	76	C	76	C	2715.26	14129.50
	0.55	9.23		174.24	5822.32	6599.77	80	C	81	B	2181.83	11381.54

SAP 2009 MODEL SENSITIVITY ANALYSIS (WITH MVHR VENTILATION STRATEGY)

			Total Fabric Heat Losses	Heat Loss Coefficient	Space Heating Demand	Space Heating Fuel	SAP Rating		EI rating		Carbon Emissions	Primary Energy
Baseline Data			**121.98**	**161.47**	**5236.78**	**5936.05**	**79.00**	**C**	**80.00**	**C**	**2230.31**	**11720.09**
U Values (Wall)	%	Value										
	5.00	0.22	122.89	162.38	5282.88	5988.30	79.00	C	80.00	C	2240.58	11772.83
	10.00	0.23	123.80	163.29	5328.92	6040.49	79.00	C	80.00	C	2250.80	11825.50
	15.00	0.24	124.71	164.20	5374.89	6092.60	79.00	C	80.00	C	2261.01	11878.10
	20.00	0.25	125.62	165.11	5420.86	6144.71	79.00	C	80.00	C	2271.22	11930.71
	25.00	0.26	126.53	166.02	5466.79	6196.77	79.00	C	80.00	C	2281.43	11983.27
	30.00	0.27	127.44	166.93	5512.57	6248.66	79.00	C	80.00	C	2291.60	12035.68
	40.00	0.29	129.26	168.75	5604.15	6352.47	79.00	C	80.00	C	2311.95	12140.53
	50.00	0.32	131.07	170.57	5695.48	6456.00	79.00	C	80.00	C	2332.26	12245.12
	- 5.00	0.20	121.07	160.56	5190.60	5883.70	79.00	C	81.00	B	2220.09	11667.27
	- 10.00	0.19	120.16	159.65	5144.41	5831.34	79.00	C	81.00	B	2209.83	11614.45
	- 15.00	0.18	119.25	158.74	5098.21	5778.97	79.00	C	81.00	B	2199.58	11561.62
	- 20.00	0.17	118.34	157.83	5051.92	5726.50	79.00	C	81.00	B	2189.30	11508.70
	- 25.00	0.16	117.43	156.92	5005.58	5673.97	80.00	C	81.00	B	2179.02	11455.74
	- 30.00	0.15	116.52	156.01	4959.22	5621.42	80.00	C	81.00	B	2168.74	11402.76
	- 40.00	0.13	114.70	154.19	4866.31	5516.11	80.00	C	81.00	B	2148.13	11296.59
	- 50.00	0.11	112.88	152.37	4773.26	5410.63	80.00	C	81.00	B	2127.50	11190.32
U Values (Roof)	%	Value										
	5.00	0.17	122.42	161.91	5259.11	5961.36	79.00	C	80.00	C	2235.30	11745.63
	10.00	0.18	122.86	162.35	5281.43	5986.66	79.00	C	80.00	C	2240.25	11771.17
	15.00	0.18	123.30	162.80	5303.74	6011.95	79.00	C	80.00	C	2245.21	11796.69
	20.00	0.19	123.74	163.27	5326.04	6037.23	79.00	C	80.00	C	2250.16	11822.20
	25.00	0.20	124.18	163.68	5348.37	6062.54	79.00	C	80.00	C	2255.12	11847.75
	30.00	0.21	124.62	164.12	5370.67	6087.81	79.00	C	80.00	C	2260.07	11873.27
	40.00	0.22	125.50	165.00	5415.20	6138.29	79.00	C	80.00	C	2269.97	11924.23
	50.00	0.24	126.38	165.88	5459.67	6188.70	79.00	C	80.00	C	2279.85	11975.12
	- 5.00	0.15	121.53	161.03	5214.40	5910.68	79.00	C	80.00	C	2225.37	11694.50
	- 10.00	0.14	121.09	160.59	5192.03	5885.32	79.00	C	81.00	B	2220.40	11668.91
	- 15.00	0.14	120.65	160.15	5169.65	5859.95	79.00	C	81.00	B	2215.43	11643.31
	- 20.00	0.13	120.21	159.71	5147.29	5834.61	79.00	C	81.00	B	2210.47	11617.75
	- 25.00	0.12	119.77	159.27	5124.86	5809.18	79.00	C	81.00	B	2205.49	11592.10
	- 30.00	0.11	119.33	158.83	5102.45	5783.78	79.00	C	81.00	B	2200.52	11566.48
	- 40.00	0.10	118.45	157.95	5057.62	5732.96	79.00	C	81.00	B	2190.57	11515.22
	- 50.00	0.08	117.57	157.06	5012.71	5682.06	80.00	C	81.00	B	2180.60	11463.88
U Values (Floor)	%	Value										
	5.00	0.22	122.55	162.05	5266.10	5969.28	79.00	C	80.00	C	2236.85	11753.63
	10.00	0.23	123.13	162.63	5295.39	6002.48	79.00	C	80.00	C	2243.35	11787.14
	15.00	0.24	123.71	163.21	5324.66	6035.66	79.00	C	80.00	C	2249.85	11820.62
	20.00	0.25	124.29	163.79	5353.93	6068.84	79.00	C	80.00	C	2256.35	11854.11
	25.00	0.26	124.87	164.37	5383.20	6102.01	79.00	C	80.00	C	2262.86	11887.60
	30.00	0.27	125.45	164.95	5412.42	6135.14	79.00	C	80.00	C	2269.35	11921.05
	40.00	0.29	126.61	166.10	5470.78	6201.29	79.00	C	80.00	C	2282.31	11987.84
	50.00	0.32	127.76	167.26	5529.09	6267.39	79.00	C	80.00	C	2295.27	12054.59
	- 5.00	0.20	121.40	160.89	5207.41	5902.76	79.00	C	80.00	C	2223.82	11686.50
	- 10.00	0.19	120.82	160.32	5178.05	5869.47	79.00	C	81.00	B	2217.30	11652.92
	- 15.00	0.18	120.24	159.74	5148.68	5836.18	79.00	C	81.00	B	2210.78	11619.33
	- 20.00	0.17	119.66	159.16	5119.28	5802.85	79.00	C	81.00	B	2204.25	11585.71
	- 25.00	0.16	119.08	158.58	5089.84	5769.49	79.00	C	81.00	B	2197.72	11552.06
	- 30.00	0.15	118.50	158.00	5060.42	5736.14	79.00	C	81.00	B	2191.19	11518.43
	- 40.00	0.13	117.35	156.84	5001.46	5669.30	80.00	C	81.00	B	2178.11	11451.03
	- 50.00	0.11	116.19	155.69	4942.47	5602.44	80.00	C	81.00	B	2165.02	11383.62
U Values (Windows/Doors)	%	Value										
	5.00	1.68	124.29	163.79	5353.93	6068.84	79.00	C	80.00	C	2256.36	11854.11
	10.00	1.76	126.59	166.09	5470.19	6200.62	79.00	C	80.00	C	2282.18	11987.16
	15.00	1.84	128.88	168.38	5575.53	6320.03	79.00	C	80.00	C	2307.81	12119.21
	20.00	1.92	131.16	170.66	5677.13	6435.20	79.00	C	80.00	C	2333.24	12223.17
	25.00	2.00	133.43	172.93	5787.38	6560.17	78.00	C	79.00	C	2358.47	12349.49
	30.00	2.08	135.69	175.18	5896.81	6684.21	78.00	C	79.00	C	2383.52	12474.89
	40.00	2.24	140.16	179.66	6112.80	6929.04	78.00	C	79.00	C	2433.00	12722.50
	50.00	2.40	144.60	184.09	6325.17	7169.77	78.00	C	79.00	C	2482.54	12966.09
	- 5.00	1.52	119.65	159.15	5116.61	5799.83	79.00	C	81.00	B	2204.11	11575.87
	- 10.00	1.44	117.31	156.80	4999.47	5667.05	80.00	C	81.00	B	2177.70	11448.70
	- 15.00	1.36	114.96	154.46	4878.78	5530.24	80.00	C	81.00	B	2151.08	11309.69
	- 20.00	1.28	112.59	152.09	4760.97	5396.70	80.00	C	81.00	B	2124.29	11175.09
	- 25.00	1.20	110.22	149.71	4642.25	5262.13	80.00	C	82.00	B	2097.30	11039.51
	- 30.00	1.12	107.83	147.32	4522.54	5126.43	80.00	C	82.00	B	2070.12	10902.86
	- 40.00	0.96	103.01	142.51	4280.37	4851.93	81.00	C	82.00	B	2015.22	10626.64
	- 50.00	0.80	98.14	137.64	4034.59	4573.33	81.00	B	83.00	B	1959.63	10346.61
U Value (Party Wall)		Value										
		0.10	125.18	164.68	5399.02	6119.95	79.00	C	80.00	C	2266.37	11905.71
		0.50	138.02	177.52	6042.02	6848.81	78.00	C	79.00	C	2409.33	12642.19
Thermal Bridging	y value											
	y=0.15		121.98	161.47	5236.78	5936.05	79.00	C	80.00	C	2230.31	11720.09
	y=0.08		105.93	145.42	4416.59	5006.33	80.00	C	82.00	C	2048.49	10783.27
	y=0.04		96.76	136.26	3943.36	4469.91	81.00	B	83.00	B	1943.84	10244.17
	y=0.1		110.51	150.01	4652.13	5273.33	80.00	C	82.00	B	2100.65	11052.01
	y=0.2		133.44	172.93	5813.51	6589.78	78.00	C	79.00	C	2358.50	12380.32
	y=0.3		156.36	195.85	6940.67	7867.46	77.00	C	77.00	C	2609.49	13673.29
	y=0.4		179.28	218.77	8030.02	9102.27	75.00	C	75.00	C	2852.52	14925.27
	y=0.5		202.21	241.70	9082.05	10294.78	73.00	C	73.00	C	3087.53	16135.91

SAP 2009 MODEL SENSITIVITY ANALYSIS (WITH MVHR VENTILATION STRATEGY)												
			Total Fabric Heat Losses	**Heat Loss Coefficient**	**Space Heating Demand**	**Space Heating Fuel**	**SAP Rating**		**EI rating**		**Carbon Emissions**	**Primary Energy**
Baseline Data			**121.98**	**161.47**	**5236.78**	**5936.05**	**79.00**	**C**	**80.00**	**C**	**2230.31**	**11720.09**
Air Pressure Test	q50											
	7.00		121.98	161.47	5236.78	5936.05	79.00	C	80.00	C	2230.31	11720.09
	8.00		121.98	165.65	5476.46	6207.73	79.00	C	80.00	C	2281.61	11984.19
	9.00		121.98	169.83	5696.86	6457.56	78.00	C	80.00	C	2332.62	12246.98
	10.00		121.98	174.01	5924.74	6715.86	78.00	C	79.00	C	2383.32	12508.17
	11.00		121.98	178.18	6151.04	6972.39	78.00	C	79.00	C	2433.70	12767.68
	12.00		121.98	182.36	6375.89	7227.26	77.00	C	78.00	C	2483.77	13025.64
	13.00		121.98	186.54	6599.17	7480.36	77.00	C	78.00	C	2533.52	13281.91
	14.00		121.98	190.72	6820.87	7731.65	77.00	C	77.00	C	2582.93	13536.45
	15.00		121.98	194.90	7041.05	7981.24	79.00	C	79.00	C	5632.02	13789.35
	6.00		121.98	157.29	5004.63	5672.90	80.00	C	81.00	B	2178.72	11454.17
	5.00		121.98	153.11	4770.79	5407.83	80.00	C	82.00	B	2126.88	11187.12
	4.00		121.98	148.94	4535.88	5141.56	80.00	C	82.00	B	2074.78	10918.74
	3.00		121.98	144.76	4299.84	4874.00	81.00	C	82.00	B	2022.48	10649.30
MVHR Efficiency	% Efficiency											
	90.00		121.98	161.47	5236.78	5936.05	79.00	C	80.00	C	2230.31	11720.09
	80.00		121.98	165.18	5424.12	6148.40	79.00	C	80.00	C	2271.95	11934.44
	70.00		121.98	168.88	5610.79	6360.00	79.00	C	80.00	C	2313.43	12148.13
	60.00		121.98	172.59	5796.56	6570.57	78.00	C	79.00	C	2354.73	12360.90
	50.00		121.98	176.30	5981.42	6780.11	78.00	C	79.00	C	2395.85	12572.73
Divide by 20 Rule	Division Factor	q50 Eqivalent										
	20.00	7.00	121.98	161.47	5236.78	5936.05	79.00	C	80.00	C	2230.31	11720.09
	15.00	9.20	121.98	170.66	5742.53	6509.33	78.00	C	79.00	C	2342.81	12299.32
	10.00	14.00	121.98	190.72	6820.87	7731.65	77.00	C	77.00	C	2582.93	13536.45
	5.00	28.00	121.98	249.21	9767.69	11071.97	72.00	C	72.00	C	2340.99	16926.49
	25.00	5.50	121.98	155.20	4887.73	5540.39	80.00	C	81.00	C	2152.93	11320.79
	30.00	4.70	121.98	151.86	4700.43	5328.08	80.00	C	81.00	B	2111.27	11106.71
0.5 ACH	ACH	q50 Equivalent										
	0.10	5.00	121.98	153.28	4770.79	5407.83	80.00	C	81.00	B	2126.88	11187.12
	0.20	5.50	121.98	155.33	4887.73	5540.39	80.00	C	81.00	B	2152.83	11320.79
	0.30	6.00	121.98	157.38	5004.63	5672.90	80.00	C	81.00	B	2178.72	11454.17
	0.40	6.50	121.98	159.43	5120.68	5804.44	79.00	C	81.00	B	2204.55	11587.23
	0.50	7.00	121.98	161.47	5236.78	5936.05	79.00	C	80.00	C	2230.31	11720.09
	0.60	7.50	121.98	163.53	5352.25	6066.93	79.00	C	80.00	C	2256.00	11852.27
	0.70	8.00	121.98	165.58	5467.46	6197.53	79.00	C	80.00	C	2281.61	11984.19
	0.80	8.50	121.98	167.63	5582.33	6327.73	79.00	C	80.00	C	2307.15	12115.76
	0.90	9.00	121.98	169.68	5696.86	6457.56	78.00	C	80.00	C	2322.62	12246.98
	1.00	9.50	121.98	171.73	5811.01	6586.95	78.00	C	79.00	C	2358.01	12377.80

Appendix 9 - Thermal Chamber Summary Data

COHEATING TEST DATA - THERMAL CHAMBER - ORIGINAL UNALTERED CONSTRUCTION (CONTROL TESTS)

Date	Mean Internal Temp (°C)	Mean External Temp (°C)	Temperature Difference (K)	TOTAL (Wh)	TOTAL (W)	HLC (W/K)
10K ΔT						
25/05/13	23.57	10.19	13.38	2002	236	17.60
26/05/13	23.68	10.31	13.37	5567	232	17.35
27/05/13	23.55	10.30	13.25	5516	230	17.35
28/05/13	23.62	10.32	13.30	2683	233	17.54
28/05/13	27.36	10.82	16.53	3270	273	16.48
29/05/13	27.14	10.80	16.34	6600	275	16.83
30/05/13	26.90	10.76	16.14	4170	278	17.22
5K ΔT						
30/05/13	25.85	5.27	20.58	2973	350	17.00
31/05/13	25.93	5.30	20.63	8349	348	16.86
01/06/13	25.92	5.22	20.70	8425	351	16.96
02/06/13	25.99	5.26	20.72	8416	351	16.92
03/06/13	25.98	5.20	20.78	3479	348	16.74

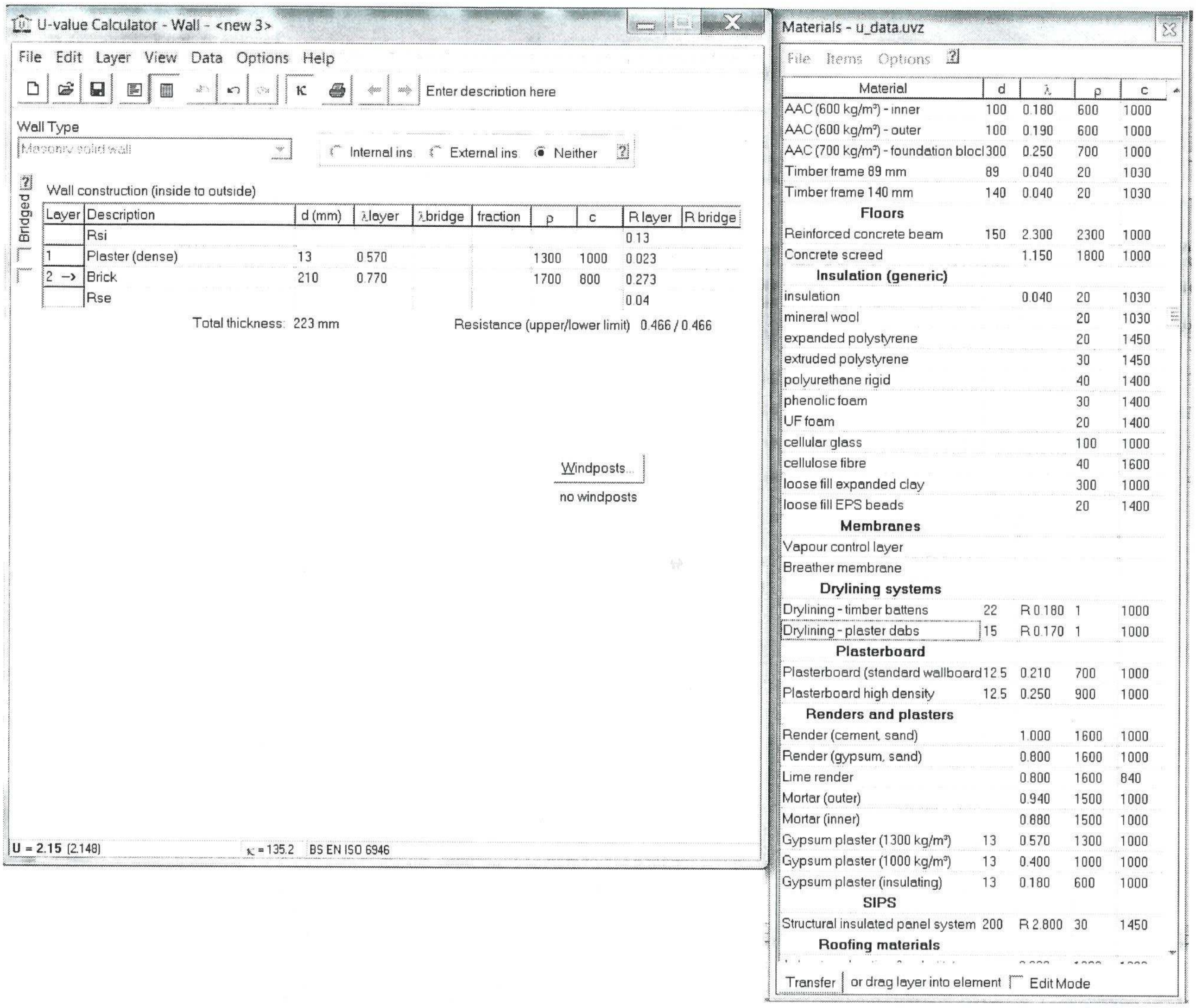
COHEATING TEST DATA - THERMAL CHAMBER - SOLID BRICK WALL CONSTRUCTION

Date	Mean Internal Temp (°C)	Mean External Temp (°C)	Temperature Difference (K)	TOTAL (Wh)	TOTAL (W)	HLC (W/K)	
10K ΔT							
03/08/13	24.91	14.84	10.07	4547	189	18.82	
04/08/13	24.93	14.90	10.03	4416	184	18.34	
05/08/13	24.90	14.88	10.02	4427	184	18.41	
06/08/13	24.89	14.90	9.99	4450	185	18.56	
07/08/13	24.86	14.93	9.93	4453	186	18.69	
08/08/13	24.89	14.81	10.07	4451	185	18.41	
15K ΔT							
16/07/13	25.23	9.57	15.67	6586	274	17.52	
17/07/13	25.20	9.61	15.58	6632	276	17.73	
18/07/13	25.21	9.62	15.59	6609	275	17.66	
19/07/13	25.22	9.61	15.61	6583	274	17.58	
20/07/13	25.19	9.67	15.52	6559	273	17.61	
21/07/13	25.16	9.69	15.47	6557	273	17.66	
22/07/13	25.18	9.64	15.55	6538	272	17.52	
23/07/13	25.14	9.65	15.50	6500	271	17.48	
25/07/13	25.35	9.75	15.60	6509	271	17.39	
26/07/13	25.44	9.77	15.67	6515	271	17.32	
27/07/13	25.39	9.75	15.64	6509	271	17.34	
28/07/13	25.33	9.76	15.56	6479	270	17.34	
29/07/13	25.35	9.75	15.59	6496	271	17.36	
5K ΔT							
31/07/13	24.50	4.69	19.81	8567	357	18.02	
01/08/13	24.28	4.61	19.66	8551	356	18.12	
02/08/13	24.30	4.60	19.71	5277	352	17.85	
SOLAR TESTS							**SOLAR (W/m^2)**
10/08/13	24.81	9.99	14.82	5481	228	15.41	222.98
11/08/13	24.78	10.00	14.77	5532	231	15.60	222.91
12/08/13	24.74	10.15	14.58	2782	232	15.90	222.05
16/08/13	25.57	11.65	13.92	5799	242	17.35	99.83
17/08/13	25.57	11.69	13.88	5929	247	17.79	99.43
18/08/13	25.51	11.67	13.84	5945	248	17.89	98.77
14/08/13	25.57	12.22	13.35	5615	234	17.53	192.09
15/08/13	25.57	12.17	13.40	5497	229	17.09	191.04
16/08/13	25.51	12.19	13.32	2722	227	17.03	193.60
17/08/13	25.85	12.82	13.03	4753	198	15.19	348.97
18/08/13	25.88	12.70	13.18	4693	196	14.83	345.28
09/09/13	25.87	12.36	13.51	4777	199	14.74	342.70

COHEATING TEST DATA - THERMAL CHAMBER - SOLID BRICK WALL & EXTERNAL INSULATION CONSTRUCTION

Date	Mean Internal Temp (°C)	Mean External Temp (°C)	Temperature Difference (K)	TOTAL (Wh)	TOTAL (W)	HLC (W/K)	
10K ΔT							
15/10/13	26.21	15.24	10.97	4003	167	15.21	
16/10/13	26.21	15.31	10.90	3887	162	14.86	
17/10/13	26.18	15.22	10.96	3863	161	14.69	
18/10/13	26.16	15.25	10.91	3825	159	14.61	
15K ΔT							
08/10/13	26.26	10.43	15.84	5876	245	15.46	
09/10/13	26.19	10.39	15.80	5496	229	14.50	
10/10/13	26.06	10.38	15.69	5445	227	14.46	
11/10/13	26.11	10.30	15.80	5438	227	14.34	
12/10/13	26.04	10.32	15.73	5432	226	14.39	
13/10/13	26.02	10.39	15.63	5387	224	14.36	
14/10/13	26.09	10.61	15.48	2506	228	14.72	
5K ΔT							
19/10/13	26.00	5.40	20.60	6693	279	13.54	
20/10/13	25.96	5.36	20.60	6848	285	13.85	
21/10/13	25.98	5.35	20.63	6885	287	13.91	
22/10/13	26.02	5.40	20.62	6841	285	13.82	
23/10/13	26.00	5.43	20.57	3415	285	13.84	
SOLAR TESTS							**SOLAR (W/m^2)**
08/11/13	25.53	10.06	15.47	5372	224	14.47	102.00
09/11/13	25.49	10.08	15.42	5383	224	14.55	102.25
10/11/13	25.52	10.03	15.48	5423	226	14.59	99.54
11/11/13	25.56	10.04	15.52	5356	223	14.38	101.97
25/10/13	25.73	10.13	15.61	5194	216	13.87	231.22
26/10/13	25.70	10.13	15.57	5163	215	13.82	231.98
27/10/13	25.65	10.07	15.58	5155	215	13.79	231.09
23/10/13	25.62	10.74	14.87	4698	196	13.16	373.68
24/10/13	25.69	10.66	15.02	4593	191	12.74	371.27
25/10/13	25.77	10.34	15.44	2074	207	13.44	371.30

Appendix 10 - BRE Calculator U-Value Calculations



Wall Type: Masonry solid wall

○ Internal ins. ○ External ins. ● Neither

Wall construction (inside to outside)

Bridged	Layer	Description	d (mm)	λlayer	λbridge	fraction	ρ	c	R layer	R bridge
		Rsi							0.13	
☐	1	Plaster (dense)	13	0.570			1300	1000	0.023	
☐	2 ->	Brick	210	0.770			1700	800	0.273	
		Rse							0.04	

Total thickness: 223 mm

Resistance (upper/lower limit) 0.466 / 0.466

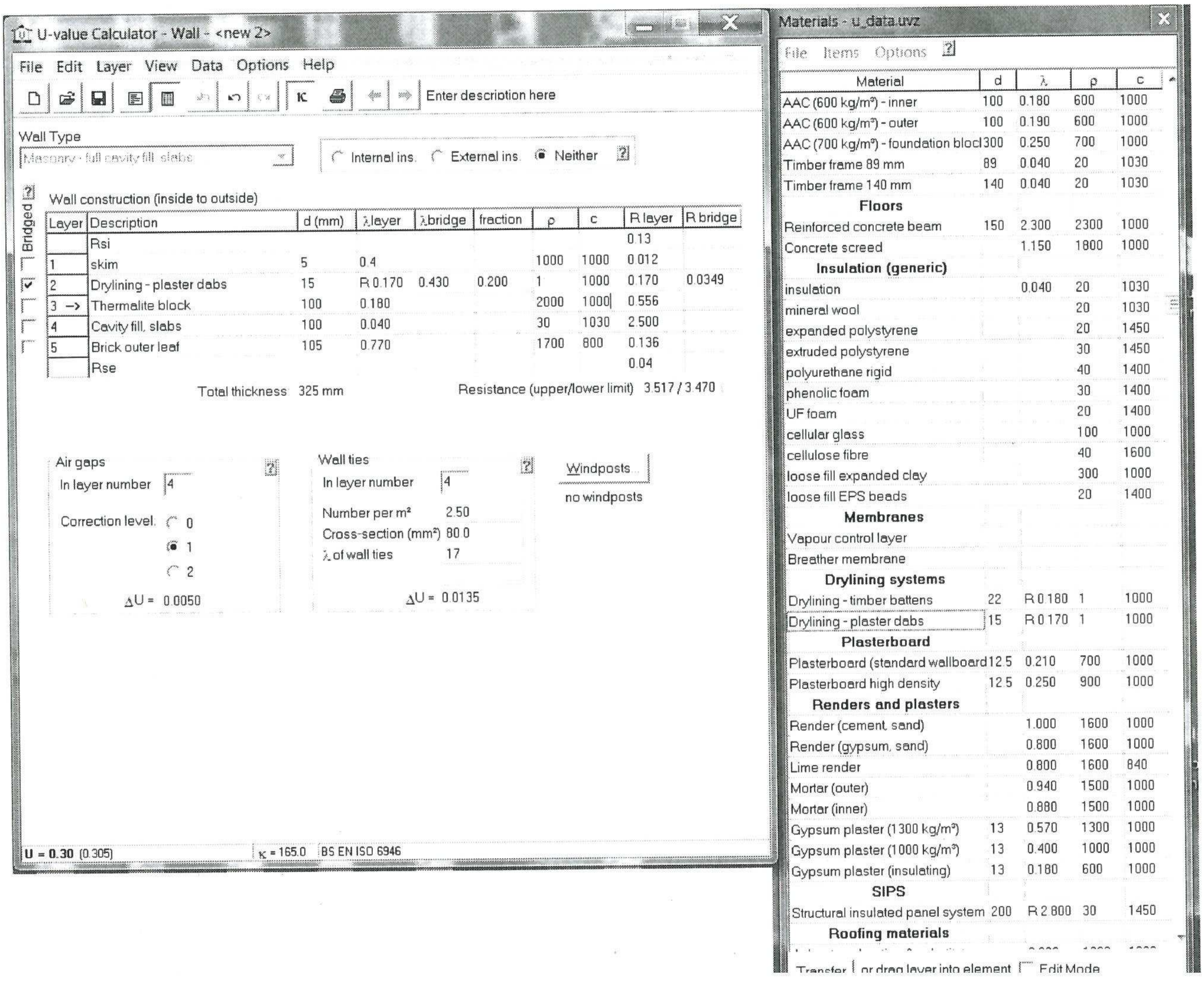
no windposts

U = 2.15 (2.148)

κ = 135.2

BS EN ISO 6946

Material	d	λ	ρ	c
AAC (600 kg/m³) - inner	100	0.180	600	1000
AAC (600 kg/m³) - outer	100	0.190	600	1000
AAC (700 kg/m³) - foundation bloc	300	0.250	700	1000
Timber frame 89 mm	89	0.040	20	1030
Timber frame 140 mm	140	0.040	20	1030
Floors				
Reinforced concrete beam	150	2.300	2300	1000
Concrete screed		1.150	1800	1000
Insulation (generic)				
insulation		0.040	20	1030
mineral wool			20	1030
expanded polystyrene			20	1450
extruded polystyrene			30	1450
polyurethane rigid			40	1400
phenolic foam			30	1400
UF foam			20	1400
cellular glass			100	1000
cellulose fibre			40	1600
loose fill expanded clay			300	1000
loose fill EPS beads			20	1400
Membranes				
Vapour control layer				
Breather membrane				
Drylining systems				
Drylining - timber battens	22	R 0.180	1	1000
Drylining - plaster dabs	15	R 0.170	1	1000
Plasterboard				
Plasterboard (standard wallboard	12.5	0.210	700	1000
Plasterboard high density	12.5	0.250	900	1000
Renders and plasters				
Render (cement, sand)		1.000	1600	1000
Render (gypsum, sand)		0.800	1600	1000
Lime render		0.800	1600	840
Mortar (outer)		0.940	1500	1000
Mortar (inner)		0.880	1500	1000
Gypsum plaster (1300 kg/m³)	13	0.570	1300	1000
Gypsum plaster (1000 kg/m³)	13	0.400	1000	1000
Gypsum plaster (insulating)	13	0.180	600	1000
SIPS				
Structural insulated panel system	200	R 2.800	30	1450
Roofing materials				



Wall Type: Masonry - full cavity fill, slabs

○ Internal ins. ○ External ins. ● Neither

Wall construction (inside to outside)

Bridged	Layer	Description	d (mm)	λlayer	λbridge	fraction	ρ	c	R layer	R bridge
		Rsi							0.13	
☐	1	skim	5	0.4			1000	1000	0.012	
☑	2	Drylining - plaster dabs	15	R 0.170	0.430	0.200	1	1000	0.170	0.0349
☐	3 ->	Thermalite block	100	0.180			2000	1000	0.556	
☐	4	Cavity fill, slabs	100	0.040			30	1030	2.500	
☐	5	Brick outer leaf	105	0.770			1700	800	0.136	
		Rse							0.04	

Total thickness: 325 mm

Resistance (upper/lower limit) 3.517 / 3.470

Air gaps
In layer number: 4
Correction level: ○ 0 ● 1 ○ 2
ΔU = 0.0050

Wall ties
In layer number: 4
Number per m²: 2.50
Cross-section (mm²): 80.0
λ of wall ties: 17
ΔU = 0.0135

no windposts

U = 0.30 (0.305)

κ = 165.0

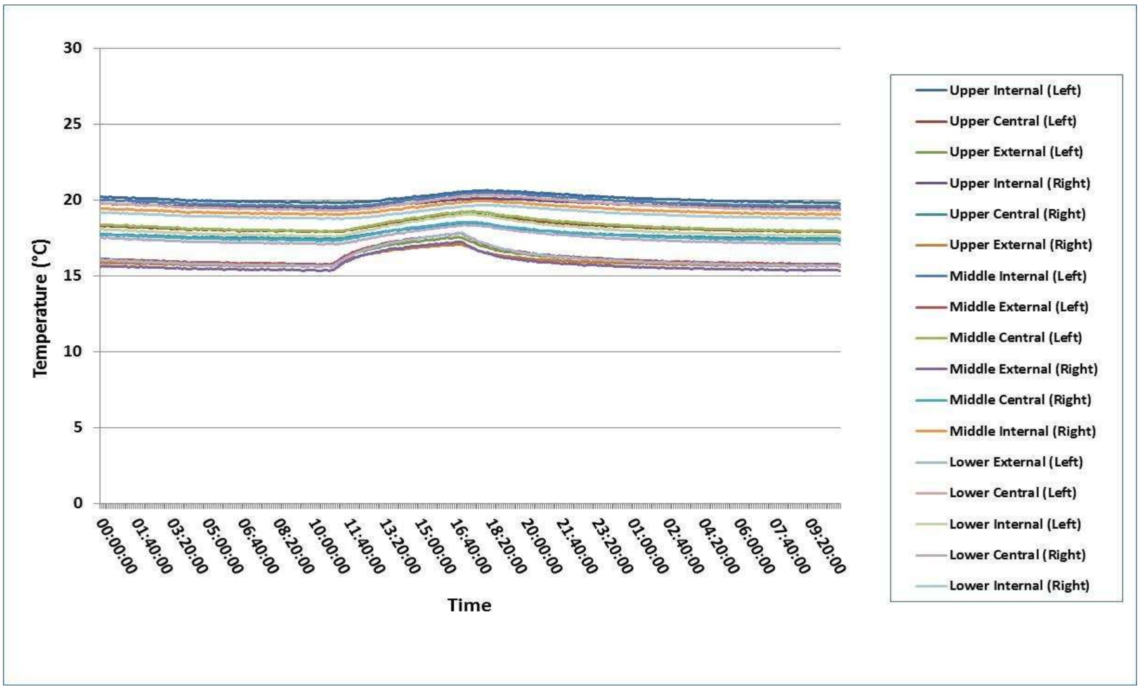
BS EN ISO 6946

Material	d	λ	ρ	c
AAC (600 kg/m³) - inner	100	0.180	600	1000
AAC (600 kg/m³) - outer	100	0.190	600	1000
AAC (700 kg/m³) - foundation bloc	300	0.250	700	1000
Timber frame 89 mm	89	0.040	20	1030
Timber frame 140 mm	140	0.040	20	1030
Floors				
Reinforced concrete beam	150	2.300	2300	1000
Concrete screed		1.150	1800	1000
Insulation (generic)				
insulation		0.040	20	1030
mineral wool			20	1030
expanded polystyrene			20	1450
extruded polystyrene			30	1450
polyurethane rigid			40	1400
phenolic foam			30	1400
UF foam			20	1400
cellular glass			100	1000
cellulose fibre			40	1600
loose fill expanded clay			300	1000
loose fill EPS beads			20	1400
Membranes				
Vapour control layer				
Breather membrane				
Drylining systems				
Drylining - timber battens	22	R 0.180	1	1000
Drylining - plaster dabs	15	R 0.170	1	1000
Plasterboard				
Plasterboard (standard wallboard	12.5	0.210	700	1000
Plasterboard high density	12.5	0.250	900	1000
Renders and plasters				
Render (cement, sand)		1.000	1600	1000
Render (gypsum, sand)		0.800	1600	1000
Lime render		0.800	1600	840
Mortar (outer)		0.940	1500	1000
Mortar (inner)		0.880	1500	1000
Gypsum plaster (1300 kg/m³)	13	0.570	1300	1000
Gypsum plaster (1000 kg/m³)	13	0.400	1000	1000
Gypsum plaster (insulating)	13	0.180	600	1000
SIPS				
Structural insulated panel system	200	R 2.800	30	1450
Roofing materials				

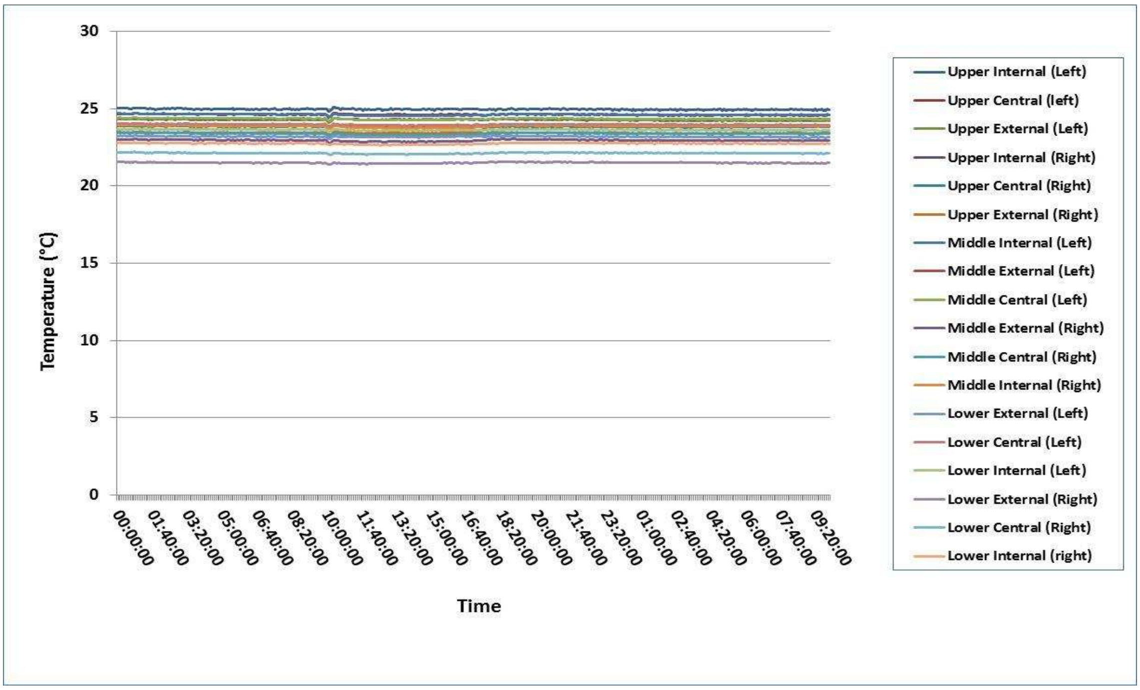
Appendix 11 – Thermal Chamber Solar Cycle Graphs

100W Solar Cycle Test Temperature Profile Graphs

Uninsulated Brick Wall – 100W Cycle – Temperature Profile

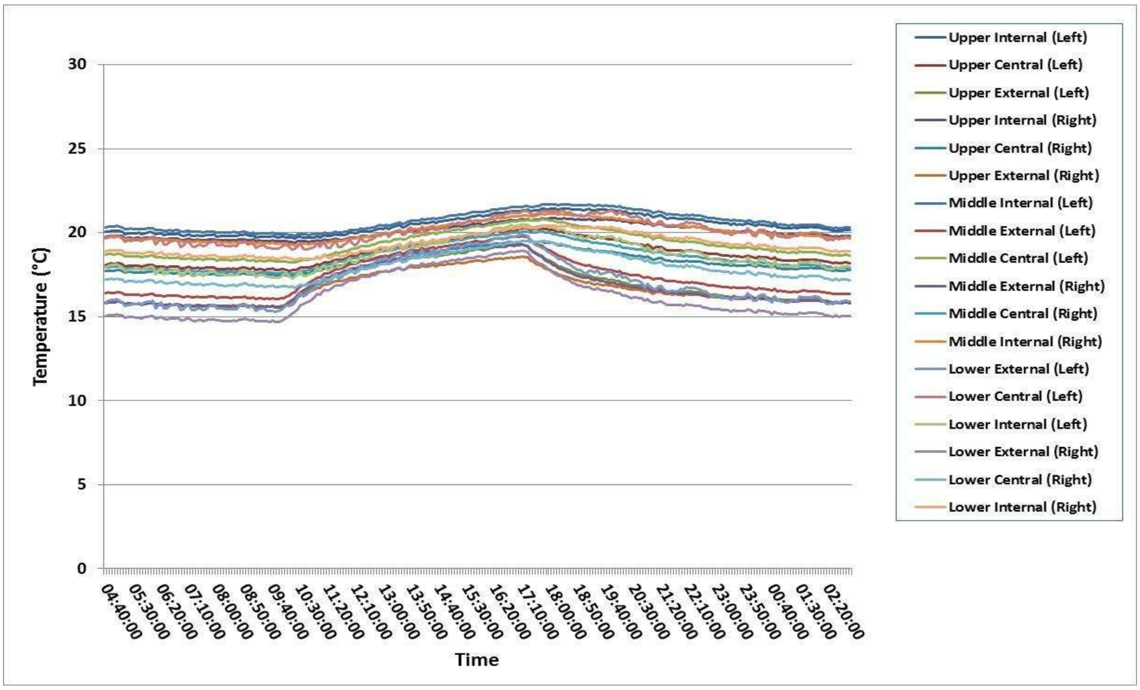


Insulated Brick Wall – 100W Cycle – Temperature Profile

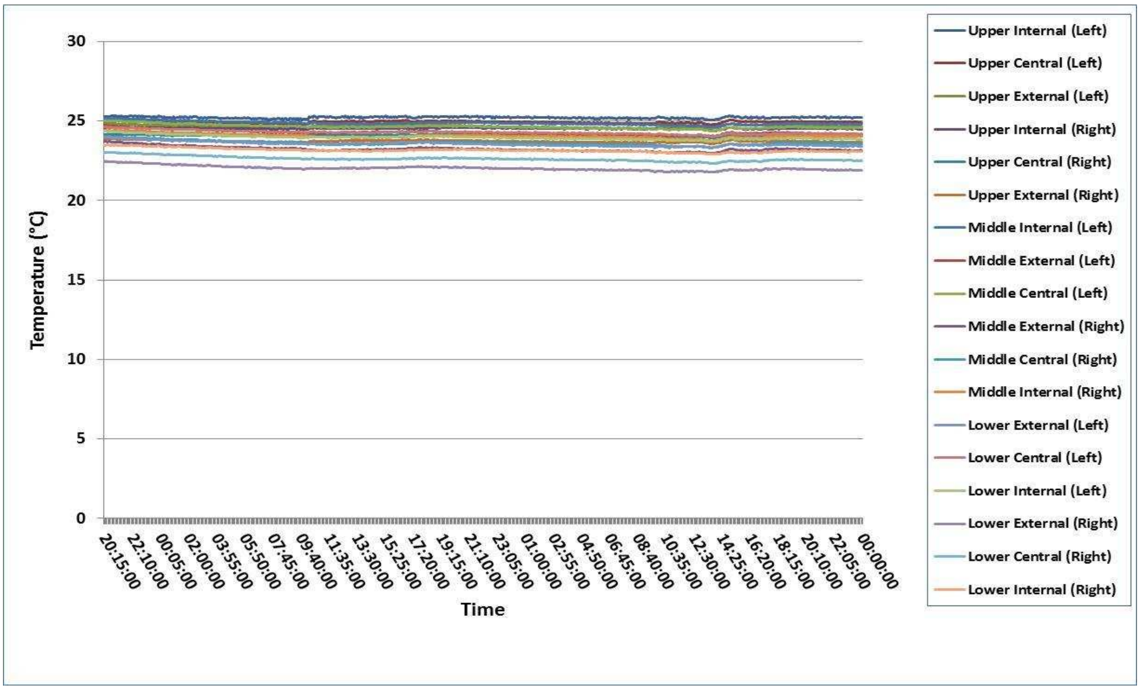


200W Solar Cycle Test Temperature Profile Graphs

Uninsulated Brick Wall – 200W Cycle – Temperature Profile

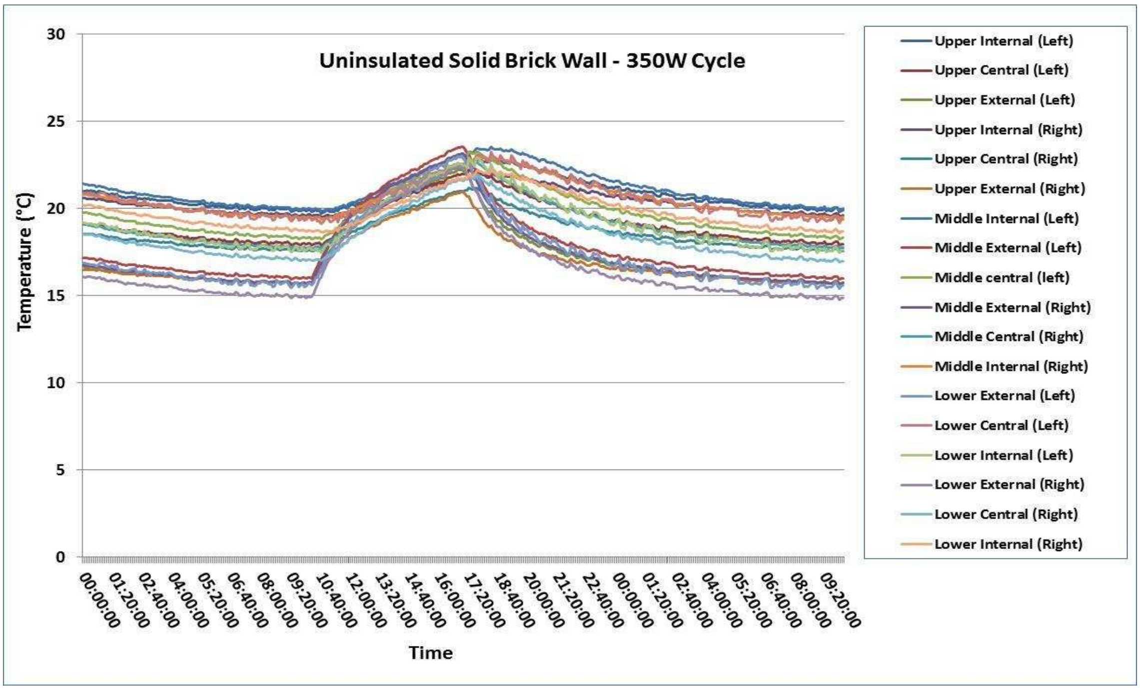


Insulated Brick Wall – 200W Cycle – Temperature Profile

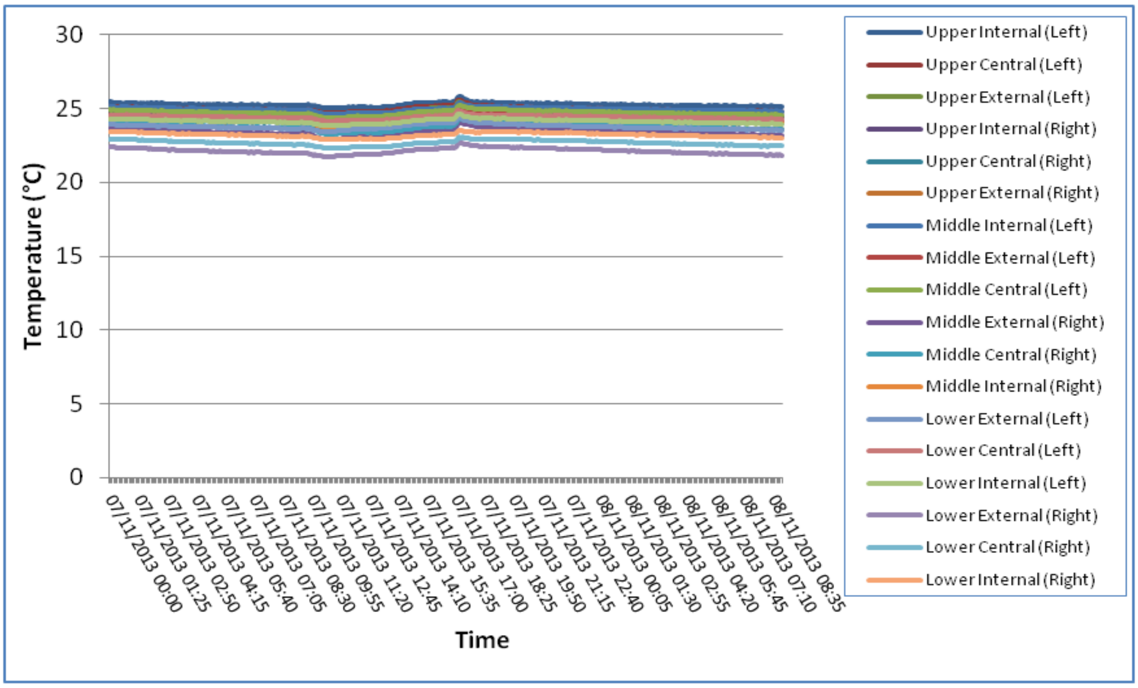


350W Solar Cycle Test Temperature Profile Graphs

Uninsulated Brick Wall – 350W Cycle – Temperature Profile

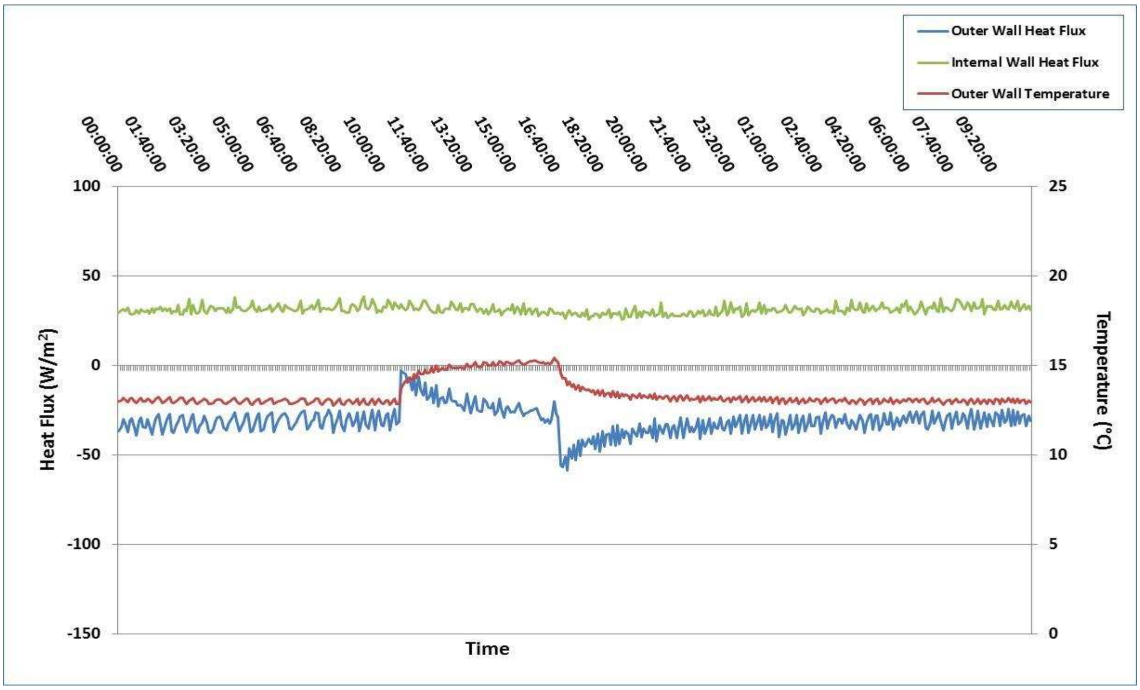


Insulated Brick Wall – 350W Cycle – Temperature Profile

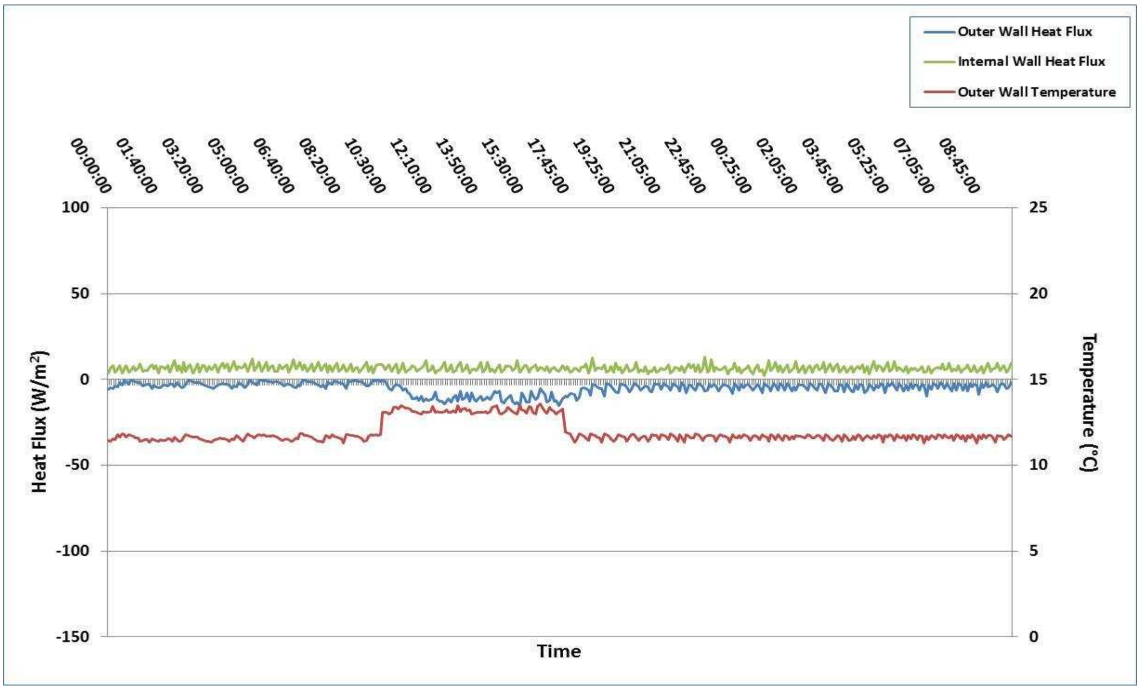


100W Solar Cycle Test Heat Flux Profile Graphs

Uninsulated Brick Wall – 100W Cycle – Heat Flux Profile

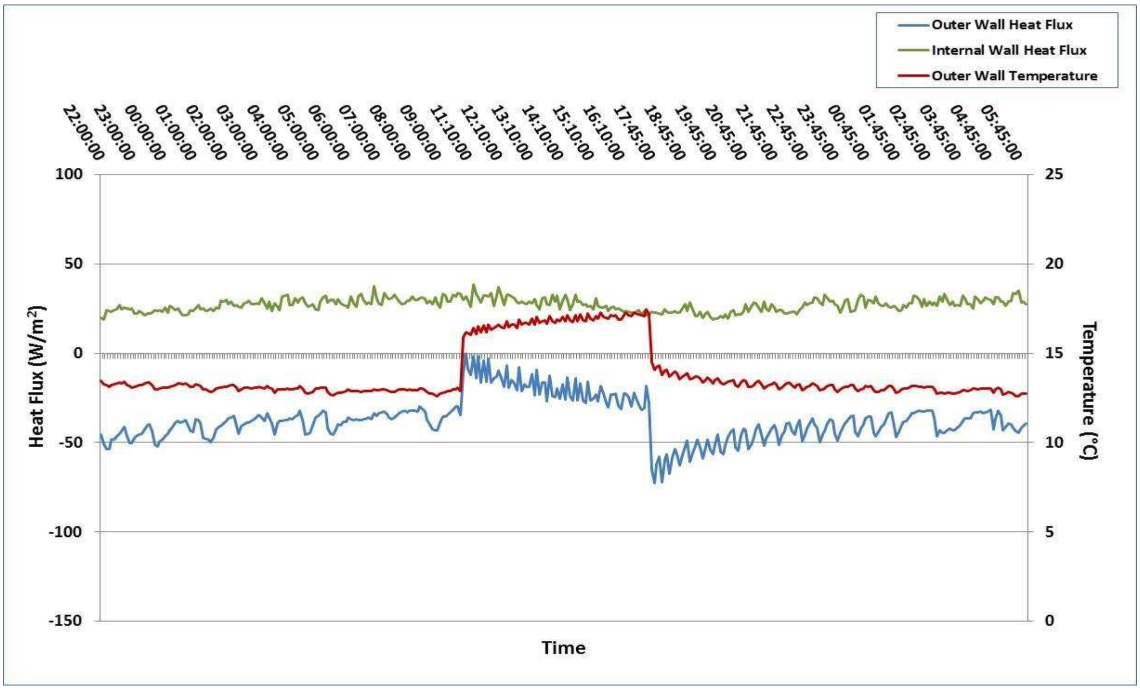


Insulated Brick Wall – 100W Cycle – Heat Flux Profile

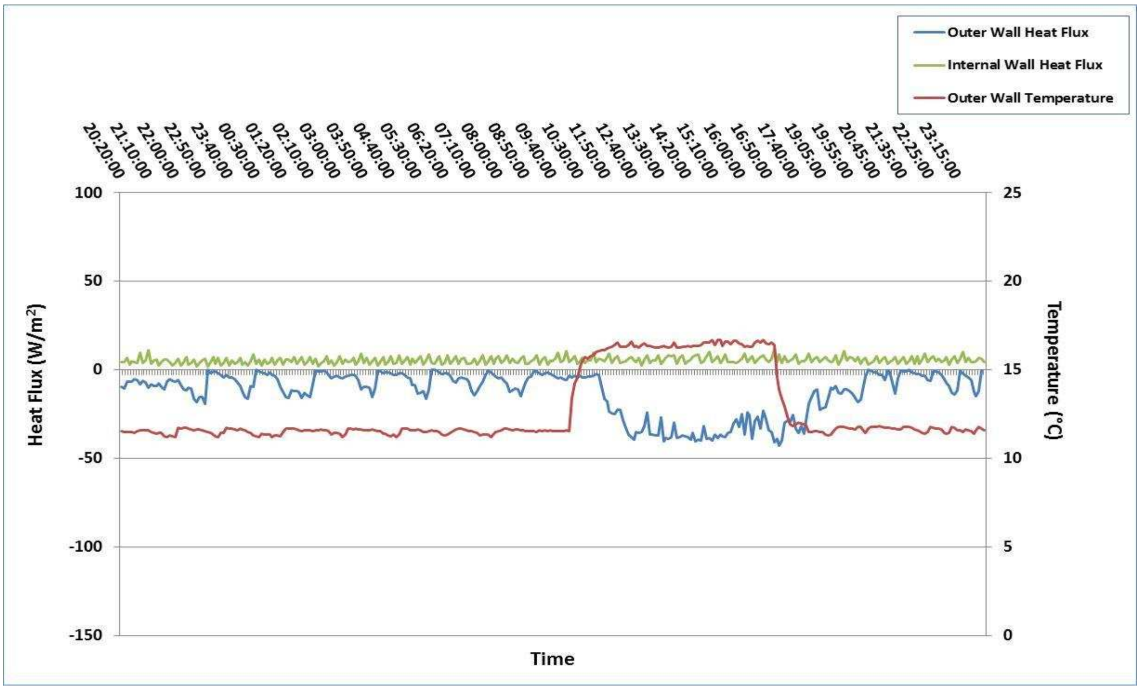


200W Solar Cycle Test Heat Flux Profile Graphs

Uninsulated Brick Wall – 200W Cycle – Heat Flux Profile

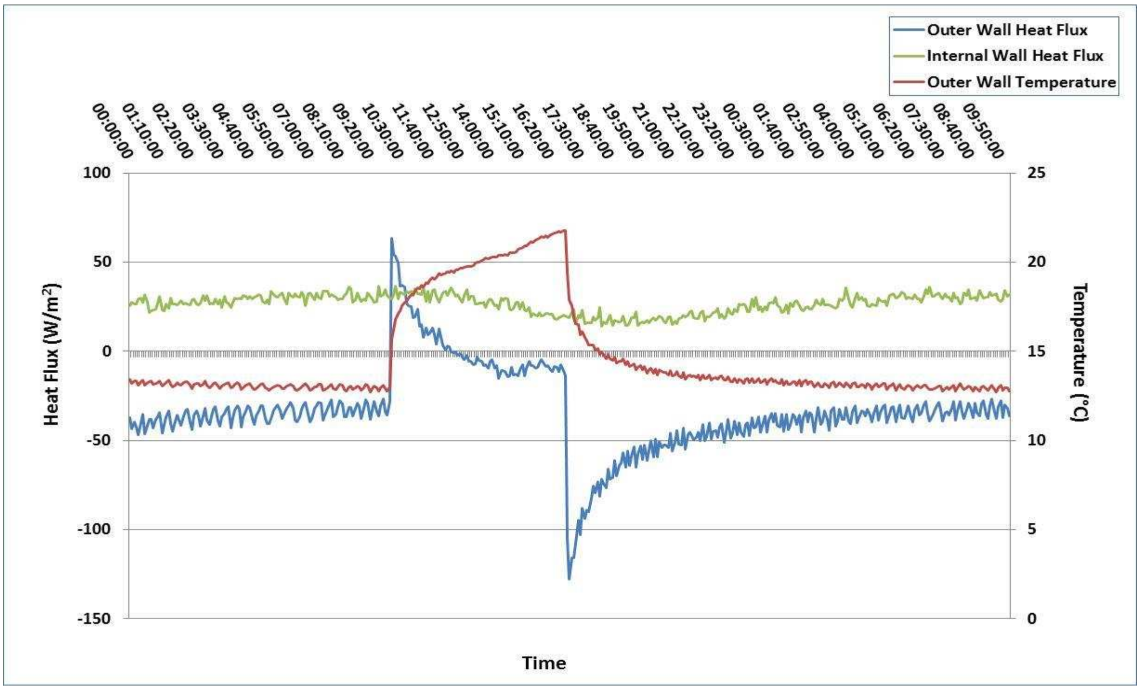


Insulated Brick Wall – 200W Cycle – Heat Flux Profile



350W Solar Cycle Test Heat Flux Profile Graphs

Uninsulated Brick Wall – 350W Cycle – Heat Flux Profile



Insulated Brick Wall – 350W Cycle – Heat Flux Profile