AN INVESTIGATION INTO THE PERFORMANCE OF LOW ENERGY AND ZERO CARBON BUILDINGS IN A CHANGING CLIMATE

- APPLYING THE PASSIVHAUS STANDARD TO THE UK CONTEXT -

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What is the use of a house if you haven’t got a tolerable planet to put it on?

- Henry David Thoreau

DECLARATION

This work has not previously been accepted in substance for any degree and is not concurrently submitted in candidature for any degree.

Signed: (candidate) Date: 30 September, 2013

STATEMENT 1

This thesis is being submitted in partial fulfilment of the requirements for the degree of PhD.

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This thesis is the result of my own independent work/investigation, except where otherwise stated. Other sources are acknowledged by explicit references.

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I hereby give consent for my thesis, if accepted, to be available for photocopying and for inter-library loan, and for the title and summary to be made available to outside organisations.

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The foundations for this research were laid during 2007-2010 whilst I was the Technical Manager of BRE Wales and South West. This period marked the arrival of a new era in the development of the Passivhaus concept in the UK. I was fortunate to play a role in this transition as the Principle Passivhaus Consultant on the Lime and Larch Passivhaus projects at Ebbw Vale (the first zero carbon, Code 5 and 6 social housing projects to be built to the Passivhaus standard in the UK) as well as a number of other pioneering schemes. As a result of collaborative research relationships with Professors John Miles and Yacine Rezgui during this time I was offered the possibility to undertake a PhD, in what is now known as the BRE Institute of Sustainable Engineering, at Cardiff University.

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SUMMARY

Energy consumption and Green House Gas (GHG) emissions from the UK built environment are reflective of the wider situation across Europe, where according to the Energy Performance in Buildings Directive (EPBD) “buildings account for 40% of total energy consumption in the Union” (European Commission, 2010). In December 2006 the UK Government announced a rapid transition to ‘zero carbon’ new buildings, as a key step forward in reducing GHG emissions from the domestic and non-domestic sectors (DCLG, 2006a; Weaver, 2007).

The Passivhaus standard is the fastest growing energy performance standard in the world and in a growing number of regions across Europe it has been implemented as a mandatory minimum standard for all new buildings (iPHA, 2013). This thesis investigates the applicability of this low energy standard to the UK context, in comparison to conventional alternatives, by examining four inter-related themes: (i) in relation to climate change policy and the UK Government’s plan for all new homes to be zero carbon from 2016; (ii) by addressing the limitations of the climate data currently used to design Passivhaus buildings, and developing a new methodology for creating higher resolution probabilistic climate data; (iii) by exploring the uncertainty about the future performance of Passivhaus dwellings in relation to future overheating risk and thereby proposing methods to improve whole life design optimization; (iv) by investigating the hygrothermal implications for new build and retrofit Passivhaus projects and highlighting areas where current risk assessment methods are inadequate.

This thesis has argued that the transfer of the Passivhaus standard, or any advanced energy performance standard, from one country or region to another should be accompanied by an extensive programme of context specific research and application testing. The findings of this research have shown that the implementation of the Passivhaus standard, in its present format, in the UK is not without risk and uncertainty. This thesis concludes that that the majority of such risks can be substantially mitigated, through the incorporation of high resolution probabilistic climatic data, transient hygrothermal assessments and global sensitivity analysis techniques. The energy saving and thermal comfort potential of the Passivhaus approach have been shown to be substantial and therefore merits the challenges involved in addressing its successful implementation.

PUBLICATIONS

JOURNAL PUBLICATIONS

The following peer reviewed journal publications were written and published based on the research findings of this PhD. Copies of these papers can be found in Appendix B.

1. McLeod R., Hopfe, C., and Rezgui, Y., 2012. An investigation into recent proposals for a revised definition of Zero Carbon homes in the UK. *Energy Policy*, 46 (2012) 25–35 http://dx.doi.org/10.1016/j.enpol.2012.02.066

2. McLeod R., Hopfe, C., and Rezgui, Y., 2012. A proposed method for generating high resolution current and future climate data for Passivhaus design. *Energy and Buildings*, 55 (2012) 481–493 http://dx.doi.org/10.1016/j.enbuild.2012.08.045

3. McLeod, R., and Hopfe, C., 2013. Hygrothermal implications of low and zero energy standards for building envelope performance in the UK. *Journal of Building Performance Simulation*, 6, (2013) Issue 5, 1-18, Special Issue: Heat and moisture - issues and applications. DOI: 10.1080/19401493.2012.7628094

4. McLeod, R., Hopfe, C., and Kwan, A., 2013. An investigation into future performance and overheating risks in Passivhaus dwellings. *Building & Environment* 70 (2013) 189-209. http://dx.doi.org/10.1016/j.buildenv.2013.08.024

CONFERENCE PAPERS

The following peer reviewed conference papers were published in support of the research.

1. McLeod, R., and Tweed, C., 2008. Meeting the 2011 zero carbon building target for Wales using the Passivhaus standard. Paper 732 (Keynote speech): PLEA 2008, *25th Conference on Passive and Low Energy Architecture*, 22-24 October 2008, Dublin, Ireland.

2. McLeod, R. S., Hopfe, C. J., and Rezgui, Y., 2010. Passivhaus and PHPP – Do continental design criteria work in a Welsh climatic context? *3rd BauSIM Conference*, 22 -24 September 2010, Vienna, Austria.

3. Price, A., Hopfe, C., and McLeod, R., 2010. An investigation into the achievable energy savings provided by low energy lighting systems and the corresponding levels of visual comfort. *3rd BauSIM Conference*, 22-24 September 2010, Vienna, Austria.

4. McLeod, R., and Hopfe, C., 2011. Application and limitations in the use of regionally derived and future probabilistic climate data in Passivhaus design. Paper 756: *Building Simulation 2011* (International IBPSA conference) 14-16 November 2011, Sydney, Australia.

PROFESSIONAL PUBLICATIONS AND ARTICLES

The following professional publications and articles were published during the course of the research, copies of these publications can be found in Appendix C.

1. McLeod, R., Mead, K., and Standen, M., 2012. *Passivhaus Primer: Designers guide: A guide for the design team and local authorities.* Available at: www.passivhaus.org.uk

2. McLeod, R., Tilford, A., and Mead, K., 2012. *Passivhaus Primer: Contractors guide: So you have been asked to build a passivhaus?* Available at: www.passivhaus.org.uk

3. Jaggs, M., and McLeod, R., 2013 (in press). *Passivhaus Primer: Airtightness guide*. Available at: www.passivhaus.org.uk

4. McLeod, R., 2010. *Thermal Mass - is more always better?* Special Report: Passivhaus. EcoTech 24, Sustainable Architecture Today: November 2010. ISSN 1474-5054

BOOKS

1. McLeod, R., and Hopfe, C., (eds.) 2014 (in press), *The Passivhaus Designer's Manual*. Routledge. Available at: http://media.routledgeweb.com/catalogs/architecture_2013_uk

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NOMENCLATURE AND SYMBOLS

The following nomenclature and symbols have been used in this thesis. Symbols in italics are variables, whilst those in regular typeface are numerical values in the units specified.

SYMBOL	DESCRIPTION	UNITS
A_{exp}	Total area of external elements	m^2
ach	Air changes per hour	h^{-1}
C	Cloud cover coefficient (0.0 =clear sky, 1.0 = totally overcast)	-
$CDF_{i,m,y}$	Cumulative Distribution Function of variable i, in month m, year y	-
$CO_{2\ e}$	Carbon dioxide equivalent	ppm
CO_2	Carbon dioxide	ppm
D	Daily diffuse irradiation on a horizontal plane	$Wh/m^2.day$
DDH	Dry Degree Hours (dehumidification)	kKh/yr
E	Daily extra-terrestrial irradiation on a horizontal plane (in the absence of an atmosphere)	$Wh/m^2.day$
EE_i^n	Elementary Effect of the *n*th trajectory of the *i*th input variable	-
f_r	Response factor	-
$FS_{m,y}$	Finkelstein Schafer statistic in month m, year y	-
$FS_{sum,i}$	Sum of the weighted FS statistics	
G	Daily global irradiation on a horizontal plane	$Wh/m^2.day$
G_t	Heating degree hours	kKh/yr
H^k	k dimensional unit hypercube	-
I_B	Global irradiation on a horizontal plane	kWh/m^2
I_D	Diffuse irradiation on a horizontal plane	kWh/m^2
I_G	Global irradiation on a horizontal plane	kWh/m^2
K	Temperature in degrees Kelvin	K
K	Coefficient for cloud height	-
K_T	Clearness index (ratio of G/E)	-
L	Length	m
m	Relative air mass (ratio of air mass in slant path to air mass in zenith direction at std. pressure)	-
m'	Air mass corrected for atmospheric pressure	-
n	Daily hours of sunshine	h
N	Day length	h
p_C	Specific Peak Cooling Load (SPCL)	W/m^2
p_H	Specific Peak Heating Load (SPHL)	W/m^2
PDF	Probability Density Function	-
PPD	Predicted Percentage Dissatisfied vote	%
q_C	Specific Cooling Demand (SCD)	$kWh/m^2.yr$
q_H	Specific Heating Demand (SHD)	$kWh/m^2.yr$
q_{PE}	Specific Primary Energy Demand (SPED)	$kWh/m^2.yr$

R	Ideal or universal gas constant	8.3144621(75)J/K.mol
R^2	Mean coefficient of determination	-
r_s	Ground albedo	-
RH	Relative Humidity	%
RMSE	Root Mean Square Error	-
S	Sunshine hours	h
Sd	Vapour diffusion thickness	m
$\mathrm{S_T}$	Total sensitivity index	-
T	Thermodynamic temperature	K
T_a	Ambient air temperature	°C
T_{db}	Dry bulb temperature	°C
T_{dp}	Calculated dew point temperature	°C
T_{sky}	Effective sky temperature (calculated in K, entered into the PHPP model in °C)	K /°C
TFA	Treated Floor Area	m^2
U	U-value, thermal transmittance coefficient	$W/m^2.K$
U	Resultant U-value, the thermal transmittance coefficient after the two-dimensional linear thermal bridging transfer coefficients are added	$W/m^2.K$
U_0	Elemental U-value, thermal transmittance coefficient before the two-dimensional linear thermal bridging transfer coefficients are added	$W/m^2.K$
V	Volume of gas (or air)	m^3
W1	Peak load climatic data during W1 period	-
W2	Peak load climatic data during W2 period	-
ws	Wind speed	m/s
y	y-value, adjustment to thermal transmission coefficient accounting for linear thermal bridging	$W/m^2.K$
y	Adjustment to thermal transmission coefficient to account for linear thermal bridging	$W/m^2.K$
Y	Thermal admittance	$W/m^2.K$
ε	Sky emissivity	-
θ_e	Annual mean external dry bulb air temperature	°C
$\varphi_{\downarrow}$	Downward longwave irradiation flux	W/m^2
σ	Stefan-Boltzmann constant	$5.67*10^{-8}$ $W/m^2.K^4$
$\tau_r, \tau_\alpha, \tau_g, \tau_o, \tau_w$	Atmospheric transmittances for Rayleigh, Mie, mixed gases, ozone and water vapour scattering	-
μ_{HR}	Efficiency of heat recovery ventilation	-
λ	psi value, thermal conductivity	W/m.K
λ_{dry}	Dry state thermal conductivity	W/m.K
ρ_{bulk}	Bulk density	kg/m^3
μ_{VR}	Vapour diffusion resistance factor	-
μ	Mean of the elementary effects	-
μ^*	Mean of the absolute elementary effects	-
χ	Chi value – point thermal bridging coefficient	W/K
ψ	Psi value – linear thermal bridging coefficient	W/m.K

ACRONYMS AND ABBREVIATIONS

The following acronyms and abbreviations have been used in this thesis:

AR4	(IPCC) Fourth Assessment Report
BPS	Building Performance Simulation
BRE	Building Research Establishment
C&C	Contraction and Convergence
CCC	Committee on Climate Change
CDF	Cumulative Distribution Frequency
CEPHEUS	Cost Efficient Passive Houses as European Standards
CSH	Code for Sustainable Homes
DCLG	Department of Communities and Local Government
DECC	Department of Energy and Climate Change
DRT	Dry Resultant Temperature
EE	Elementary Effect
EPBD	Energy Performance in Buildings Directive
EPW	EnergyPlus Weather file
FEES	Fabric Energy Efficiency Standard
FS	Finkelstein Schafer statistic
GCM	Global Climate Model
GHG	Green House Gas
GSA	Global Sensitivity Analysis
HAM	Heat Air and Moisture simulation
HEP	Human Energy Production
HHSRS	Housing Health and Safety Rating System
IAQ	Indoor Air Quality
IES	Integrated Environmental Solutions
iPHA	International Passive House Association
IPCC	Intergovernmental Panel on Climate Change
LZC	Low and Zero Carbon (Technologies)
OT	Operative Temperature
PHI	Passive House Institute (Passivhaus Institut)
PHPP	Passive House Planning Package
RCM	Regional Climate Model
RH	Relative Humidity
SAP	Standard Assessment Procedure
SRES	(IPCC) Special Report on Emission Scenarios
NCM	National Calculation Methodology
MRM	Meteorological Radiation Model
MVHR	Mechanical Ventilation with Heat Recovery
UHI	Urban Heat Island
UKGBC	UK Green Building Council
WG	Weather Generator
ZCH	Zero Carbon Hub

CHAPTER 1 | INTRODUCTION

1.1 OVERVIEW

Buildings play a major role in global energy consumption and Green House Gas (GHG) emissions (Winter, 2011). At present, commercial, residential and industrial buildings use nearly 40% of the energy in the UK and produce almost half of the CO_2 emissions at a national scale (Committee on Climate Change, 2010). Nearly 60% of this energy consumption is used for heating and cooling of the premises; the rest is consumed by electrical appliances, lighting and other uses (DTI, 2001; Winter, 2011). Consequently many Annex I[i] governments have decided to significantly increase the thermal performance of their building stock as a means of reducing national carbon emissions (WAG, 2004).

Despite a continued fall in the proportion of energy used for hot water generation and cooking in UK dwellings since the 1970's, there has been a pronounced rise in the proportion used for lighting and appliances (DECC 2012); this when coupled with an expanding housing stock (DCLG, 2007a) means that the overall situation is worsening. According to the UK Government Environmental Audit Committee:

> "Unless significant measures are put in place to reduce emissions from the housing sector, from their current level of around 40 MtC a year, they could constitute over 55% of the UK's target for carbon emissions in 2050; nearly doubling the current 30% contribution" (House of Commons, 2005, p48 item 125).

In light of these findings the UK Government announced a rapid transition to 'zero carbon' new buildings in December 2006, as a key step forward in reducing the Green House Gas (GHG) emissions from the domestic and non-domestic sectors (DCLG, 2006a; Weaver, 2007).

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[i] The United Nations Framework Convention on Climate Change (UNCCC) divides treaty members into three main groups: Annex I governments' include industrialised countries that were members of the OECD (Organisation for Economic Co-operation and Development) in 1992, as well as countries with economies in transition (the EIT Parties), including the Russian Federation, the Baltic States, and several Central and Eastern European States. Non Annex I parties are mostly developing countries.

The UK built environment is reflective of the wider situation across Europe, where according to the Energy Performance in Buildings Directive (EPBD) “buildings account for 40% of total energy consumption in the Union” (European Commission, 2010).

At a national level the UK Climate Change Act (2008) has established a legally binding target requiring that GHG emissions are reduced by at least 80% by 2050, compared to 1990 baseline levels (DEFRA, 2007). This target was established on the basis of achieving the GHG emission reductions required for the UK to converge on an equal per capita global emissions target of 2 $tCO_{2\,e}$/person, allowing for anticipated population growth (Meyer, 2000; CCC, 2010).

Research accounting for all Carbon Dioxide equivalent ($CO_{2\,e}$) emissions suggests that even deeper reductions, in the region of 90% relative to the 1990’s baseline, are required by 2050 in order to prevent the consequences of irreversible climate change (Bows, 2006; Forrest, 2005). Achieving CO_2 emission cuts of 80–90 % from the total UK built environment by 2050 represents an enormous technological and logistical challenge. Low rates of demolition and replacement of the existing UK housing stock means that the majority of newly built dwellings contribute to expanding the stock, thereby directly adding to the emissions problem. By 2050 it is estimated that there could be as many as 23% (Boardman, 2007) to 40% (DECC, 2010a) more households in the UK. It is therefore evident that any new buildings will need to go well beyond operational zero carbon in order to heavily compensate for older buildings and make a significant contribution to reducing net GHG emissions, relative to the 1990 baseline.

In order to address these compounding issues, the European Parliament developed a resolution entitled ‘An Action Plan for Energy Efficiency’ (European Commission, 2008). This document attempts to unite multiple European Commission objectives and, “calls on the Commission to propose a mandatory requirement that all new buildings needing to be heated and/or cooled shall be constructed to passive house or equivalent non-residential standards from 2011 onwards; including a requirement to use passive heating and cooling solutions from 2008.” It is notable that this document specifically refers to the adoption of the German Passivhaus standard (Feist et al, 2012) from 2011 onwards.

The German Passivhaus standard is the fastest growing energy performance standard in the world. Since its inception in the early 1990’s, over 40,000 buildings have been built to the standard on a voluntary basis across Europe (iPHA, 2013). The Passivhaus standard’s strengths lie in the simplicity of its approach: by using passive design principles, providing excellent thermal performance, as well as an exceptional airtightness and the use of mechanical ventilation with heat recovery (MVHR). The low space heating demand of Passivhaus buildings (≤15 kWh/m^2.yr) and capped Primary Energy demand (≤120 kWh/m^2.yr) means that annual space heating costs are reduced by a factor of 3–5 compared to current UK new build housing whilst net operational CO_2 emissions are reduced by 50–75 % relative to a FEES standard dwelling (McLeod et al 2012b) .

In response to the UK government's overarching climate change mitigation strategy (DEFRA, 2007; HM Government, 2011) and the recast European Energy Performance in Buildings Directive (EPBD)(European Commission, 2010), targets have been set for the implementation of a revised 'zero carbon' dwelling standard in the UK by 2016 (DCLG, 2011; ZCH, 2011; McLeod et al, 2012b). As a result of these legislative drivers and the voluntary adoption of advanced performance standards, such as the Passivhaus standard, there have been significant changes in the way dwellings are being designed and constructed both in the UK and across Europe.

Over the past decade the evolution of Approved Document L1A (Conservation of fuel and power for new dwellings) of the UK Building Regulations (HM Government, 2010) has prioritised incrementally reducing space heating consumption, since this has historically dominated the CO_2 emissions profile of UK dwellings (DECC, 2012). Attempts to further reduce energy consumption and $CO_{2\ e}$ emissions in Passivhaus, FEES and advanced performance standards have largely focused on reducing thermal transmission losses and making optimal use of passive solar gains (Feist et al, 2012; ZCH, 2009) with only nominal regard to the implications for long-term thermal comfort and occupant wellbeing.

Implementation of these advanced energy performance standards is taking place against a background of rapid climatic change. Bows and Anderson (2008) suggest that a revised interpretation of atmospheric $CO_{2\ e}$ concentration indicates that stabilization much below 650 ppmv by the end of this century is now improbable. Earlier predictions by Meinshausen (2006) estimated the mid-range probability of exceeding a 4 °C threshold at approximately 40 per cent for 650 ppmv. Bows and Anderson (2008, p18) state that, "given this analysis has not factored in a range of other issues with likely net positive impacts, adapting for estimated impacts of at least 4 °C appears wise." A 4 °C average global temperature increase by the end of this century is consistent with the Intergovernmental Panel on

Climate Change (IPCC) best estimate for the A1FI trajectory, commonly known as the ‘High’ emission scenario, (IPCC, 2007a; Table 3.1). Reframing likely emissions in this light suggests that modelling the impacts of the A1FI scenario can no longer be regarded as a cautionary approach, when evaluating the future performance of the built environment.

In light of the policy framework and the evolving climatic context in which future low and zero carbon dwellings are being built, it is evident that whatever performance standard is adopted it must be capable of achieving substantial climate change mitigation and adaptation benefits. In other words the template that future ‘zero carbon’ homes are built to must simultaneously achieve the maximum carbon emission reductions possible whilst also providing optimal protection from the impact of the climatic changes predicted to occur across its entire lifespan.

1.2 PROBLEM DESCRIPTION

The research in this thesis sets out to address four issues that could pose significant challenges to the widespread adoption of the Passivhaus standard as a template for low energy and zero carbon housing in the UK. These issues concern:

- Barriers imposed by UK ‘zero carbon’ policy and Building Regulations
- The availability of micro-regional and future probabilistic climate data required for accurate Passivhaus design and modelling
- Climate change implications for the future performance of Passivhaus dwellings
- The limitations of adapting existing UK construction typologies to cope with the hygrothermal implications of super-insulated dwellings

Without robustly addressing these issues it is likely that the widespread implementation of the Passivhaus standard will be beset by regulatory challenges, over and under engineered buildings, additional cost implications and numerous ‘unforeseen’ performance consequences.

Historically the UK has lagged behind many of its neighbouring Northern and Central European counterparts in imposing stricter standards of energy performance in buildings (NHBC, 2009). Despite this situation, the UK Government announced in 2006 their intention to make all new dwellings zero carbon by 2016 (DCLG, 2006a; Weaver, 2007), three years ahead of the deadline mandated by the Energy Performance in Buildings Directive of the European Parliament (European Commission, 2010).

Irrespective of the precise definition of 'zero carbon' the enormity of the technical and logistical challenge of building in excess of 200,000 new dwellings a year (DCLG, 2007c) to a stringent energy performance standard cannot be underestimated. Whilst the predicted carbon and energy savings resulting from the implementation of advanced energy efficiency standards appear to be substantial (DECC, 2010a); these benefits will only materialise if the buildings continue to perform in accordance with their design predictions throughout their operational lifetimes.

The performance of Passivhaus and ultra-low energy buildings is known to be highly sensitive to both the internal and external boundary conditions (Schnieders, 2003; Morehead, 2010; McLeod et al, 2012a). In a parametric study of Passivhaus dwellings in Southern Europe Schnieders (2009) emphasised the need to consider each Passivhaus in its own climatic context, rather than prescribing a generic specification for all Passivhaus dwellings in a larger region. From a building simulation perspective the UK climatic context cannot be considered to be either homogenous (Eames et al, 2012; McLeod and Hopfe 2013a) or static (Wright et al, 2005; Jenkins et al, 2010;), and yet the implications of micro-regional and future climatic variations for Passivhaus and low energy designs in the UK are yet to be fully considered.

Equally the occupancy profiles and habitation patterns of UK households are changing. On average the size of social housing is being reduced (Housing Corporation, 2002; Boardman et al 2005) the population is aging (ONS, 2012), household sizes are diminishing (DCLG, 2013) whilst people are living longer (ONS, 2013) and spending more time in their homes (ONS, 2005). Many of these factors will influence building performance and the epidemiological risks associated with climatic changes.

If there is to be a rapid transition to zero carbon and low-energy housing in the UK, then an informed decision needs to be made regarding the best method of achieving this objective. Does the German Passivhaus standard present a ready-made solution to this goal? If so, is it then possible to implement this standard successfully without considering the UK's diverse and transient climatic and social contexts, as outlined above? Or can new methods and research improve our understanding of design predictions and thereby reduce the risks and uncertainty associated with implementing Passivhaus and ‘zero carbon’ dwellings on a large scale?

1.3 HYPOTHESIS

The hypothesis governing this work is that: *“The Passivhaus standard has the potential to become a robust template for the widespread implementation of low energy and zero carbon design in the UK.”*

1.4 RESEARCH QUESTIONS

The research presented in this thesis addresses a number of questions that are central to substantiating the above hypothesis (Section 1.3).

1) Is the Passivhaus concept capable of achieving substantially greater CO_2 emission savings than an equivalent Fabric Energy Efficiency Standard (FEES) dwelling?

2) Are methodological differences between the Standard Assessment Procedure (SAP) and the Passive House Planning Package (PHPP) masking a transparent assessment of the energy and carbon savings that can be achieved by Passivhaus dwellings?

3) Can the Passivhaus concept reduce the need for ‘allowable solutions and carbon offsetting’ mechanisms?

4) Do the requirements for higher levels of air-tightness and the use of Mechanical Ventilation with Heat Recovery (MVHR) in Passivhaus dwellings pose a potential health risk to occupants?

5) Is the current use of 22 regional proxy datasets BRE (2013), and the methodology by which these datasets were generated, sufficiently accurate for the design optimization of Passivhaus and ultra-low energy buildings across all of the UK’s micro climatic zones?

6) Does the UKCP09 Weather Generator (WG) provide a robust basis for the development of more accurate micro regional and future probabilistic climate data for Passivhaus design?

7) Will the use of higher resolution climate data result in more accurate design predictions, thereby preventing over and under engineering of Passivhaus designs?

8) Do Passivhaus dwellings, as currently designed in the UK, offer a robust model in the face of future climatic changes?

9) Will Passivhaus dwellings perform better or worse than an equivalent FEES 'zero carbon' dwelling faced with identical climatic change scenarios?

10) Can the application of Global Sensitivity Analysis (GSA) techniques be used to improve whole life performance, by isolating the key design variables influencing the future performance of Passivhaus dwellings?

11) Are there additional issues specific to UK construction methods and the UK's maritime climate that may adversely affect the long-term hygrothermal performance of Passivhaus and EnerPHit dwellings?

1.5 THESIS OUTLINE

The structure of this thesis follows a European 'thesis by publication' format, wherein the core research chapters (Chapters 2–5) are based upon expanded versions of research published by the author in four peer reviewed academic journal publications (Appendix B). The diverse nature of the research required to comprehensively answer the research questions set out above (Section 1.4) lends itself to this structure. All of the chapters are therefore self-contained with respect to having independent: backgrounds, literature reviews, methodologies, results/analysis and conclusions. A summary outline of Chapters 2–5 is provided in sections 1.5.1–1.5.4, below.

A metanarrative commentary is provided by means of a discursus at the beginning of each chapter. The intention of this brief discursus is to guide the reader through the thesis, by providing linkages between preceding and subsequent sections. Chapter 6 provides a brief discussion and further remarks relating to the wider implications of the research findings. Chapter 7 presents a summary of the conclusions, drawn from the body of research, in relation to the research questions posed in section 1.4 - along with recommendations for future work. A summary outline of the overall thesis structure with respect to: the aims, research questions, and research methodologies, is found in Table 1.

1.5.1 OVERVIEW OF CHAPTER 2: POLICY – DRIVERS AND BARRIERS FOR CHANGE IN THE UK CONTEXT

In 2009 the prevailing definition of ‘zero carbon’ homes was substantially revised in the UK. One of the most striking features of the revised definition was that, despite the increased severity of recent climate science findings (Pope et al., 2010; Bows et al., 2006; Bows, A., and Anderson, K., 2008; IPCC, 2007b), the Zero Carbon Hub (ZCH) had advocated a significant *slackening* of the key energy efficiency parameters required to achieve a ‘zero carbon’ dwelling compared to the original definition (DCLG, 2007b).

The research presented in Chapter 2 elaborates on whether the revised definition of ‘zero carbon’ dwellings in the UK (2009) and the approach to implementing this policy, advocated by the ZCH, is coherent with overarching climate change and energy policies (Climate Change Act, 2008; HM Government, 2011; European Commission, 2010). The research examines the barriers to, and benefits of, adopting higher minimum standards of fabric energy efficiency; by comparing the Fabric Energy Efficiency Standard (FEES) (ZCH, 2009) with the German Passivhaus standard (Feist et al, 2012).

1.5.2 OVERVIEW OF CHAPTER 3: CLIMATE DATA – IMPROVING DESIGN PREDICTIONS

The sensitivity of low energy and passive solar buildings to their climatic context engenders a requirement for accurate local climate data (Morehead, 2010; Eames et al 2012). This situation takes on increasing importance in the context of Passivhaus buildings where the absence of conventional oversized heating and cooling systems implies a greater reliance upon fabric and system optimization (Schnieders, 2009; McLeod et al 2010).

Currently, many widely used building performance simulation (BPS) tools still rely on very limited sources of climate data (Künzel, 2006; DECC, 2011; McLeod and Hopfe, 2013a). Until 2010 the availability of climate data in the PHPP format was limited to a single complete dataset for Manchester and a number of partial datasets for major UK cities. In 2010 this situation was improved by the generation of 22 UK datasets in PHPP format which were intended to represent regional averages (BRE, 2013). However the use of ‘near neighbour’ proxy datasets and long range interpolation methods are known to endanger considerable uncertainty (Remund, 2010; Eames et al, 2012; McLeod et al 2012a).

The research in Chapter 3 proposes a new method for generating high resolution current and future probabilistic climate data for Passivhaus design using data sourced from the UKCP09 Weather Generator (UKCP, 2013) and generated using solar geometry and established inter-variable relationships. In order to validate this approach, measured data from Met office climate stations is compared with data generated via the proposed models algorithms. The final PHPP datasets generated were then compared to known sources of climate data, and the modelled outputs evaluated in the context of a micro regional case study (McLeod et al, 2012a).

1.5.3 OVERVIEW OF CHAPTER 4: AN INVESTIGATION INTO FUTURE PERFORMANCE AND OVERHEATING RISKS IN PASSIVHAUS DWELLINGS

Despite genuine motivations to mitigate climate change and alleviate fuel poverty there is a lack of research investigating the long-term performance of Passivhaus buildings in a rapidly changing UK climate (McLeod et al, 2013b). Future climatic changes may pose serious implications for the performance of super insulated, passive solar buildings (Orme et al 2003; ZCH, 2010; NHBC 2012) as a result of increasing mean summer temperatures and solar irradiation fluxes (Jenkins et al, 2010).

Chapter 4 sets out to investigate whether Passivhaus dwellings will be able to continue to provide high standards of thermal comfort in the future, or whether they are inherently vulnerable to overheating risks. A Dynamic Simulation Programme (DSP) was used in conjunction with future probabilistic climatic data to establish the transitional performance of three different Passivhaus constructions relative to a FEES standard dwelling over a notional 80 year lifespan. A Global Sensitivity Analysis (GSA) technique was then coupled with the DSP in order to provide a method of ranking design parameters in accordance with their influence on key performance criteria (such as overheating risk, peak loads and annual heating demand). The methodology presented (in Chapter 4) provides a robust yet economical optimization procedure that is capable of enhancing the future proofing of Passivhaus and low energy design.

1.5.4 OVERVIEW OF CHAPTER 5: HYGROTHERMAL IMPLICATIONS OF LOW AND ZERO CARBON STANDARDS

Moisture is known to be a major cause of damage and contamination issues in dwellings. Guidance is provided in Part C of the UK Building Regulations (HM Government, 2010b) with respect to appropriate methods for addressing such issues. The 'Dew Point' or Glaser method (Glaser, 1959) is a widely used steady–state method for the calculation of vapour pressure differences in a building's envelope. The Glaser method (BS EN 13788, 2012) analyses the moisture balance of a building component by considering vapour diffusion transport from its interior. The Glaser method is known to have a number of major limitations however, since it ignores a number of important physical phenomena (including the transient and inhomogeneous nature of boundary conditions). Consequently the method is considered applicable only to situations where these effects are negligible (Künzel, 2000). The application and limitations of the method are described in BS EN 13788 (2002; 2012). Despite these limitations it remains the principal method used to assess condensation risks and moisture response in UK buildings (McLeod and Hopfe, 2013).

The hygrothermal consequences of meeting advanced thermal performance standards have been widely overlooked in the UK Governments ambition to deliver 'zero carbon' dwellings, and improve the performance of the existing stock. UK climate change projections indicate that increasingly warmer and wetter summers are likely for much of the UK (Jenkins et al, 2007). The combination of super-insulated constructions and warmer and wetter external climatic conditions may have serious compounding effects on the hygrothermal performance of ultra-low energy buildings (McLeod and Hopfe, 2013).

Chapter 5 therefore evaluates the risks inherent in adapting existing UK construction typologies (such as cavity walls) to meet the reduced thermal transmission coefficients demanded by Passivhaus, EnerPHit and 'zero carbon' building standards. This chapter reviews current UK and European guidance on moisture related issues and points to the need for accurate in-situ prediction of moisture problems in buildings using transient hygrothermal modelling techniques (EN 15026, 2007), which are based on realistic boundary assumptions.

Table 1 Thesis outline

CHAPTER TITLE	AIM	RESEARCH QUESTION	RESEARCH METHODOLOGY
Chapter 1 | Introduction Pages 1-17	Establishing the context, formulating the problem statement and research questions (Section 1.4)	see pages 6-7	Literature review (LR)
Chapter 2 | An Investigation into Recent Proposals for a Revised Definition of Zero Carbon Homes Pages 19-52	Investigates whether the revised ZC definition fulfils wider climate change objectives. Assesses barriers and drivers for adoption of PH	Addresses research questions No. 1-4	LR & comparative analysis of CO_2 emissions between PH and FEES dwellings
Chapter 3 | Generation of High Resolution Current and Future Climate Data Pages 53-90	Present a new method for generating 5km grid cell data in PHPP format from UKCP WG. Establish whether high resolution data improves the accuracy of design predictions	Addresses research questions No. 5-7	LR & prototyping using statistical sorting techniques, solar models and inter-variable relationships. Followed by quantitative case study
Chapter 4 | Future Performance and Overheating Risks Pages 95-148	Establish the likely future performance characteristics of PH and FEES dwellings in relation to climate change and overheating risks	Addresses research questions No. 8-10	LR & quantitative case study combining Sensitivity Analysis (SA) with dynamic simulation
Chapter 5 | Hygrothermal Implications of Low and Zero Energy Standards for Building Envelope Performance Pages 153-188	Assess the potential for hygrothermal issues arising as a result of simplified assessment methods and the adaptation of UK construction typologies to meet PH thermal criteria	Addresses research question No. 11	LR & comparative analysis of case study examples
Chapter 6 | Discussion and Further Remarks Pages 193-194	Discussion of the wider implications of the findings in the context of existing policy and praxis.	General discussion, relationship to wider context	
Chapter 7 | Conclusions and Further Work Pages 199-204	To draw conclusions in relation to the research questions and suggest further work that would strengthen the research	Responds to all of the research questions and identifies future work	

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CHAPTER 2 | AN INVESTIGATION INTO RECENT PROPOSALS FOR A REVISED DEFINITION OF ZERO CARBON HOMES

DISCURSUS:

The preceding chapter has presented an outline of the wider environmental, policy and technical context in which this thesis is grounded. This chapter describes in greater detail the evolving policy context that has led to a revised definition of 'zero carbon' in the UK (Section 2.1), before going on to examine the potential barriers and benefits to adopting higher minimum standards of fabric energy efficiency, in particular the German Passivhaus standard (Section 2.2).

It further elaborates on whether the revised definition of 'zero carbon' dwellings in the UK and the approach to implementing this policy, as advocated by the Zero Carbon Hub (ZCH), is coherent with overarching climate change and energy policies (Section 2.3). An overview of the revised approach proposed by the Zero Carbon Hub and the Department for Communities and Local Government (DCLG) is presented in Section 2.4.

By comparing methodological differences associated with the ZCH Fabric Energy Efficiency Standard (FEES) and the Passivhaus standard (and normalising the principal methodological differences), an estimate of the real world energy and carbon savings has been determined (Section 2.5). This process allows a more accurate comparison of the net energy and CO_2 mitigation benefits achieved from both standards.

Section 2.6 concludes that adopting a more robust 'fabric first' approach, would achieve better coherence with UK climate change and energy policies, whilst mitigating the risks associated with the use of carbon offsetting mechanisms.

2.1 BACKGROUND – A NEW DEFINITION OF ZERO CARBON

A formal definition of a ‘zero carbon home’ was established in the UK in December 2006 when The Code for Sustainable Homes (CSH) was introduced as a voluntary six-tiered sustainability rating system leading to Code Level 6 or a ‘zero carbon home’ (DCLG, 2006b). The original definition stated that, “The home will have to be completely zero carbon (i.e. zero net emissions of carbon dioxide (CO_2) from all energy use in the home” (DCLG, 2006b, p27).

In July 2007, the Government issued a policy statement which reiterated that, “zero carbon means that, over a year, the net carbon emissions from all energy use in the home would be zero” (DCLG, 2007a). At this time The Code for Sustainable Homes Technical Guide (DCLG, 2007b) defined a ‘true zero carbon dwelling’ (Code Level 6), as one where: “Net carbon dioxide emissions from ALL energy used in the dwelling are zero or better” (DCLG, 2007b, p30). In addition, “a ‘zero carbon home’ is also required to have a Heat Loss Parameter (covering walls, windows, air tightness and other building design issues) of 0.8 W/m^2K or less, as well as net zero carbon dioxide emissions from use of appliances in the homes (i.e. on average over a year)” (DCLG, 2007b, p30).

However, by December 2008 the Department for Communities and Local Government (CLG) had initiated a new consultation process on the definition of zero carbon homes. This consultation was purportedly in response to uncertainty over the existing definition and concerns from the construction industry regarding the workability of the definition (ZCH, 2009a). One of the main participants in this process, the UK Green Building Council (UKGBC), is cited by the ZCH as stating that the existing zero carbon definition (based on Level 6 of the Code for Sustainable Homes) would be unattainable for as many as 80% of new homes (ZCH, 2009a). This information is presented slightly differently in the UKGBC Task Group Report, which states that: “According to all the available evidence, anywhere from 10% to 80% of new homes may not be able to meet the current definition of zero carbon” (UK Green Building Council, 2010).

Paradoxically the supporting evidence for these statements is largely based on a report produced for the Renewables Advisory Board (RAB) entitled ‘The Role of Onsite Energy Generation in Delivering Zero Carbon Homes’ which was published in November 2007 (UK Green Building Council, 2010). According to RAB the main findings of the report are extremely positive with respect to onsite renewable energy generation for zero carbon homes in the UK. As a result RAB (2007) recommended to the Government that they bring forward delivery of the zero carbon policy by creating an even earlier target, in advance of 2016, via the planning system. Furthermore RAB advised that the zero carbon homes policy should “minimise the use of remote offsite energy generation in meeting zero carbon standards e.g. by setting a tight cap on its use and a high ‘buy-out’ cost for any offsite generation fund” (BERR, 2007). Such recommendations run counter to the UKGBC and ZCH interpretations of the same report. These conflicting interpretations suggest that economic considerations in the building industry might be a greater determinant to the revised definition of zero carbon than the technical limitations of the renewable energy industry.

Nonetheless on dense urban sites several studies have suggested that it can be both technically challenging and expensive to achieve the original zero carbon definition (DCLG, 2008). According to CLG: “If the definition of zero carbon is too rigid (such as requiring all renewable energy generation to be onsite) or too costly, it could potentially prejudice smaller urban brownfield developments in favour of larger greenfield sites because larger sites offer greater economies of scale in energy supply technologies” (DCLG, 2008). It is clear that a robust zero carbon policy should not jeopardize wider environmental and social concerns: including preservation of biodiversity and agricultural land, minimization of urban sprawl and carbon emissions from transport, whilst providing good access to community infrastructure.

Evidence that such challenges can be coherently addressed on a large scale is documented in the European Energy Cities project (Energy Cities, 2012a). European case studies of successfully implemented large scale zero carbon developments include: the German Kronsberg scheme with 6000 Passivhaus dwellings proposed for 15,000 people relying mainly on solar and wind energy (Energy Cities, 2012b); the Vauban district, located on a former French barrack site with all buildings meeting the Passivhaus standard (Energy Cities, 2012c); or a recently completed district close to Stockholm, Sweden providing 10,000 apartments for 25,000 inhabitants using 100% renewable energy (RE) systems (Energy Cities EU, 2012d).

In addition to the avoidance of perverse consequences, the current economic downturn is undoubtedly a factor influencing UK zero carbon policy. Recognition that financial pressures on major house builders may be weakening their support for zero carbon policies came from a former Minister of Housing and Planning. In her forward to the CLG 2008 Zero Carbon Definition consultation document, Margaret Beckett (Minister for Housing and Planning in 2008) acknowledged that, “the house building industry is facing very difficult conditions,” but at the same time cautioned: “Yet it is critical that we don’t lose sight of our longer term responsibilities. A failure to invest in reducing climate change now would be disastrous for future generations” (DCLG, 2008).

2.2 THE ROLE OF THE PASSIVHAUS STANDARD IN UK CLIMATE AND ENERGY TARGETS

Attempts to quantify the carbon savings achievable by zero carbon homes in the UK have arrived at some ambiguous findings. According to the Energy White Paper (DTI, 2007) overall carbon reductions from energy efficiency in the residential sector are predicted to be between 4.7–7.6 MtC/yr by 2020 relative to a 2006 emissions baseline of 40 MtC/yr (DTI, 2007). When compared to the 1990 baseline, as used by the UK Climate Change Act, this annual saving represents a net reduction of only 11–18% by 2020 (Boardman, 2007); far short of the 40% reduction required to maintain a planned trajectory towards an 80% reduction[ii] in GHG emissions by 2050. According to the Energy White Paper zero carbon homes will contribute to saving 1.1–1.2 MtC/yr by 2020 (over 2006 levels) (DTI, 2007); however it is notable that this estimate is predicated upon the original (2007) definition of a zero carbon home (DCLG, 2007a)[iii].

Viewed on a meta scale, recent modelling by the Department of Energy and Climate Change (DECC) illustrates that the implementation of an advanced energy efficiency

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[ii] The 2050 GHG emissions reduction target of 80% (from 1990 levels) forms part of the UK Climate Act (2008). Carbon Budget emission levels are recommended by the Committee on Climate Change (CCC), an independent statutory body advising the UK Government. Once enacted these carbon budgets form the basis of the UK’s commitment to a global emissions reduction pathway. According to the Third and Fourth Carbon Budgets by 2020 the UK should have reduced GHGs by 40% relative to 1990 and by 2030 the UK should aim to have reduced total greenhouse gases by 60% (CCC, 2010).

[iii] It should also be noted that the Carbon Budget trajectory targets were established in relation to the climate science at the time of the Climate Act (2008); the implications of recent developments in climate science are discussed in Section 4.1. A decision on whether to include international aviation and shipping emissions within the UK’s net carbon account was deferred by the Government on 19 Dec 2012 (DECC, 2012) and as such the above figures do not account for these emissions.

standard (such as the Passivhaus standard - Level 4) is the only approach that leads to a long term reduction in the total domestic heating demand.

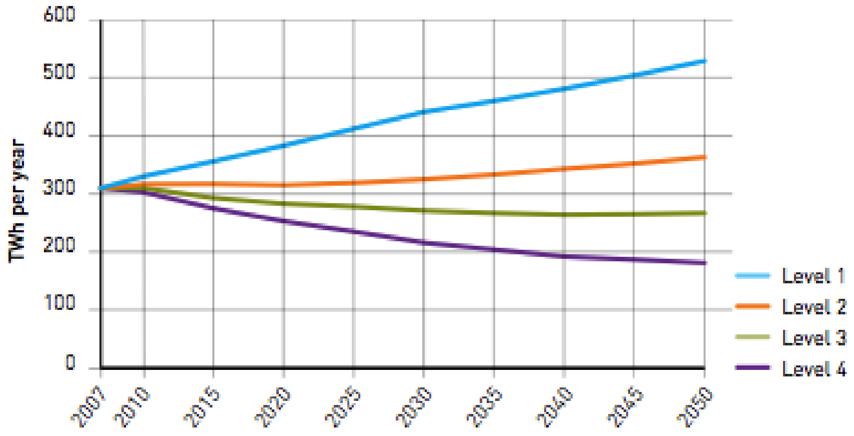

Figure 1 Trajectories for total domestic heat demand under four levels of change (DECC, 2010a)

Given that the scenario modelled as Level 4 (Passivhaus) requires a contiguous roll out of extensive refurbishment measures to 96% of the existing stock, and an accompanying drop in the average heating set point to 16°C there appears to be no margin to construct new build dwellings to a more lax standard (DECC, 2010). When the projected growth in domestic cooling demand is also considered the importance of adopting a Passivhaus type standard becomes even more apparent[iv].

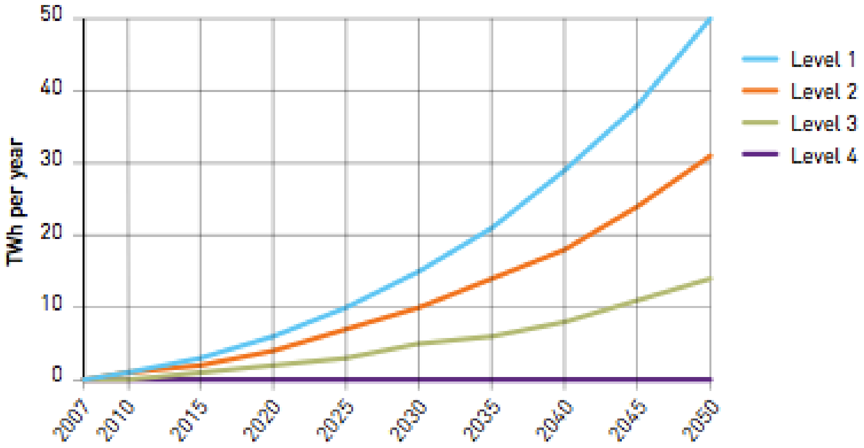

Figure 2 Trajectories for total domestic cooling demand under four levels of change (DECC, 2010a)

[iv] The assumption that Level 4 (Passivhaus) is consistent with zero cooling demand to 2050, as illustrated by the 2050 Pathway Analysis (DECC, 2010a) is assessed in Chapter 4.

The growth in domestic cooling demand forecast to occur by 2050 (Figure 2) could place an additional 50 TWh/yr burden (DECC, 2010a) on the net climate change impacts of the UK dwelling stock, a fact which appears to have been entirely overlooked by the ZCH energy efficiency proposals. According to the recast EPBD (2010) "the methodology for calculating energy performance should be based not only on the season in which heating is required, but should cover the annual energy performance of a building. That methodology should take into account existing European standards" (EC, 2010). When total annual energy performance is considered the DECC modelling shows that only the Passivhaus (Level 4) scenario delivers a net overall decrease in heating, cooling and hot water energy demand (DECC, 2010a).

These findings are broadly in agreement with a German study of national emissions reductions scenarios in the built environment (Vallentin, 2009) based upon atmospheric stabilisation in accordance with the Contraction and Convergence ($C\&C_{2050}$) model. The C&C mechanism provides a simple and scalable means of implementing GHG emission pathways based on the principle of an equitable per capita distribution of emission rights (Meyer 2000). The C&C model involves a transitional phase in order to achieve convergence on equal per capita emissions in a structured manner. Vallentin's research has relevance to the UK context since Germany has similar levels of CO_2 emissions per capita to the UK and a parallel trajectory of emission reductions of 40% by 2020 and 80% by 2050. According to his emissions trajectory analysis of the built environment the total primary energy consumption for domestic heating, ventilation, hot water and appliances should be no greater than 100 $kWh/m^2_{TFA}.yr$[v] in 2010, and will need to fall progressively to $\leq 60\ kWh/m^2_{TFA}.yr$ by 2050 (Vallentin, 2009). In order to meet this stabilization trajectory, Vallentin concluded that: "By 2015 the Passivhaus standard must be applied to all new buildings, and Passivhaus components must be made mandatory in renovation projects" (2009, p255). This view is endorsed by the European Parliament resolution on an Action Plan for Energy Efficiency which called on the EC to "propose a binding requirement that all new buildings needing to be heated and/or cooled be constructed to passive house[vi] or equivalent non-residential standards from 2011 onwards" (EC, 2008, item 29).

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[v] TFA refers to Treated Floor Area, as defined in the Passive House Planning Package (PHPP), Feist et al (2012) and further elaborated by Hopfe and McLeod (2010). For normalisation purposes specific energy consumption in Passivhaus buildings is stated relative to the building's TFA.

[vi] Where 'passive house' (in this context) refers to the German Passivhaus standard.

2.3 THE UK GOVERNMENT'S REVISED APPROACH TO ZERO CARBON

Uncertainty over the existing definition of 'zero carbon' and concerns from the construction industry regarding the workability of the definition are cited as the main drivers for a revised definition (ZCH, 2009a). During the 2008 consultation the Government set out their preferred hierarchy for the delivery of zero carbon homes in the UK. This tiered approach of progressive solutions was, according to the Government, predicated upon the principle that 'very high standards of energy efficiency' should form the basis of this policy (DCLG, 2008). This was followed by on-site renewables and direct connected district heating solutions forming the second tier. Where the new policy differs from the previous definition is in the inclusion of a third tier based on cost capped 'allowable solutions' (Figure 3).

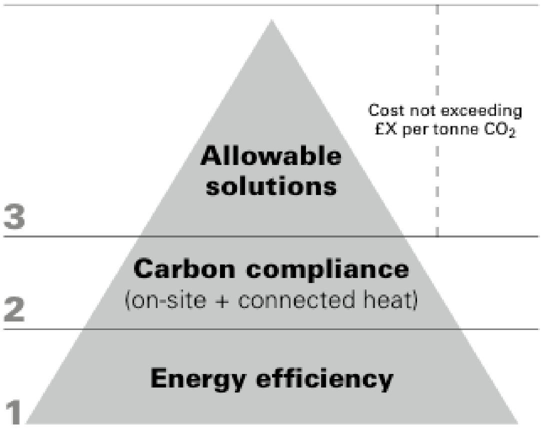

Figure 3 UK government's preferred hierarchy - showing carbon offset measures (DCLG, 2008)

Although the Government's Energy Hierarchy appears to be based upon prioritising energy efficiency (Figure 3) the introduction of allowable solutions has effectively introduced a 'buyout clause'. Depending upon what level of Carbon Compliance is finally adopted, market based 'allowable solutions' could comprise the majority of the net carbon savings from a 'zero carbon' home. The introduction of 'allowable solutions' was strongly welcomed by the ZCH since "rather than placing reliance solely on the development itself (through energy efficiency and on-site renewable energy) to deliver zero carbon, a range of additional, mostly off-site solutions, would be made available to developers in the new definition" (ZCH, 2009a).

The UK Green Building Council (UKGBC) initially proposed an alternative approach to the concept of 'allowable solutions' based on the concept of a Community Energy Fund. In theory such a concept could have been used to create a relatively simple fiscal mechanism to directly fund off-site carbon savings via regional investment in new large and medium scale renewables infrastructure. The proposal was rejected by CLG however who stated that the Government was not proposing to take forward the concept of a buyout fund (DCLG, 2008).

Under the revised definition of 'zero carbon', the national minimum energy efficiency specification for zero carbon homes becomes all important. This is because it effectively defines the minimum construction quality and energy efficiency as well as the climate change adaptation and the mitigation potential of the UK's future housing stock. The level at which this energy efficiency standard in new buildings is set also determines the requirement for on-site renewables energy and the subsequent volume of allowable solutions (or carbon offsetting) needed to make these buildings zero carbon.

2.4 OVERVIEW OF THE REVISED APPROACH BY ZCH AND CLG

2.4.1 ZCH BACKGROUND

The ZCH was formed as an initiative of the National House Building Council (NHBC) Foundation in 2008 with a stated aim of "facilitating the mainstream delivery of low and zero carbon homes" (ZCH, 2009a). In response to the Government's consultation on a revised definition of 'zero carbon' (in December 2008), the ZCH convened a series of meetings across the UK in order to gauge the opinion of industry stakeholders. These meetings were held in parallel with a formal consultation carried out by the Department for Communities and Local Government (CLG). During the ZCH consultation meetings, a series of pre-formulated questions were put to over 500 industry stakeholders; the response to these questions formed the basis of the ZCH 'Have Your Say' (2009) report. Based on this industry consultation process the 'Have Your Say' report (ZCH, 2009a) presented a series of findings and recommendations many of which differ significantly from the original working definition of 'zero carbon' (DCLG, 2007b).

The ZCH proposals represent a methodological shift from the approach set forth in strategic UK housing reports such as the '40% House Report' (Boardman et al., 2005), the 'Home Truths' report (Boardman, 2007) and well documented European approaches to Zero Energy homes (Voss, 2008). What is most striking about the ZCH recommendations is that despite the increased severity of recent findings on climate science (Pope et al., 2010; Bows et al., 2006; IPCC, 2007) the ZCH have effectively advocated a significant *relaxation* of the key energy efficiency parameters required to achieve a Zero Carbon Home compared to the original definition (DCLG, 2007b).

The question remains whether such an approach is fully consistent with: the energy efficiency and carbon reduction targets set out in the UK Climate Change Act (Climate Change Act, 2008), zero-carbon building policies set out in the EU Energy Performance in Buildings Directive (EPBD) (European Commission, 2010) and current peer reviewed scientific research (Bows and Anderson, 2008). Addressing these issues is fundamental to the successful delivery of legally binding national and international GHG reduction measures. Implementing a revised definition of 'zero carbon' that introduces the concept of carbon offsetting to the built environment raises a number of critical uncertainties. The choice of methodological approach, the definition of boundaries used in the reporting of emissions, and ultimately the efficacy of the chosen policy approach in responding to climate change must all be evaluated.

2.4.2 KEY RECOMMENDATIONS OF THE ZCH

Carbon compliance was a key issue in the CLG consultation on the revised definition of 'zero carbon' (HM Government, 2008). On the issue of where the revised carbon compliance threshold should be set, the ZCH (2009) report concluded that most of the industry participants surveyed favoured a 70% CO_2 compliance target (relative to Part L 2006 levels) (ZCH, 2009a). In July 2009 John Healey (then Minister for Housing) confirmed that the new 'zero carbon' definition would require a regulatory minimum level of onsite carbon compliance (taking account energy efficiency and on-site energy supply) amounting to an emissions reduction of 70% from the level permitted in the 2006 Building Regulations (Healey, 2009).

Based on the assumption that Part L 2006 methodology already omits between one third (Reason and Olivier, 2006) and a half (DCLG, 2007a) of the total CO_2 emissions from a dwelling then a 70% compliance target would imply an actual reduction of 35–46% of the dwellings total operational CO_2 emissions. In other words under such a revised definition more than half of the carbon compliance measures required to achieve a 'true zero carbon dwelling' (DCLG, 2007b) would now be permitted to be offset by 'allowable solutions'.

Evidence that the UK government were eager to adopt the ZCH's revised definition of 'zero carbon' was provided in a Ministerial Statement presented by the then Housing Minister, John Healey, in July 2009 (Healey, 2009). Although the definition of an 'allowable solution' has not yet been fully established by CLG, a number of proposals have been put forward in order to gauge the acceptability of the new mechanisms for delivering the revised definition of 'zero carbon'. These solutions were voted upon during the ZCH 'Have Your Say' consultation (ZCH, 2009a) and the results are illustrated in Table 2, below:

Table 2 ZCH hierarchy of allowable solutions and implementation potential (ZCH, 2009a)

'ALLOWABLE SOLUTION'	WHO VOTED FOR INCLUSION? (%)	POTENTIAL FOR IMPLEMENTATION*
Energy efficient appliances and controls	82	0.70
Continuing carbon compliance	81	0.73
Off-site renewable – direct connection	74	0.50
Section 106 credit for LZC[I] infrastructure	69	0.57
Improving existing stock fabric	65	0.52
Investment in off-site renewables	65	0.48
Export of LZC[I] heat to existing stock	61	0.36

*Potential for implementation was ranked on a scale from 0 to 1; where 1.00 = high potential and 0.00 = no potential

[I] Low and Zero Carbon Technologies

Based on the highest ranking percentage of those in favour of a given solution combined with the potential for implementation of the solution, it appears likely that 'energy efficient appliances and controls' and 'continuing carbon compliance' will feature amongst the 'allowable solutions'. Although not elaborated in significant detail in the ZCH consultation document, it was stated that delegates raised significant concerns over the complexity of some of the 'Allowable Solutions' (ZCH, 2009a).

2.4.3 IMPLICATIONS OF THE ZCH AND CLG RECOMMENDATIONS

In order to understand the wider implications of the Government's preferred hierarchy (Figure 3) it is important to understand the framework boundaries and the uncertainties associated with each tier. The hierarchy can be considered robust in the context of addressing climate change abatement targets if it achieves the requisite GHG emission reductions in an appropriate time step as set out in Meyer (2000) and the Climate Change Act (2008). Besides the discrepancy associated with individual calculation methodologies (for instance how the space heating demand is calculated by PHPP or SAP), there is often a marked difference between what building energy models (Norford, 1994; NES, 2005;

Bordass et al, 2004) and carbon offsetting reports (Kill et al, 2010) (Haya, 2009) predict and the reality of what is achieved. Hence, consideration not only of the uncertainty associated with predictive models but also potential weaknesses in the overall quality assurance system is central to the final outcome.

2.4.3.1 FRAMEWORK BOUNDARIES AND OMISSIONS

The revised 'zero carbon' definition, as set out in the 'Have Your Say' report (ZCH, 2009) and confirmed in the Budget 2011 (HM Treasury, 2011), suggests that a significant reduction in the overall scale of the new build housing sector's emissions is possible whilst omitting two key sources of GHG emissions. These are the appliance energy consumption, that may account for up to 50% (DCLG, 2007a) of the operational emissions from a dwelling, and the emissions released during the manufacture and construction the building, which may account for up to 50% of the net 80-year emissions from a low energy dwelling (McLeod, 2007). Therefore the revised definition does not accord with the emissions that will be registered in the atmosphere.

When the net GHG emissions (including embodied energy) are considered in the context of a 'zero carbon' dwelling the on-site savings achieved by the revised 'zero carbon' definition diminishes to as little as one sixth of the total GHG emissions incurred over an eighty year period (Figure 4).

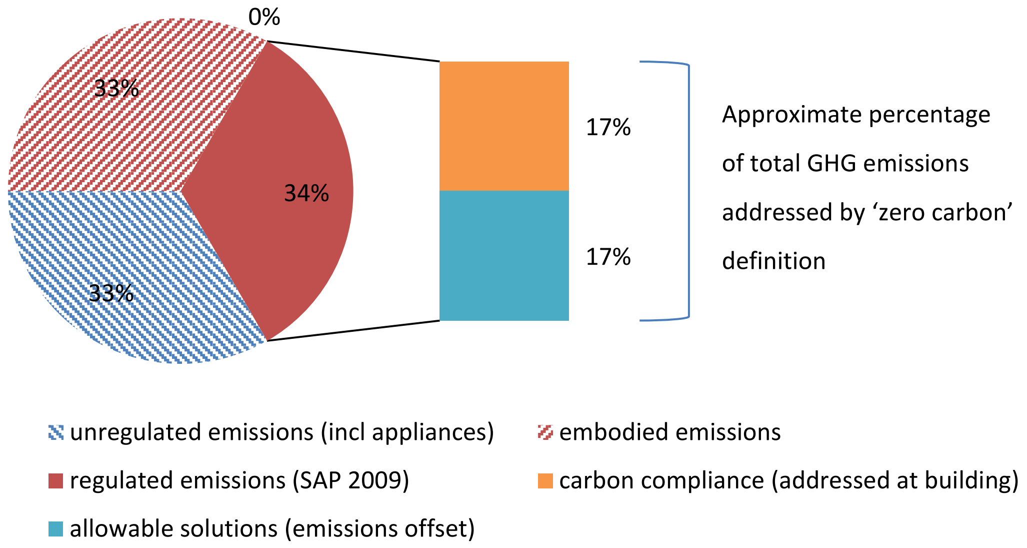

Figure 4 Indicative[vii] ratio of net (operational and embodied) GHG emissions relative to those covered by the revised 'zero carbon' definition

The truncation of large proportion of the net dwelling GHG emissions from the revised 'zero carbon' homes definition (Figure 4) may lead to cheaper forms of 'compliance' in the short term; a real question remains as to the efficacy of this approach in the delivery of long term carbon reduction strategies. Sectoral boundaries must be carefully defined and adhered to if real world emission reductions are to play a coherent role in national GHG inventory reporting; wherein the sum of the sectoral emissions must accord with the national target.

Whilst domestic appliances are typically powered by electricity that could theoretically be supplied by large scale renewable sources elsewhere, the UK currently generates only 7% of its electricity from renewable sources (DECC, 2010b). Considering (i) the replacement time of national energy infrastructure, (ii) increasing UK domestic electricity demand (DECC, 2010c) and (iii) the urgency of climate change abatement measures (Bows et al., 2006; Pope et al., 2010), it seems prudent that viable domestic scale renewable energy (RE) production should continue to be incentivised.

[vii] Figure 4 is labelled as 'indicative' since the absolute GHG emission ratio depends largely on the magnitude of the embodied energy (and the unregulated emissions), which vary significantly according to the reference source quoted. In the context of a low energy dwelling the figure used here for embodied energy is likely to be conservative, see Stephan et al (2013) and McLeod (2007).

There is currently no UK energy performance standard that makes detailed reference to the embodied energy or embodied carbon emissions from a building. According to Monahan and Powell (2009) the embodied carbon consequences of building 3 million new homes, using conventional methods, could range between 110 and 167 $MtCO_2$ depending on the proportions of all-timber to traditional masonry construction used. Research on embodied energy in Passivhaus and low energy buildings by McLeod (2007), Lazarus (2004) and Marsh (2004) suggests that embodied energy and embodied carbon typically account for between 30 and 50% of the net 80-year lifecycle CO_2 emissions from a Passivhaus standard dwelling, depending on the construction type and heating system used. McLeod (2007) determined that up to 50 tonnes of embodied CO_2 emissions could be avoided from the construction of a single $70m^2$ terraced Passivhaus if conventional masonry materials were replaced with locally sourced biomaterials. A recent parametric life cycle assessment (LCA) study of Belgian Passivhaus typologies by Stephan et al (2013) concluded that the embodied energy of a Passivhaus can represent up to 77% of the total embodied and operational energy over 100 years.

Despite the potential magnitude for energy and emissions savings through carbon optimized construction there is no mention of embodied energy or the role building materials play in the revised ‘zero carbon’ definition. In practice, embodied emissions can be readily quantified and there is at least one documented precedent of embodied energy savings being considered as an acceptable means of exemption from the renewable energy requirement imposed under UK Planning Policy Statement (PPS) 22 (Waugh et al., 2009). Despite the magnitude of these implications the inclusion of a robust life cycle assessment methodology appears one step beyond the current ‘zero carbon’ debate in the UK, and for this reason further discussion of these issues is beyond the scope of this thesis.

2.4.3.2 ‘ALLOWABLE SOLUTIONS’ AND CARBON OFFSETTING

The concept of ‘allowable solutions’ is effectively a form of carbon offsetting. The economic rationale behind this approach is that emission reductions can be made at the least capital expenditure, thus maximising the short term economic benefit to industry (Kill et al, 2010). This type of indirect carbon reduction strategy has the fundamental weakness that it does not directly address the source of the problem and as such is vulnerable to the issues which affect carbon offset mechanisms in general.

For example, accounting for the emissions from the use of domestic appliances is excluded from the revised ‘zero carbon’ definition (HM Treasury, 2011); however the use of ‘energy efficient appliances and controls’ achieves a high ranking on the ZCH hierarchy of preferred ‘allowable solutions’ (Table 2). This is an example of emissions occurring outside the regulatory framework being used to offset emissions occurring within the regulatory framework; despite both emissions occurring within the same physical system (the dwelling).

As with most forms of carbon offsetting, the use of ‘allowable solutions’ contains two inherent vulnerabilities: (i) additionality and (ii) permanence, which will be explained in the following. Allocating carbon credits for emission reductions that may have occurred anyway is a problem common to many offsetting schemes, and is referred to as ‘non-additionality’ (i.e., the carbon offsetting did not create additional carbon savings relatively to what would have happened anyway). It is possible that the overall emissions may even increase in the situation where emission reductions are falsely justified with the help of carbon offsetting strategies as explained in Granda (2005, p.59).

Several studies have shown that a significant percentage of offset credits awarded under the Clean Development Mechanism (CDM), the mechanism for generating offset credits for countries with reduction commitments under the Kyoto Protocol, were not actually additional (Schneider, 2007; Müller, 2009; Haya, 2009). Although this increase or ‘additionality’ is central to the concept of carbon offsetting, the Carbon Trust has stated that it can never be scientifically proven (Carbon Trust, 2008).

The second issue affecting the durability of carbon offsetting is what is referred to as ‘permanence’. Even if the carbon offsets are truly additional, there is the risk of reversal over time. If the offset mechanisms that are justifying the emissions elsewhere are not permanent, then potentially the atmosphere could receive two sets of emissions: firstly, from the original emissions being offset, and secondly, when the offset mechanism reverts to being an emission relative to the notional baseline. Most appliances have inherently short lifespans (Seiders et al, 2007) and without on-going monitoring there is no guarantee that the ‘allowable solution’ will actually endure the period for which the offset carbon credit has been claimed. In this context reversal could occur if, for example, a low energy appliance was subsequently sold or replaced with a higher-energy consuming appliance (or multiple appliances).

In contrast to the lifespan of many appliances and small Low and Zero Carbon (LZC) technologies, which are unlikely to last beyond 10–20 years (Phillips et al, 2007; Seiders et al, 2007), fabric measures implemented via quality assured design approaches such as the Passivhaus standard are likely to achieve carbon savings that will exceed 60 or even 100 years (BLP, 2010). Such large differences in the permanence of ‘allowable solutions’ raises further questions regarding how the weighting, monitoring and validation of short term solutions should be dealt with. For the analysis in the impact assessment study which CLG commissioned, it was assumed that only 30 years of residential emissions would need to be covered via an ‘allowable solution’ (DCLG, 2008). Unless the carbon credit awarded for such short-term ‘allowable solutions’ is down-weighted in proportion to their anticipated life spans this approach is likely to perversely disincentivise long term ‘fabric first’ approaches to carbon compliance.

According to Kill et al. (2010), most forms of carbon offsetting, are inherently complex to implement and monitor, and the ‘allowable solutions’ so far proposed are unlikely to be an exception to this. It has been further argued that such mechanisms may actually undermine the evolution of coherent sustainability policies by simply allowing the leakage of emissions from one sector to another (Haya, 2009). In practice, there are also many limitations on whether offsets can actually deliver least cost solutions. Both, in the built environment and in the wider response to climate change there is a growing body of evidence suggesting that carbon trading and offsetting does not lead to emission reductions (Müller, 2009; Bullock et al., 2009). Therefore if ‘allowable solutions’ look unlikely to deliver least cost solutions (viewed over the medium to long term) the question remains as to why higher levels of carbon compliance at source, such as the Passivhaus standard, are not being mandated.

2.4.3.3 CONTINUING CARBON COMPLIANCE

‘Continuing carbon compliance’ refers to the voluntary use of an improved building fabric specification or the use of additional onsite LZC technologies that would gain benefit in reducing the Dwelling Emission Rate (DER) used in the UK (SAP) calculation. Continuing carbon compliance in this sense can be seen as providing credit for steps back towards the original definition of Zero Carbon. In theory such measures are reasonably robust since they can be quantified at the design stage and verified on site by Building Control and do not incur the risks of non-additionality associated with the use of energy efficient appliances or more remote offset measures.

Fabric measures are likely to considerably outlast the lifespan of most LZCT's and should therefore be prioritised to the maximum extent attainable. Since the permanence of emission reductions is integral to achieving deep long term emission cuts, the weighting of improved fabric efficiency measures demands further consideration. Conversely localised climatic factors, poor installation or commissioning pose danger of credit being given for LZT technologies that do not perform as well onsite as theoretical predictions might suggest. Guaranteeing continuing carbon compliance in such cases should require on-going in situ performance verification.

2.4.3.4 THE ENERGY EFFICIENCY TARGETS

Following the 'Have Your Say' (2009) consultation, the ZCH convened an Energy Efficiency Task Force to investigate the minimum level of energy efficiency that would be required to partially fulfil the 70% Carbon Compliance target. Despite choosing a clear metric from which to define the energy efficiency of the space heating requirement (kWh/m^2.yr) the actual levels proposed by the ZCH for the specific space heating demand (SHD) of a 'zero carbon' dwelling appear to be remarkably high. Two different maximum levels of space heating have been proposed by the ZCH according to the dwelling type: multi-residential and mid-terraced properties are set at 39 kWh/m^2.yr; whilst end of terrace, semi-detached and detached dwellings are set at 46 kWh/m^2.yr (Figure 5) (ZCH, 2009b). These figures are based on the UK SAP methodology minus internal domestic hot water (DHW) gains (ZCH, 2009b). Collectively these energy efficiency standards are referred to as the Fabric Energy Efficiency Standard (FEES).

According to the ZCH task group report, the rationale behind this two tiered approach is that it allows a similar fabric specification to meet the target across the different building typologies (ZCH, 2009b). Given that the performance of low energy buildings is predicated upon a wide number of factors, including orientation, form and micro climate, this logic appears rather simplistic. It is hypothesised that this two tiered policy, may serve to financially incentivise the continued construction of thermally inefficient detached dwelling formats.

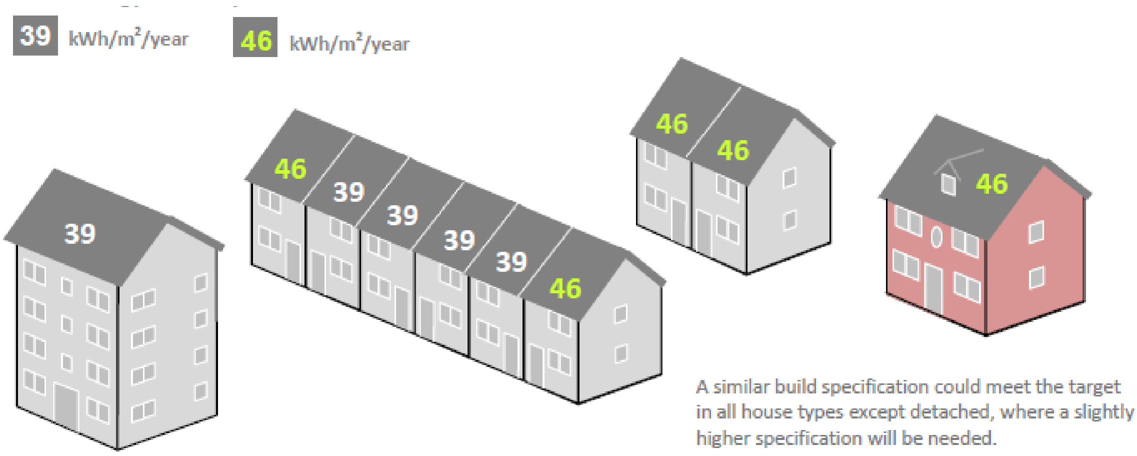

Figure 5 Fabric Energy Efficiency Standard (FEES) levels proposed in the ZCH Standard (Figure from ZCH, 2009b)

Despite terraced and semi-detached houses constituting the majority (56%) of the existing UK housing stock (Shorrock and Utley, 2003), more detached houses have been built in the UK since the 1980's than any other dwelling format (Hick and Allen, 1999). Private purchasers continue to demonstrate a clear preference for larger than average living spaces when they are able to afford them (Boardman et al., 2005). Given the additional cost involved in building to a zero carbon specification, the demand for detached and semi-detached dwellings driven by more affluent private home buyers is likely to continue. Continuation of this trend suggests it is probable that the majority of the next generation of UK 'zero carbon' dwellings could have a specific heat demand (SHD) in the region of 46 kWh/m^2.yr or even higher if modelled in PHPP (due to modelling differences, such as lower internal gains assumed in the calculation).

2.5 ANALYSIS AND IMPLICATIONS

According to the ZCH Energy Efficiency task force report the proposed standard, "equates to around a 20–25% reduction in carbon dioxide emissions compared to current Part L 2006 compliance" (ZCH, 2009c). In other words, if the ZCH recommendations are implemented many of the nation's future 'zero carbon' dwellings may perform little better than buildings being constructed to comply with the legal minimum standards permitted under Part L (2010) of the UK Building Regulations. Furthermore the projected increase in energy demand resulting from the growth in new households in the UK by 2050 is anticipated to be greater (Boardman, 2007; DECC, 2010a) than the percentage savings achieved by the FEES energy efficiency standards. Accounting for stock expansion means that the net contribution of the new energy efficiency standards to national GHG abatement targets is likely to be negative. If the anticipated 50% growth in UK domestic hot water consumption and rising cooling demand (DECC, 2010a; Littlefair, 2005) is also factored into this equation then it is highly unlikely that the FEES standards can make a contribution to the UK's climate change abatement targets.

In contrast to the proposed FEES standard the German Passivhaus standard achieves at least threefold better levels of fabric energy efficiency (Figure 5), by limiting the maximum specific SHD to less than 15 $kWh/m^2_{TFA}.yr$ and further limiting the total primary energy consumption to 120 $kWh/m^2_{TFA}.yr$ (Feist, 2007). It should be noted that there are inherent inaccuracies when attempting to directly compare predicted SHD calculated according to the SAP methodology with those determined using the Passive House Planning Package (PHPP), which is the accepted software for demonstrating compliance with the Passivhaus standard. The SHD determined by the Passivhaus standard generally follows the EN13790 methodology (Feist, 2007) but is based upon far lower internal gain assumptions and different climatic datasets than the UK SAP methodology, making direct comparisons invalid. As a result of the significantly higher internal gains assumptions used in SAP (which are approximately three times higher) (Henderson, 2009) compared to the 2.1 W/m^2 used in PHPP (AECB, 2009); the SHD predictions in SAP will appear artificially low when compared to PHPP. This situation is further amplified by a number of other modelling conventions including the methodology used to determine the Treated Floor Area (TFA) in PHPP (Hopfe and McLeod, 2010) which tends to underestimate the treated floor area, resulting in a higher specific SHD relative to SAP (Clarke, 2008) .

The magnitude of these different methodological assumptions in skewing valid comparison of the results in the context of Passivhaus and ultra-low energy buildings can be easily demonstrated. Assuming for example a notional Passivhaus dwelling based in a mid-England location (such as Manchester) then a $4W/m^2$ increase in useful internal gains would, assuming a 94% free heat utilisation factor (Feist et al, 2012), over the heating season reduce the effective SHD by as much as (4 W/m^2 x 205[viii]days/yr x 0.024 kh/day x

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[viii] In PHPP the length of the heating season is calculated in relation to the mean external monthly temperature from the PHPP climate file for a given location. In months where T_{ext} >16°C then no heating is assumed to be used; in months where T_{ext} <6 °C then heating is considered to be used continuously. For months where T_{ext} ≥6 °C≤ 16 °C a fourth order polynomial regression equation is

0.94 = 18.5 kWh/m^2.yr) (McLeod et al., 2010). The predicted SHD of dwellings approaching the Passivhaus energy standard is therefore highly sensitive to the internal gains assumptions. As UK lighting, appliances and hot water systems become more efficient, there will be less 'free' heat available and the benefits of higher fabric performance specifications and highly efficient MVHR systems will become more pronounced.

For comparative purposes it is possible to attempt to normalize the internal gain assumptions of SAP models to the level of those permitted by PHPP[ix]. Using this approach an indication of the scale of the operational carbon emission reductions required by the ZCH framework to achieve 'carbon compliance' and 'zero carbon', for two different dwellings standards (FEES and Passivhaus), relative to the Part L (2006) baseline is illustrated in Figure 6. By comparing the Passivhaus and FEES SHD's on a normalised 'like for like' internal gains basis it can be shown that significant potential gains in energy efficiency and corresponding reductions in carbon emissions (circa 40%) will be lost by the adoption of the weaker FEES standard.

The additional unregulated energy savings that would be achieved by the Passivhaus standard as a result of the inclusion of a primary energy limit (using representative data from the Camden, London Passivhaus (Camden Passivhaus, 2010)) was included as scenario PH (PHPP) and included in Figure 6. The baseline data for this figure is taken from the ZCH 'Defining a Fabric Energy Efficiency Standard' report (2009c) with the SHD of the dwellings normalised in accordance with internal gains as described above and with the exclusion of DHW gains as per the ZCH report (ZCH, 2009c, p 65).

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used to estimate the coefficient of the maximum heating load as a function of the monthly mean T_{ext} (see Feist et al, 2012).

[ix] More precise comparisons would require parametric modelling using a common model with realistic internal gains assumptions for each standard across a range of climatic locations

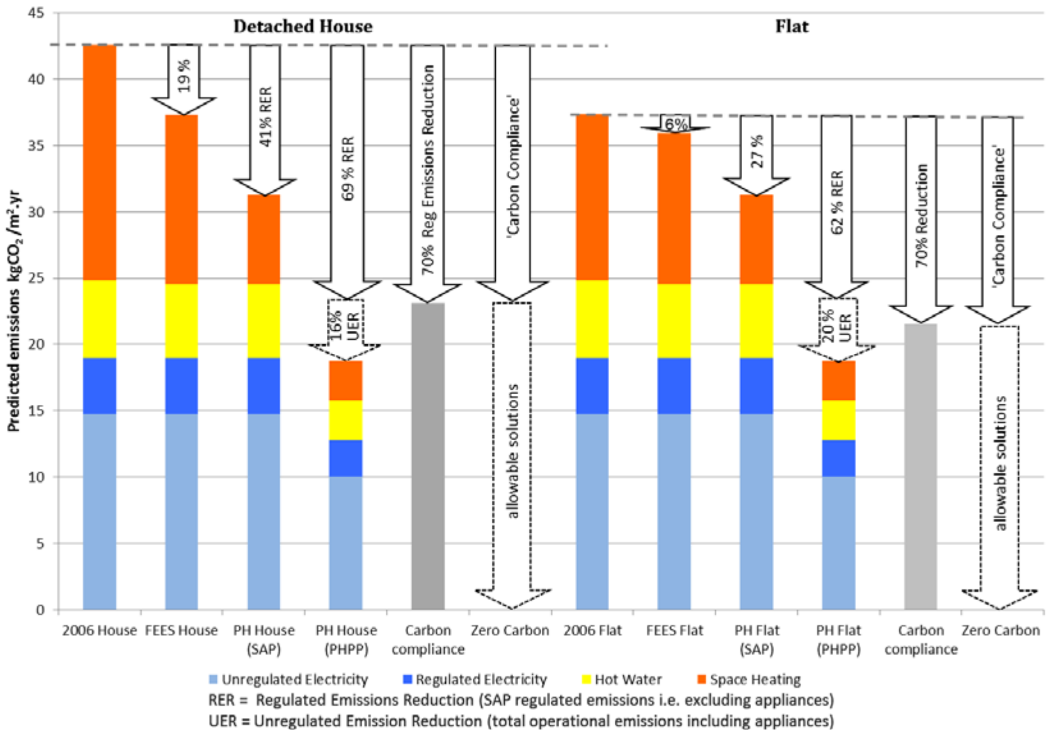

Figure 6 Indicative C0$_2$ emission[‡] reductions for different performance standards – with internal gains normalised to PHPP levels.

[‡] assumes gas used for heating and hot water, electricity for lighting and appliances using SAP 2005 emissions factors Gas 0.194 kgCO2/kWh, electricity 0.422 kgCO2/kWh (DECC, 2009)

When the SAP outputs are normalised to account for the reduced PHPP internal gains assumptions, the magnitude of the regulated emissions reductions in the Passivhaus dwellings falls only marginally short of the 70% Carbon Compliance level. If the TFA was also normalised for parity with PHPP the projected savings would be even greater. It should be noted that a significant additional reduction in unregulated emissions (16%) in the Passivhaus modelled has also been achieved as a result of the PHPP primary energy limit. Therefore when viewed in context the use of the Passivhaus standard (when correctly modelled in PHPP) results in approximately a 56% further reduction in net operational carbon emissions relative to the FEES standard for a detached house and a 76% reduction for a flat. In both cases the combined (regulated and unregulated emissions) reductions would significantly exceed the actual carbon savings required to meet a 70% 'Carbon Compliance' target.

2.5.1 RESISTANCE TO ADOPTING THE PASSIVHAUS STANDARD

In an independent report published in May 2009, the Energy Saving Trust (EST) investigated the suitability of the proposed energy efficiency metrics to be used in the revised 'zero carbon' definition. The EST report primarily focused upon evaluating a number of different energy efficiency metrics whilst also investigating the level at which the SHD (kWh/m^2.yr) should be set. Despite concurring with the ZCH task force report regarding the use of the kWh/m^2.yr metric, the EST report proposed that the limit to the SHD was set to a level between 15 and 25 kWh/m^2.yr; with adjustment occurring to take account of the building form (Hodgson, 2009).

Justification given by the ZCH task force for dismissing the Passivhaus standard and the Energy Savings Trust Advanced Practice standard in favour of significantly weaker standards of energy efficiency are presented in the full report from the Energy Efficiency Task Group (ZCH, 2009b). Notably the comparative analysis of the energy performance standards presented in this report appears to overestimate the SHD of the Passivhaus (Spec D), suggesting that it would result in a SHD between 23 and 29 kWh/m^2.yr when modelled in SAP (ZCH, 2009b, p66).

When the ZCH consultees were asked to express an opinion on the buildability of Passivhaus the outcome was divided: "One being that the Passivhaus range of performance (Spec D) represented the 'level' of ambition required and that the resulting construction specifications were indeed buildable (...). Whilst 47% of people had serious concerns about the buildability of Specification D (Passivhaus) at mass scale in 2016" (ZCH, 2009b p. 39). The survey size and relevant experience of the 47% who expressed serious concerns about the buildability of Passivhaus dwellings on a mass scale is not given. The report itself acknowledges that the audience, "did not see themselves as experts and many underestimated significantly the challenge of zero carbon" (ZCH, 2009a, p13).

Under estimation of the energy savings potential, combined with uncertainty regarding the buildability of the Passivhaus concept, appear to be key barriers to its widespread adoption.

2.5.2 PRECONCEPTIONS WITH RESPECT TO MECHANICAL VENTILATION AND INDOOR AIR QUALITY

A second major concern outlined by the ZCH as a barrier to adopting Passivhaus standards of energy efficiency was the issue of Indoor Air Quality (IAQ) associated with air tight dwellings reliant upon mechanical ventilation systems. The ZCH report states that “there is currently a lack of detailed understanding across industry in this area” and concludes that “the link between reduced air permeability and suitable ventilation systems requires increased levels of monitoring and technical research” (ZCH, 2009b).

Contrary to the ZCH findings there is a growing body of post-occupancy research studies correlating improved IAQ and occupant wellbeing in both domestic and non-domestic low energy buildings ventilated by means of mechanical ventilation (MV) systems. Snijders et al (2001) found that dedicated ventilation systems may slow down the development of Chronic Obstructive Pulmonary Disease (COPD) and prolong the independence of those affected by the condition. Furthermore, Harving et al (1994) demonstrated that the number of allergen producing dust mites and fungi in buildings was reduced by low indoor RH levels induced by a suitable ventilation system.

The vast majority of post occupancy studies concerning Passivhaus dwellings show that consistently high levels of occupant satisfaction and very good IAQ levels are typically reported in dwellings served by whole house MVHR systems (Feist et al., 2001; Feist et al., 2005; Brunsgard and Jensen, 2008; Larsen and Jensen 2009). Similar findings have also been confirmed in MVHR ventilated Passivhaus schools, a context characterised by high occupant densities typically necessitating higher rates of ventilation air changes as a result (Bretzke, 2010).

In 2009, the NHBC commissioned a well referenced review of the international literature on IAQ and ventilation systems. This report provides significant evidence of the IAQ and user satisfaction of properly commissioned whole house MVHR systems when installed in low energy dwellings (Crump at al., 2009). One example of such a low energy standard is the Canadian R-2000™ which is an energy performance standard approaching Passivhaus performance levels where whole house MVHR is required. It is significant that the National Building Code of Canada has for the past 20 years permitted ventilation systems in such dwellings to be sized to mechanically deliver supply air at a similar base level to the minimum level recommended by the Passivhaus standard, i.e. 0.3 air changes per hour (ach), (Feist et al., 2010) without apparent concern of any health risks. According to the report,

> “The National Building Code of Canada (1985) requires all dwelling units to have a MV system capable of providing 0.5 ach and this was modified in 1990 to 0.3 ach. CSA standard F326 was adopted as the ventilation standard for R-2000™ in 1991 (…). A substantial majority of occupants considered the indoor climate to be good or very good in winter and 88% were satisfied or very satisfied in summer. Air quality was rated as good or very good by 95% of occupants” (Crump et al., 2009, p29).

Similarly high levels of occupant satisfaction with the MVHR systems are recorded in the Kronsberg (Hanover) Passivhaus development (Schnieders and Hermelink, 2006; Energy-cities EU, 2012). When asked about their satisfaction with their ventilation system, 96% of the Passive House occupants stated that they were either satisfied or very satisfied[x] (Feist et al., 2001, p.79). This research was carried out as part of the CEPHEUS project (Cost Efficient Passive Houses as European Standards) that involved the construction and evaluation of 221 housing units built to Passivhaus standards in five European countries (Germany, Austria, Switzerland, Sweden and France) (Feist et al., 2001). A critical requirement of the Passivhaus standard is the attainment of a highly airtight envelope demonstrated by an n_{50} pressure test value of $\leq$0.6 ach (Feist et al., 2010). Although there was little detailed evaluation of individual air pollutants in the CEPHEUS reports, several projects included measurements of temperature and relative humidity (RH), as well as post-occupancy satisfaction with the ventilation system and IAQ (Feist et al., 2001; Schnieders and Hermelink, 2006).

Despite the wealth of international literature on this subject there have been very few peer reviewed studies published specifically addressing the IAQ of highly energy efficient homes in the UK (Crump et al., 2009). One of the main criticisms levelled at the existing data and post occupancy studies however, is that they focus primarily on CO_2 and RH as proxy indicators of IAQ and not formaldehyde and volatile organic compounds (VOC’s) (Swainson, 2010). One of the few UK research papers investigating formaldehyde, VOC’s and other key IAQ indicators (CO_2, CO, NO_2, TVOCs) was a monitored study of 6 low energy dwellings

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[x] By way of comparison, the corresponding percentage for all Kronsberg residents (including passivhaus, low-energy houses and other tenants) was 55%.

carried out in 2006. Notably, only the two dwellings that were ventilated using MVHR systems in this study achieved the highest possible IAQ rating across a range of measured indicators (Mawditt, 2006, p63). Mawditt makes the important observation that,

> “Minimising the source of the pollutant has a far greater effect on overall concentration than relying on dilution by ventilation” (Mawditt, 2006, p62).

It seems likely that detailed MVHR design guidance, quality assurance and commissioning protocols issued by organisations such as the Passivhaus Institut, R-2000 and Minergie are partially responsible for ensuring high levels of occupant satisfaction and IAQ associated with these systems. However the need for routine maintenance with MVHR systems is a critical issue in maintaining high levels of occupant satisfaction. This issue was highlighted by Austrian contributors (with direct experience of Passivhaus buildings) in the Sullivan Report (Scottish Building Standard Agency, 2007), who emphasised the need for occupants to maintain the filters on MVHR systems to ensure continued adequate ventilation.

Whilst further research on VOC’s and formaldehyde concentrations in both, naturally and mechanically ventilated airtight dwellings in the UK is warranted, it seems unlikely that this issue will present a real barrier to the widespread adoption of properly installed MVHR systems in the UK. Indeed, a recent report by the ZCH Ventilation and Indoor Air Quality (VIAQ) Task Group states that, “the use of MVHR will continue to grow and become the dominant form of ventilation, standard in most new homes post–2016” (ZCH, 2012, p42).

2.6 CONCLUSIONS

Zero carbon building policy is still evolving and a final decision is awaited on several key aspects including the definition of ‘allowable solutions’. Recent revisions to the definition of ‘zero carbon’ in the UK have resulted in a significant weakening of the minimum energy efficiency standard used to define a zero carbon dwelling. If the current working definition becomes policy then the proposed methodology will make it possible to offset in excess of 50% of a UK ‘zero carbon’ dwelling’s emissions by purchasing market based ‘allowable solutions’. Although these ‘allowable solutions’ are not yet clearly defined the transition away from meeting the balance of the annual energy requirement through high levels of energy efficiency and from directly connected renewable energy infrastructure will have significant implications, both for GHG emissions as well as for a number of wider social and sustainability indicators.

A number of dynamic factors including significant increases in the absolute number of UK households, increasing hot water demand, appliance consumption and a growing cooling demand appear to have been overlooked during the recent review of UK zero carbon dwelling standards. Scenario modelling by DECC (2010a) illustrates that the Passivhaus standard is the only energy efficiency standard capable of delivering long term reductions in space heating, cooling and hot water energy consumption. The assumption that the 'residual emissions' are static and can simply be offset elsewhere, appears to be a dangerous and short sighted argument which is not supported by evidence on the efficacy of carbon offsetting mechanisms.

Limitations with the existing UK SAP methodology are currently masking significant energy and carbon savings that can be achieved by Passivhaus dwellings when they are more accurately modelled. This is due to differences in the underlying assumptions (including internal gains and Treated Floor Area assumptions) between PHPP and SAP, and the fact that the SAP model relies upon a single climate data set (East Pennines) for predictive modelling of the heating demand across the entire UK (ZCH, 2011b). Preliminary modelling suggests that nearly 90% of Part L 2006 regulated emissions could be saved by adopting the Passivhaus approach, if both the regulated and unregulated emissions savings were included in the carbon compliance total (Figure 5).

Significantly higher standards of air tightness and controlled ventilation rates by mechanical means are likely to play an increasing role in the delivery of low energy housing in the UK (ZCH, 2012). Currently there is a paucity of research regarding health issues associated with internal air borne pollutants in airtight UK dwellings using mechanical ventilation. Further research is needed in order to strengthen UK domestic ventilation guidance and regulations.

If the UK is to meet its GHG reduction targets, and converge upon a harmonised European standard for zero carbon buildings, the evidence points to the need to mandate significantly increased levels of energy efficiency. Adopting a more stringent 'fabric first' approach with higher minimum energy efficiency and carbon compliance levels is consistent with the CLG energy hierarchy and DECC scenario modelling and avoids many of the pitfalls and uncertainty associated with the extensive use of carbon offsetting mechanisms.

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CHAPTER 3 | GENERATION OF HIGH RESOLUTION CURRENT AND FUTURE CLIMATE DATA

DISCURSUS:

The preceding chapter described the evolution of recent developments in UK 'zero carbon' policy and provided a comparative overview of the FEES and Passivhaus standards as potential templates for low energy and zero carbon dwellings in the UK. The successful implementation of advanced energy performance standards, such as the Passivhaus standard, is largely predicated upon detailed and accurate project planning. Since low energy buildings seek to minimise reliance upon active heating and cooling systems, it is self-evident that the design optimization of Passivhaus and low energy buildings must be based on context specific environmental design.

The following chapter examines the case for regional and micro-regional climatic data when designing ultra-low energy Passivhaus buildings in the UK. Limitations associated with existing methods of deriving climate data for Passivhaus design are discussed along with the specific data format requirements necessitated by PHPP software.

A new methodology for generating this data in PHPP format is proposed in section 3.2. This new method uses data generated by the UKCP09 Weather Generator, in combination with solar geometry and intervariable relationships, and is able to provide much higher resolution climatic data for both current and future probabilistic scenario modelling.

The new method is compared to site specific (Met Office data) and regional proxy data (based on Meteonorm software interpolation methods) as well as existing Test Reference Year (TRY) data. In this context, three case studies are presented based on the PHPP model of a certified Passivhaus dwelling in a mountainous region of Wales as well as two urban locations, in close proximity, within London (Section 3.3). The results and implications are discussed and summarized in Section 3.4, followed by the conclusions and recommendations for further work in Section 3.5.

3.1 INTRODUCTION

Passivhaus Planning Package (PHPP) is a simplified quasi-steady state building simulation tool that is primarily targeted at assisting architects and mechanical engineers in designing Passivhaus buildings (Feist et al., 2012). According to the Passivhaus Institut (PHI) the verification of a Passivhaus design must be carried using PHPP; as a result it has become the de facto software used for design and compliance predictions of Passivhaus buildings in the UK and around the world. PHPP has been validated with both dynamic thermal simulations using Dynbil (Feist, 1998) and empirical data from a large number of completed Passivhaus projects (Feist et al., 2001). Dynamic simulation results predicted by Dynbil, have also been extensively compared to measured data for both dwellings and office buildings (Feist and Loga, 1997; Kaufmann and Feist, 2001; Schnieders and Feist, 2002). PHPP validation studies have generally shown good agreement between measured and predicted results including those derived from dynamic simulation (Feist et al., 2001). The current PHPP model, Version 7, (Feist et al., 2012) conforms to the calculation methods set out in EN ISO 13790 for determining heating demand according to annual or monthly methods, and contains additional algorithms to calculate peak heating and cooling loads and assess overheating risks.

In addition to delivering design energy and peak load predictions a validated PHPP worksheet is primarily used to demonstrate compliance with the Passivhaus certification criteria. The key criteria for Passivhaus certification are that the building must have a Specific Annual Heat Demand (q_H) ≤15 kWh/m^2.yr or a Specific Peak Load (p_H) ≤10 W/m^2, together with a Specific Primary Energy Demand (q_{PE}) ≤120 kWh/m^2.yr relative to the Treated Floor Area (TFA). Where a cooling requirement exists, the cooling energy demand including dehumidification must be (q_c) ≤15 kWh/(m^2.yr) + 0.3 W/(m^2.yr.K) * DDH[xi].

Like all building simulation models, the outputs from the PHPP model are predicated upon the use of appropriate boundary conditions. In the case of PHPP where, for certification

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[xi] DDH refers to Dry Degree Hours, the time integral of the difference between the dew point temperature and the reference temperature of 13 °C throughout all periods where the dew point temperature is higher than the reference temperature and cooling is required. Hence the term 0.3 W/(m^2.yr.K)*DDH addresses the partial requirement for dehumidification in addition to the sensible cooling demand. Alternatively a cooling load (p_c) ≤10 W/m^2 and a cooling demand (q_c) ≤4 kWh/(m^2.yr.K) *θ_e + 2 * 0.3 W/(m^2.yr.K) * DDH – 75 kWh/(m^2.yr); but not greater than 45 kWh(m^2.yr) + 0.3 W/(m^2.yr.K) * DDH is permissible (Feist et al, 2012,p22).

purposes, the internal gains (residential, 2.1 W/m^2) and operative temperature (20 °C) are assumed to remain constant, the key boundary conditions used to determine the annual heating demand, cooling demand and peak loads depend almost entirely on the external climate.

In the context of a Passivhaus, where all of the supplementary heating may be provided solely via a small post-air heater, the risk associated with uncertainty in the peak heating load calculations could have real consequences. Conversely, overheating risks are likely to increase with climate change and a better understanding of cooling loads and future overheating risk predictions is needed (McLeod et al., 2011). Hence, there is a need to understand the uncertainty associated with the climate files used in order to determine the sensitivity and reliability of any design or certification predictions.

Typical Meteorological Year (TMY) data sets in the USA and Test Reference Year (TRY) data in Europe have provided the basis for many of the commonly used formats of hourly weather data used in Building Performance Simulation (BPS)[xii]. The principles behind the generation of these datasets are similar in that a composite weather year is formed by selecting the mean monthly data from long-term historic data typically spanning a 20+ year period. As such these data sets represent typical (historic) conditions and the U.S. National Renewable Energy Laboratory (NREL) states that, “they are not suited for designing systems and their components to meet the worst-case conditions occurring at a location” (Marion et al., 1995).

In the original PHPP models (PHPP04 and PHPP07), climate data for the UK was derived from TRY datasets for half a dozen locations. In most cases, this data was thought to be adequate for Passivhaus verification based on calculation of the mean annual heating demand. However, since it is possible to obtain Passivhaus certification based on peak loads, questions were raised about the appropriateness of using only a single UK climate data set (Manchester) as a proxy for calculations across the entire UK (McLeod et al., 2010). Similar issues were identified in Ireland where parametric analysis by Morehead (2010) highlighted the scale of prediction errors and the over engineering potential resulting from the use of non-proximal datasets in Passivhaus design.

[xii] A summary of common simulation weather data file formats used throughout the world can be found at http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_sources.cfm

In the UK this situation was subsequently improved by the production of 22 UK regional datasets (BRE, 2011) developed using Meteonorm interpolation. These datasets were independently cross-checked against EnergyPlus Weather (EPW) files (ASHRAE, 2001) and subsequently ratified by the PHI for Passivhaus certification purposes (with the caveat that they should not be relied upon for the determination of heating loads).

The research in this chapter examines the limitations of the current system and presents a new method for obtaining much higher resolution climatic data for current and future probabilistic scenario modelling generated using the UKCP09 Weather Generator (Met Office, 2011). The results are compared to both site specific and regional proxy data (BRE, 2011) generated using Meteonorm software interpolation methods and with existing TRY data, where available.

3.2 METHODOLOGY

3.2.1 GENERATING CLIMATE DATA IN PHPP FORMAT

The original climate data provided by the PHI for design and certification in the UK was derived from TRY data (Schnieders, 2003). Since many of the original PHPP data sets lacked the data necessary to carry out peak load evaluations, a reverse engineering process (involving multi-stage dynamic simulations) was developed by the PHI for the determination of peak load irradiation data (Feist, 2005). Due to the lengthy processing time involved, complete PHPP datasets were only available for a limited number of locations.

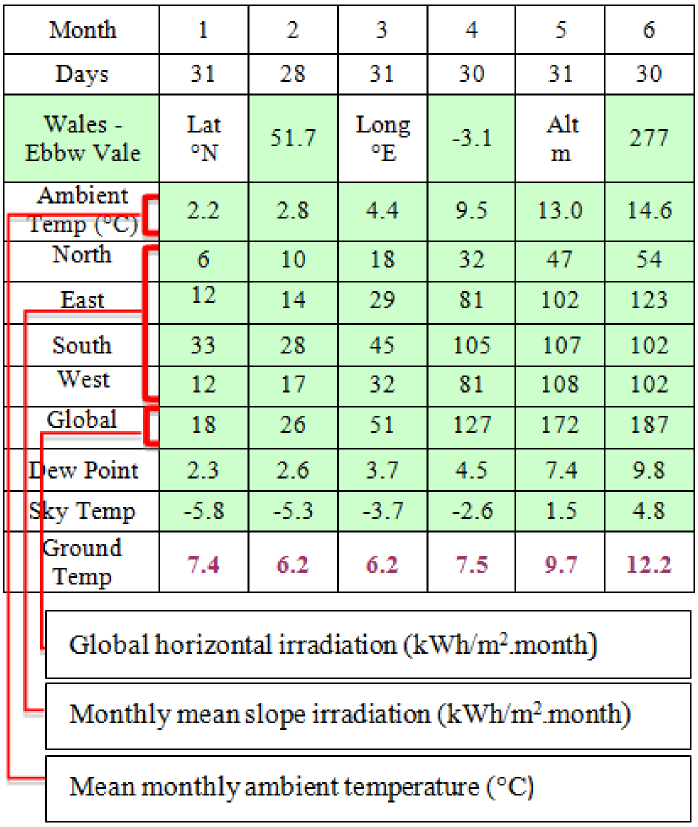
More recently, interpolation software, such as Meteonorm 6 (Remund, 2010), has made it possible to generate complete climate data sets for virtually any geographic location in the world. Schnieders (2009) however, cautions against the use of such software to derive peak load data since the reliability of the algorithms used to derive daily climate data from monthly data is not well established. Furthermore, Rawlins (1984) proposed that site-specific daily irradiation is more accurately estimated from local sunshine observations than by interpolation from nearby radiometric stations, particularly where weather stations are located more than 20km away. For the interpolation of monthly average irradiation, Rawlins states that the critical distance becomes slightly greater, at approximately 30km.

By contrast the use of daily sunshine hour recordings from a location 50km away would generate RMSEs typically in the range of 14%–22% (Rawlins, 1984).

3.2.1.1 MONTHLY CLIMATE DATA VARIABLES

The primary inputs required by PHPP to calculate the annual specific heating demand (SHD) are based on monthly mean climatic variables, namely: mean ambient temperature, global horizontal irradiation and the vertical slope irradiation for the cardinal aspects. Additional values such as sky temperature and ground temperature are subsequently derived from these values. Unlike the weather file formats used in most dynamic simulation programmes PHPP requires that the monthly irradiation data is broken down into its cardinal slope irradiance components in the weather file (Table 3).

Table 3 PHPP sample climate data (partial set/ LHS) showing 6 months of heating demand data



Month	1	2	3	4	5	6
Days	31	28	31	30	31	30
Wales - Ebbw Vale	Lat °N	51.7	Long °E	-3.1	Alt m	277
Ambient Temp (°C)	2.2	2.8	4.4	9.5	13.0	14.6
North	6	10	18	32	47	54
East	12	14	29	81	102	123
South	33	28	45	105	107	102
West	12	17	32	81	108	102
Global	18	26	51	127	172	187
Dew Point	2.3	2.6	3.7	4.5	7.4	9.8
Sky Temp	-5.8	-5.3	-3.7	-2.6	1.5	4.8
Ground Temp	7.4	6.2	6.2	7.5	9.7	12.2

Global horizontal irradiation (kWh/m^2.month)

Monthly mean slope irradiation (kWh/m^2.month)

Mean monthly ambient temperature (°C)

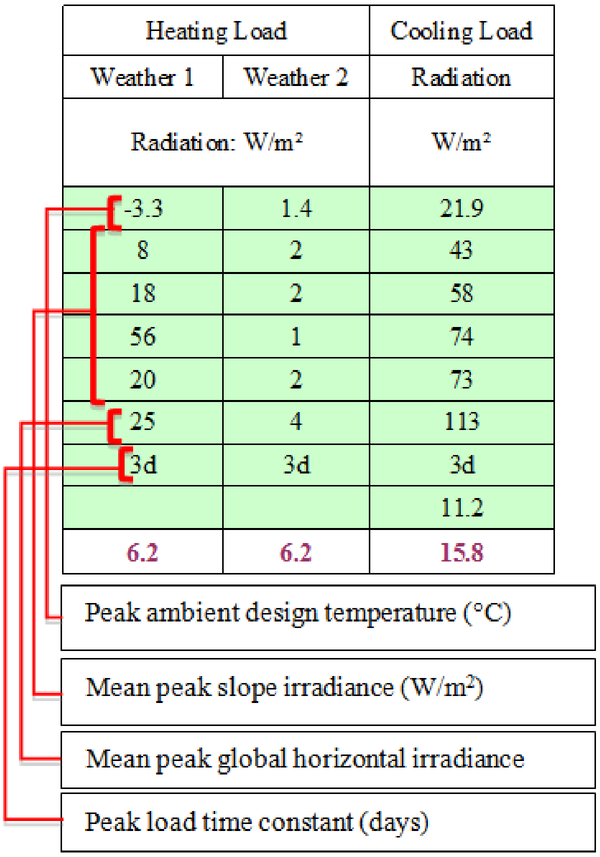
In addition to the monthly heating demand data (Table 3) the PHPP climate file also contains data for determining the peak loads at a daily time step.

3.2.1.2 PEAK LOAD DATA AND VARIABLES

By definition the peak heating and cooling loads require design temperatures and irradiation calculations to be conducted at a much smaller time step than the monthly data allows. Typically, these calculations are carried out at an hourly or sub hourly interval using a dynamic simulation. Historically the peak load slope irradiance data used by PHPP was derived using a process which involved changing the aperture area in a dynamic simulation reference model and recording the resultant impact upon monthly heating loads for each of the cardinal points (Feist 2005; Oberrauch 2008). Such a method is arguably valid in one sense since it begins by isolating the peak load and works backwards to derive the corresponding irradiation data. However, this approach is time consuming and necessitates a second (fully dynamic) model. The approach also entails a number of modelling uncertainties that are difficult to quantify, including the representivity of the TRY itself. Until recently, a significant further limitation of this approach has been the limited availability of regional and micro-regional TRY files, which have only been available for a limited number of locations in the UK.

In the case of Passivhaus buildings, which are characterised by high thermal inertia, it has been demonstrated that the peak load analysis can be carried out using data which is averaged over a longer time period than for conventional buildings (Schnieders, 2003; Schnieders, 2008; Bisanz, 1998). Further discussion of this time constant follows in Section 3.2.8. Table 4 illustrates the two periods Weather1 (W1) and Weather2 (W2) for which the peak heating load is assessed. W1 corresponds to the coldest clear period, with relatively high daily irradiation but low ambient temperatures. W2 represents a prolonged cloudy winter period with very little irradiation but slightly milder temperatures (Bisanz, 1998). These two discrete periods are entered into the PHPP peak load calculation where the maximum load derived from either scenario becomes the peak heating load (p_H). Historically the peak load climate data was isolated from a TRY data set, and this is still considered by the PHI as the preferred method (Schnieders, 2009; Feist et al., 2012). Since a TRY is effectively a mean weather year, designers need to be acutely aware of the limitations inherent in this approach with respect to peak load plant sizing.

Table 4 PHPP sample peak load data showing key variables for the calculation of W1 and W2



Heating Load		Cooling Load
Weather 1	Weather 2	Radiation
Radiation: W/m^2		W/m^2
-3.3	1.4	21.9
8	2	43
18	2	58
56	1	74
20	2	73
25	4	113
3d	3d	3d
		11.2
6.2	6.2	15.8

Peak ambient design temperature (°C)

Mean peak slope irradiance (W/m^2)

Mean peak global horizontal irradiance

Peak load time constant (days)

3.2.2 GENERATING REGIONAL CLIMATE DATA FOR PHPP HEATING DEMAND

Obtaining mean monthly climatic data suitable for use in predicting the PHPP specific heating and cooling demand is relatively straightforward as there are now a number of possibilities for obtaining this data on a regional scale. Designers working with hourly or sub-hourly dynamic simulation tools in the UK can access high-resolution data via the PROMETHEUS portal (University of Exeter, 2012), which provides hourly EPW formatted climate files using source data derived from the UKCP09 Weather Generator (WG). Worldwide it is possible for designers to generate future predictive data in a limited number of formats by using various tools such as the Meteonorm software. Various data 'morphing' procedures have been elaborated by Belcher et al (2005)**,** Crawley (2008) and Jentsch et al (2008) who set out details for a series of 'shift and stretch' functions which provide the underlying methods used to 'morph' existing TRY or baseline data sets in line with any given future climate change scenario. Crawley (2008) provides further specific procedures for shifting the ambient temperature in Urban Heat Islands. Such methods are limited by the spatial distribution of the baseline TRY datasets and knowledge of the amplitude of the climate change input signals which were typically derived from 50km (or coarser) grid models. In addition to using a much higher spatial resolution the more recent PROMETHEUS files include probabilistic prediction of the future wind speed and direction which was absent from many earlier climate generator models (Eames et al., 2010).

3.2.3 SPATIAL RESOLUTION

For individual design based predictions the finest spatial resolution data attainable is typically the most relevant, since this should include micro climatic influences. In the case of Passivhaus and ultra-low energy design concepts, this requirement is amplified by the fact that useful solar gains may be compensating up to one third of the total thermal losses (Feist, 1993). In a study comparing long term in-situ measured data on a Passivhaus project near Cork, Ireland with proxy regional TRY data (Dublin) and interpolated data Morehead (2010) concluded that a variation in the predicted space heating demand exceeding 30% was possible contingent upon the source data chosen. With implications for build costs, running costs, plant sizing and thermal comfort predicated upon these calculations the need for more accurate climate data and an understanding of limitations and associated risk becomes apparent.

Counter to this in the context of broader meta-studies, or for the purposes of standardised building certification, the use of a coarser resolution or even regional climate data may be warranted. Currently Passivhaus certification in the UK is based upon a newly adopted system that uses 22 regional data sets (Figure 7) generated by the BRE (2011) using Meteonorm interpolation methods cross-checked against ASHRAE EPW files. Whilst the regional boundaries chosen reflect, in some cases, the administrative boundaries previously defined in the UK Standard Assessment Procedure (SAP) for overheating analysis there is no precise climatic basis for the boundaries used.

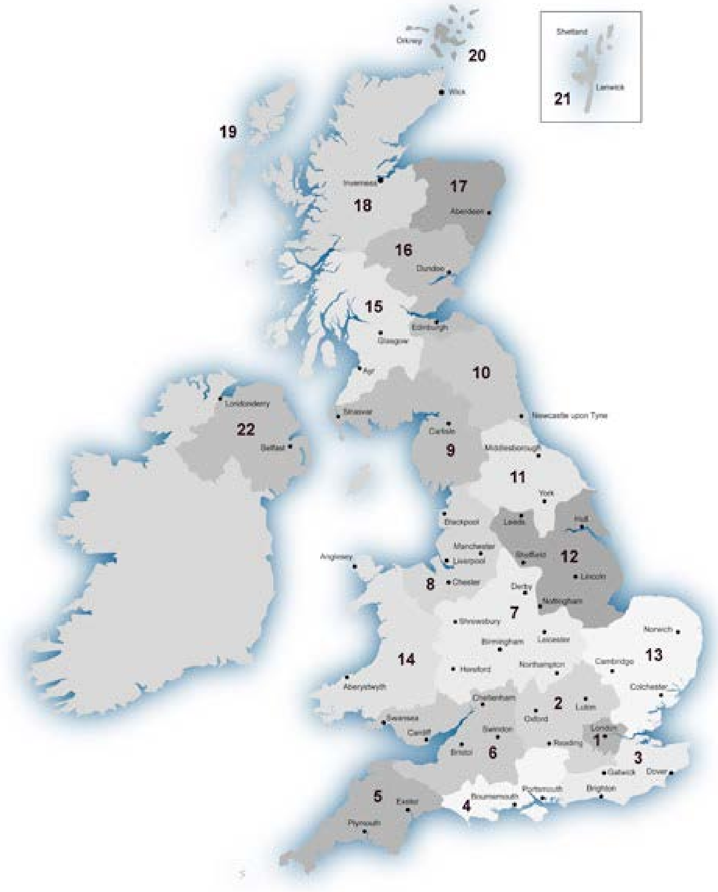


Figure 7 22 UK climatic regions currently used for Passivhaus certification (Figure from BRE, 2011)

An alternative source of regional data has been compiled by the Met Office Hadley Centre using 25km grid squares which reflect the Regional Climate Model (RCM) grid. This data is generated by averaging the 5km data sets that fall within these larger plots. Regional data for 14 administrative regions and 23 river basins has also been produced based on long-term (1961–1990) averages for all of the key monthly climatic variables. Such methods of producing representative regional data, which has been composited from finer grid resolutions, appears to offer a more robust basis for developing future regional datasets for Passivhaus certification. However, the raw data produced by the UKCP09 WG is not directly available in PHPP format.

3.2.4 UKCP09 PROBABILISTIC DATA AND WEATHER GENERATOR

The HadRM3 RCM was developed by the Met Office Hadley Centre in order to downscale the simulations provided by the Global Climate Model (GCM). The RCM operates at a 25km resolution, providing outputs on a scale that is useful for impact assessment in the built environment. This model creates 434 unique land based grid squares containing probabilistic climate projections for most of the UK. For each 25km grid location 10,000 realisations (samples of the probability density function) have been generated for each decade and emissions scenario based on equi-probable changes in the underlying climatic variables.

The WG is a climate model downscaling tool which was developed by the Hadley Centre in order to provide outputs at a higher resolution than the RCM allows. By mapping the unique climate signal contained within each 25km grid square on to a much finer 5km grid baseline (Figure 8) approximately 11,000 viable grid data locations are produced covering the entire UK landmass. Each 5km grid square thus contains a 30 year baseline dataset for the reference period 1961–1990, coupled with the possibility to sample future probabilistic scenarios at 10-year intervals from 2020 to 2080 (DEFRA, 2009b).

Figure 8 Showing UKCP 5km grid cell (3200210) and 25km grid resolutions for South Wales/ Severn region (adapted from DEFRA, 2010)

Three climate change scenario outputs are available from the WG based on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) climate principal scenarios: Low (B1), Medium (A1B) and High (A1FI). Further information on the global economic scenarios defining the SRES scenarios can be found in IPCC (2000). Each WG run randomly samples from the 10,000 change factors available to create a continuous thirty year time series based on the underlying baseline profile. A minimum of 100 randomly chosen samples of the WG climate data are needed to compile a single statistically representative climate file. Each WG run therefore results in a minimum of 3000 equi-probable future weather years of data. The WG operates at a daily temporal scale from which hourly variables are subsequently extrapolated based on existing relationship patterns in the observed baseline data.

Rainfall is the primary variable in the WG, and is estimated using the Neyman-Scott Rectangular Pulses (NSRP) model (Rodriguez et al., 1987). All of the other output variables are dependent upon the rainfall data. Inter variable relationships based on regression models developed from the measured daily station data are then used to predict mean daily temperatures, temperature range, vapour pressure and sunshine hours (IPCC, 2000). Further variables are subsequently calculated from the core variables using appropriate formulae. Hourly global solar irradiation, for example, is only recorded at approximately 90 Met-office sites around the UK using predominately CM11 pyranometers (Met Office, 2011b). Additional algorithms based on the work of Cowley (1978) and Muneer (2004) were therefore used to derive the global direct and diffuse irradiation components from the observed daily sunshine duration.

Validation work carried out by the WG team (and analysed in Section 3.2.5.3) shows good agreement between the modelled direct and diffuse irradiation predictions and measured data from selected reference sites (UKCP, 2011). This validation check of the WG meta-model data is important in the context of understanding the overall uncertainties in this research, where further downstream models are used to derive monthly and daily slope irradiation data for each scenario.

3.2.5 VALIDATION OF UKCP WEATHER GENERATOR SOURCE DATA

When solar radiation enters the earth's atmosphere some of the incident energy is lost by the scattering and absorption that occurs when the electromagnetic wave collides with a particle. The scattered radiation is called diffuse radiation (I_D) whilst the component which arrives directly at the earth's surface is known as direct or beam radiation (I_B).

Of particular relevance to the key climate data inputs required by PHPP is the method used by the WG to estimate direct and diffuse irradiation at daily and hourly levels. The use of algorithms based upon the daily hours of sunshine and day length at a given location has allowed the WG to estimate the diffuse and direct (horizontal beam) components of the Global Irradiation at grid locations which do not directly record solar radiation measurements.

3.2.5.1 DAILY IRRADIATION

For global irradiation an algorithm developed by Cowley (1978) based on sunshine duration and day length has been implemented in the WG.

Cowley's equation is given as:

$$G = E[d \left\{\left(\frac{a}{100}\right) + \left(\frac{b}{100}\right)\left(\frac{n}{N}\right)\right\} + (1 - d)a'] \quad [1]$$

where G and E are respectively the daily terrestrial and extra-terrestrial irradiation on a horizontal surface, n is the daily hours of sunshine and N is the day length, and d= 0 if n= 0, otherwise d = 1 if n > 0, and a'= average ratio of G/E for overcast days. The monthly means for the coefficients a, a' and b were taken from Appendix B1 in Muneer (2004).

To estimate daily diffuse irradiation (D) Muneer recommends the following global model, which was established using regression curves to fit the relationship between the daily diffuse ratio (D/G) and the clearness index (K_T). The regression fit characterised by this model was based upon a number of global studies, including research carried out in the UK by Saluja and Muneer (1986).

$$D/G = \ 0.962 + 0.779K_T - 4.375K_T^2 + 2.716K_T^3, \ \ for\ K_T \geq 0.2 \quad [2]$$

$$D/G = \ 0.98 \ \ for\ K_T < 0.2 \quad [3]$$

$$K_T = a + bS \quad [4]$$

where S is the sunshine hours. Muneer (2004) demonstrates the validity of a global estimate for the relationship between D/G and K_T.

3.2.5.2 HOURLY IRRADIANCE

The hourly irradiance models in the WG use Muneer's Meteorological Radiation Model (MRM) algorithm. MRM estimates the diffuse and direct components from ground based measurements: air temperature, atmospheric pressure, wet bulb temperature (or RH) and sunshine duration. The advantage of this approach is that such data is readily available world-wide and does not require sophisticated instrumentation (UKCP, 2011).

The diffuse irradiance model is given by:

$$I_D = I_E \tau_{\alpha\alpha} \tau_g \tau_o \tau_w \left(\frac{0.5(1-\tau_r)}{1-m+m^{1.02}} + \frac{0.84(1-\tau_{\alpha s})}{1-m+m^{1.02}} \right) \qquad [5]$$

where $\tau_{\alpha\alpha}$ refers to aerosol transmittance function due to absorption only, and is given by Bird and Hulstrom (1980; 1981) as:

$$\tau_{\alpha\alpha} = 1 - 0.1(1 - \tau_\alpha)(1 - m + m^{1.06}) \qquad [6]$$

and $\tau_{\alpha s}$ refers to the aerosol transmittance due to scattering alone,

$$\tau_{\alpha s} = 10^{-0.045^{m' 0.7}} \qquad [7]$$

where $\tau_r, \tau_\alpha, \tau_g, \tau_o \; and \; \tau_w$ are atmospheric transmittances[xiii] respectively for Rayleigh scattering, Mie scattering, mixed gases, ozone and water vapour which are estimated by a set of equations using coefficients given in Muneer (2004, p73) deemed suitable for UK/northern Europe, and m is the relative air mass (at a standard pressure at sea level) obtained by Kasten's (1993) formula, and $m'$is corrected for atmospheric pressure.

The global irradiance is given by:

$$I_G = (I_B + I_D)\left(\frac{1}{1-r_s r'_\alpha}\right) \qquad [8]$$

[xiii] Atmospheric transmittance coefficients account for the energy lost through radiative transfer as electromagnetic waves pass through the earth's atmosphere. Air molecules cause Rayleigh scattering (as their particle size is smaller than the wavelength of extra-terrestrial radiation). Where the particle size is of the same order of size as the wavelength the effect is known as Mie scattering. Atmospheric transmittances are assigned for Rayleigh, Mie, mixed gases, ozone and water vapour.

where r_s is the ground albedo[xiv], and $r'_\alpha = 0.0685 + 0.17(1 - \tau'_\alpha)$ is the albedo of the cloudless sky and τ'_α the Rayleigh scattering computed at m = 1.66 and I_B is the direct or beam radiation resulting from the attenuation of light passing through a medium (the earth's atmosphere) calculated according to Beer's law.

A more detailed treatment of the above, including a detailed evaluation of the MRM algorithm for clear and over cast skies is provided in Muneer (2004).

3.2.5.3 VALIDATION RESULTS

In order to test the accuracy of these algorithms, the Met Office WG team compiled daily and hourly radiation data recorded at three UK weather stations. Hemsby (Norfolk), Finningley (South Yorkshire) and Stornoway (Western Isles) were the only UK stations at the time that recoded both daily and hourly irradiation plus the additional input variables needed for a weather generator run. A weather generator 'control' run is a baseline (i.e. unperturbed) simulation run consisting of 100*30 year time periods, calibrated on the specific station data record. The half monthly means were calculated for the observed data (typically based on a 14–15 years of recorded data) and compared with those produced by the simulations. For hourly simulation of data, the method described above is employed, and the hourly figure is adjusted to equal to the daily total for consistency. Sample validation results for Hemsby (1982–1995) Finningley (1983–1995) and Stornoway (1982-1995) daily diffuse and direct irradiation are given in Figures 10–12 (below). The second standard deviations (+/- 2σ) for the 100 simulation runs are shown in order to indicate the variability inherent within a stochastic model.

[xiv] A standard ground albedo value of 0.2 is often used in the literature (Muneer, 2004) however more accurate values may be used in the modelling equations where site specific values are known.

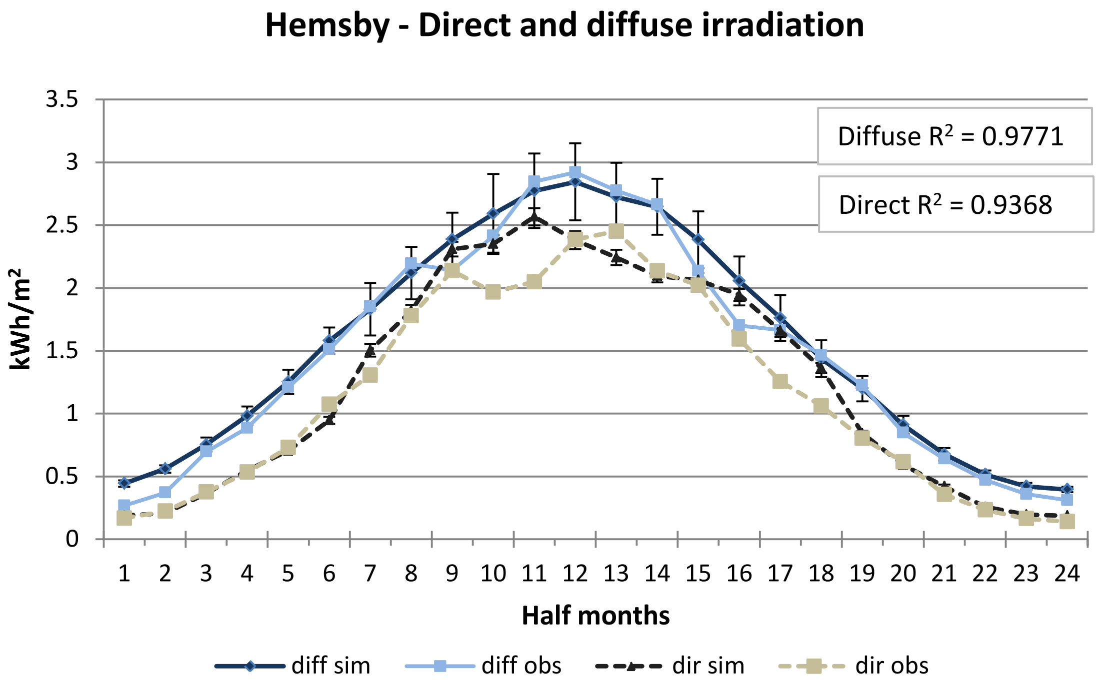


Figure 9 Compares the WG simulated diffuse and direct outputs with observed data for Hemsby (1982-1995). Error bars indicate variability over 100 WG runs at +/- 2 Standard deviations. (Data courtesy WG Team, Met Office)

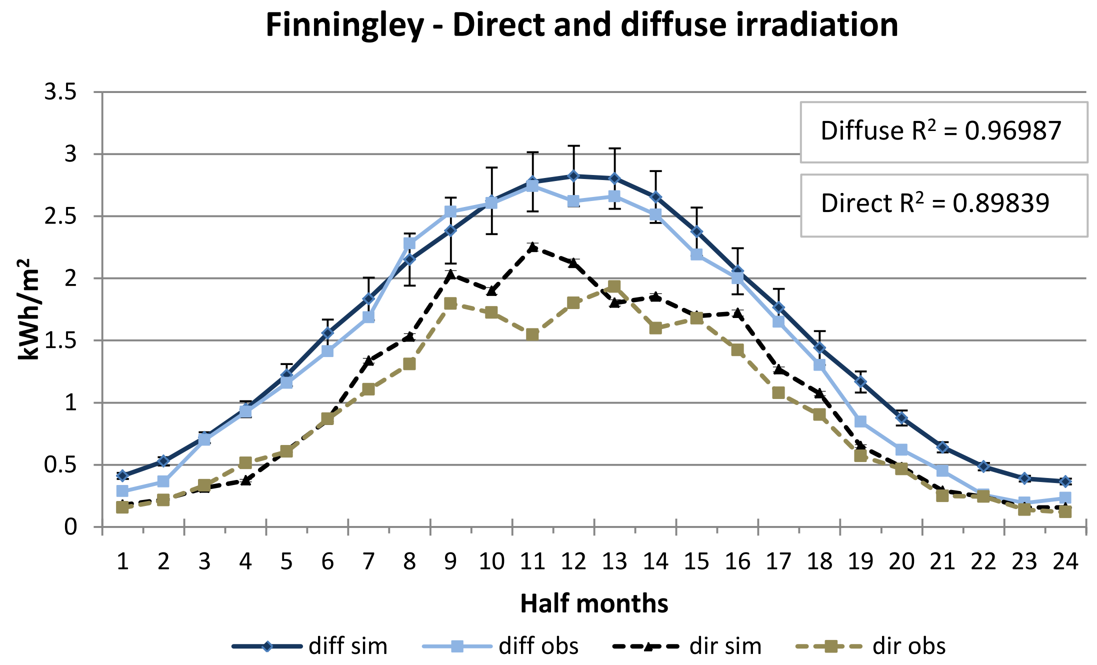


Figure 10 Compares the WG diffuse and direct output with observed data for Finningley, Doncaster (1983-1995). Error bars indicate the variability over the 100 WG runs at +/- 2 standard deviations. (Data courtesy WG Team, Met Office)

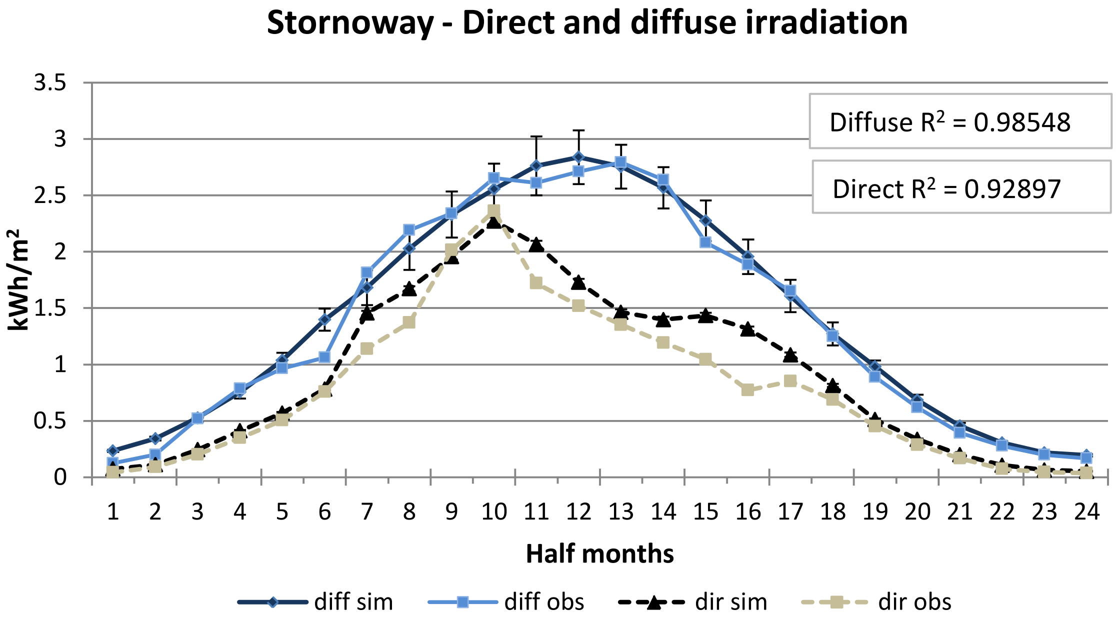


Figure 11 Compares the WG diffuse and direct output with observed data for Stornoway (1982-1995). Error bars indicate the variability over the 100 WG runs at +/- 2 standard deviations. (Data courtesy WG Team, Met Office)

The validation results suggest good agreement between the simulated and recorded data for three different sites across the UK. For the diffuse radiation the mean coefficient of determination (R^2) across the three sites was 0.9774, whilst for the direct radiation the mean value was 0.9214.

One of the strengths of using the WG model for generating the primary data for use in building simulation models is that the source model algorithms are independently validated. The current WG has undergone extensive field testing and further revisions have been made to the model as errors are reported or more accurate modelling procedures have become available (Jones and Stephens, 2011).

3.2.6 Proposed Method - Preparing WG Output Data for Building Simulation Models

Processing 3000 years of equally probable data sets per scenario for each location and time sequence is unwieldy from a building simulation perspective[xv]. In order to achieve

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[xv] Theoretically this would need to be done only once for each UKCP 5km grid location, and for each time period and emissions scenario - provided that the code in the WG model is not revised.

representative building simulation weather files the WG data needs to be processed and additional variables added. In the UK the Chartered Institute of Building Services Engineers (CIBSE) has established Test Reference Year (TRY) and Design Summer Year (DSY) formats for investigating both typical weather years and hotter than average summer years. TRYs are typically compiled from 20+ years of historical measured data (typically 1983 to 2004) which are then sorted by weighting key variables in order to create a composite year from the most typical individual months. The mathematical basis for this procedure can be found in Levermore and Parkinson (2006).

When TRY weather files are produced they are compiled from representative months and the Finkelstein-Schafer (FS) statistic is commonly used as a filter in order to select the months having the least day-to-day variance around the mean. This method is considered superior to simply using the mean month since it eliminates months that have extreme daily values and are therefore further from the long term daily mean (Finkelstein and Schafer, 1971). The FS statistic works by summing the absolute difference between the cumulative distribution function (CDF) values recorded for a particular variable on each day in a given month and the overall cumulative distribution function for each month considered, using Equation 9.

$$FS_{m,y} = \sum_{i=1}^{N_m} \left| CDF_{i,m,y} - CDF_{i,m,N_y} \right| \qquad [9]$$

The month in a given year with the lowest FS distribution is considered the most representative of all of the years for a given variable. In order to consider the most typical month where multiple variables are concerned a weighted index may be applied to each key variable. Typically dry bulb temperature (T_{db}), global irradiation (G) and wind speed (ws) are selected as the key variables in a TRY and are given an equal weighting (Eames et al, 2010). By multiplying the weighting by the FS statistic for each variable and then summing the products the overall 'typical' month may be selected as the one with the lowest weighted FS, using Equation 10.

$$FS_{sum,i} = w_1\, FS_i(T_{db}) + w_2\, FS_i(G_{Irrad}) + w_3\, FS_i(ws) \qquad [10]$$

Use of the Finkelstein-Schafer statistic method effectively reduces the risk of extreme individual daily or monthly variability occurring in the creation of a TRY. In the case of the data used by PHPP however this daily homogeneity is not a prerequisite since the model primarily relies on mean monthly inputs. In the case of the PHPP peak loads (W1 and W2) and cooling load data which are based on daily temperature and irradiation, data homogeneity is perhaps helpful in establishing ‘representative’ peak loads for a given CDF. However, peak loads by definition occur under extreme conditions and it is important to realise that in reality a one-in-ten year season is likely to contain brief periods of far more extreme data. It is also worthwhile considering the relevance of using historical baseline TRY data in the context of predicting the mean present day performance of a building. Whilst useful for illustrating the impacts of climate change the UKCP 1961-1990 (and even the CIBSE 1983-2004) baseline periods are unlikely to accurately reflect the typical performance conditions of buildings being designed today due to the recently more rapid evolution of climate change.

3.2.7 METHODOLOGY - PREPARING WG DATA FOR PHPP

For the purpose of this study, a consistent relationship was maintained between the mean dry bulb temperature and the global irradiation in order to create statistically representative months. A CDF of these two evenly weighted variables was prepared, for each climate file, from the 3000 years of WG source data. A range of statistically significant climate files may then be prepared for a sample location by sorting the data into a CDF and selecting the actual month with the closest FS fit to a given percentile.

Whilst data from the 50th percentile can be seen as representative of the mean situation, (whereby it is as likely that the weighted temperature and irradiation will be greater as it will be lower for any given scenario), the entire range of probabilistic values can be interrogated at any given percentile. This allows, for example, consideration of a one-in-ten year weather event by selecting either the 10th or 90th percentile, as appropriate. Transposing this data into a format suitable for use in the PHPP model requires several additional steps.

Monthly irradiation data (kWh/m^2.month) is needed for both the horizontal global mean values and for each of the cardinal compass directions in PHPP in order to correctly assign direct beam and diffuse irradiation to the model. Once the daily outputs from the UKCP09 generator data had been sorted and compiled into monthly percentiles, the diffuse and global irradiation was entered into a monthly radiation slope model for the appropriate latitude in order to derive the mean global slope irradiation values for vertical (90-degree tilt angle) surfaces in each percentile month. The model used here was the monthly isotropic model developed by Muneer (2004). This model was selected after evaluating Muneer's isotropic and anisotropic model outputs in comparison to the outputs from the widely used Perez model (Perez et al., 1990). In theory, an anisotropic slope model would improve the accuracy of the slope irradiation results in future refinements of this methodology as isotropic models are known to overestimate the irradiation on shaded surfaces[xvi] (Muneer, 2004).

3.2.8 METHODOLOGY - PREPARING ADDITIONAL VARIABLES FOR PHPP

Since ground temperatures are generated from formulae within the PHPP model itself, the only additional values required to complete the monthly inputs are dew point and sky temperatures. Sky temperature values are needed to calculate the long wave radiative heat transfer and external surface temperatures. A range of single-variable and more complex three-variable methods are available for computing sky temperature; the choice of appropriate model depends on the meteorological data available and also upon the limits of accuracy required. More detailed discussion of uncertainty in long wave flux and sky temperature models can be found in Aubinet (1994) and Remund (2010). Since PHPP requires only monthly mean data a relatively straightforward three-variable approach was applied here, using a combination of data available from the 5km and 25km grid models: ambient air temperature (T_{a}), relative humidity (RH) and cloud cover (C).

A modified version of the Swinbank formula (1963), after Goforth (2002) was used to calculate the downward long wave radiative flux (W/m^2):

$$\varphi_{\downarrow} = (1 + KC^2) * 8.78 * 10^{-13} * T^{5.852} * RH^{0.07195} \qquad [11]$$

A variation of the Stefan–Boltzmann law was then used to calculate the effective sky temperature (T_{sky}) based on the longwave radiation emitted from a grey body.

$$T_{sky} = \left(\frac{\varphi_{\downarrow}}{\varepsilon\,\sigma}\right)^{0.25} \qquad [12]$$

[xvi] During comparative evaluation of the monthly irradiation model outputs Muneer's isotropic model was found to return results that were more consistent with the Perez model outputs (generated using Meteonorm 6) than Muneer's monthly anisotropic model. The anisotropic model was found to return some false negative values at low sun angles, for this reason the isotropic model was used to determine the monthly irradiation values for the different vertical slope orientations (N,S,E,W) as required by PHPP.

where ε is the sky emissivity (approximated to 0.736 + 0.00577$*$ T_{dp}, for the dew point temperature range considered here[xvii]), and σ is the Stefan-Boltzmann constant (5.67*10 $^{-8}$ Wm^{-2}K^{-4}).

Dew Point temperature (T_{dp}) was calculated by rearranging Magnus-Tetens formula for vapour pressure (Barenbrug, 1974) to provide the following expression, which is valid for the range 0 °C < T_a < 60 °C, 0.01 < RH <1.00, 0 °C <T_{dp}<50 °C.

$$T_{dp} = \frac{b.\alpha(T_a,RH)}{a-\alpha(T_a,RH)} \qquad [13]$$

where a = 17.27, b = 237.7 (°C)

and

$$\alpha(T_a, RH) = \frac{\alpha.T}{b+T} + \ln(RH) \qquad [14]$$

Peak load data for periods W1 and W2 represent the mean data across the peak load period, the length of which is dependent upon the time constant of the building. The time constant in a Passivhaus is typically much longer than conventional dwellings due to the thermal inertia created by high thermal resistance of the envelope and low rate of energetically effective air changes. According to Riedel (2009) a simple equation is currently used by European Passivhaus designers to determine the approximate time constant (t_{peak}) used to isolate the appropriate peak loads used in the PHPP calculation:

$$t_{peak} = \frac{K}{\overline{U}} \qquad [15]$$

where K is the specific thermal capacity per unit treated floor area (Wh/K.m^2) multiplied by the TFA (m^2), and $\overline{U}$ is the average area weighted U value of the thermal elements (W/m^2.K) multiplied by the total external surface area of the building envelope.

The peak load time constant used in Passivhaus design is analogous to the building response factor (f_r), which is discussed in CIBSE Guide J in relation to peak load system sizing and building thermal inertia (CIBSE, 2002). The (f_r) selection method described in

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[xvii] Research by Chen et al. (1995) established a linear relationship between the sky emissivity (ε) (0<ε <1) and the dew point temperature (T_{dp}), where ε = 0.736 + 0.00577 * T_{dp}
For dew point temperatures in the range of approximately 0 °C to 30 °C the effect of T_{dp} is relatively small. At = 30 °C the influence on ε is +0.17 but converges to 0 as T_{dp} approaches 0 °C.

CIBSE J is based on the work of Jamieson (1955), and categorizes the thermal response of a building by defining two different peak load averaging times. According to CIBSE Guide J,

> "For most buildings, a 24-hour mean temperature is appropriate. However, for buildings with high thermal inertia (i.e. high thermal mass, low heat loss) having a response factor (f_r) ≥ 6, a 48-hour mean temperature is more suitable" CIBSE (2002, Section 4.1).

The response factor is defined as:

$$f_r = \frac{\left[\sum(A\,Y)+\frac{N\,V}{3}\right]}{\left[\sum(A\,U)+\frac{N\,V}{3}\right]} \qquad [16]$$

where f_r is the response factor, and $\sum(A\,Y)$ is the sum of the products of the surface area and the corresponding thermal admittance over all surfaces (W/K), N is the number of air changes per hour (h^{-1}), V is the internal air volume of the space (m^3) and $\sum(A\,U)$ is the sum of the products of surface area and the corresponding thermal transmittance value over all surfaces through which heat flow occurs (W/K). As can be seen from equations 15 and 16 the two approaches are very similar, although the CIBSE concept is likely to be more accurate as it includes terms to account for the energetically effective air change rate.

Typical peak load time constants for Passivhaus dwellings generally extend well beyond either of the two cases discussed in CIBSE Guide J, and are typically in the order of 3–7 days (Schnieders, 2003). The longer response times used in Passivhaus design can be attributed to the much higher levels of air tightness, and reduced energetically effective air change (resulting from the use of highly efficient MVHR units), as well as the lower thermal transmittance values required to comply with the Passivhaus standard.

Risk assessment in relation to building performance also plays a role in the choice of the peak load time constant. The use of a shorter time constant inevitably reduces design risks by assessing building performance under more extreme conditions, but carries with it the penalty of potential over-engineering and higher investment costs.

In this study a three day time constant was used to select the peak load data. This is consistent with time constant used to generate the BRE (2011) data and is a conservative approach in relation to the peak load time constant range proposed by Schnieders (2003), above. W1 climatic data was determined by creating a macro which isolated the lowest consecutive three day mean temperature and the corresponding irradiation from the appropriate percentile year. In the case of W2 a macro was created to select the lowest consecutive three day mean daily irradiation readings and the corresponding temperature from the appropriate percentile.

The three daily mean global horizontal irradiation levels for both W1 and W2 are entered in to an anisotropic daily slope irradiation model (Muneer, 2004) and broken down into the cardinal compass orientations (N,E,S,W) for a 90 degree tilt angle. Since the approach used here operates from daily global horizontal data the mean irradiation for E and W facing surfaces will be the same. A slightly more accurate refinement, leading to slightly different slope values for East and West facing surfaces, would be to use an hourly slope model and then averaging the values over the duration of the peak load time constant.

3.3 CASE STUDIES

The building chosen for the case study is the Larch House (see Figure 12) a 3 bedroom (87m^2 TFA) detached Passivhaus dwelling in Ebbw Vale, Wales. Completed in July 2010, this was one of the first social Passivhaus projects in the UK and the first Code for Sustainable Homes (CSH) Level 6 zero carbon Passivhaus in the UK (iPHA, 2013). The high surface area/volume (SA/V) characteristic of a small detached dwelling make this one of the most challenging typologies with which to achieve the Passivhaus standard. In addition to typical Passivhaus components, the building has exceptionally low U- values (walls 0.095 W/m^{2}K, roof 0.074 W/m^{2}K and floor 0.076 W/m^{2}K) as well as an exceptional airtightness of 0.197 ac/h @n50. It should be noted that the building uses external roller blinds to help prevent summer overheating and these have been assumed to be operational during the overheating risk analysis[xviii].

[xviii] Issues relating to overheating in passivhaus design and the reliance upon external shading devices as part of the overheating design strategy are discussed in Section 4.1.1

Figure 12 South elevation of the 'Larch' Passivhaus, Ebbw Vale (courtesy of Jefferson Smith)

Ebbw Vale is situated in a location where the effects of a maritime proximity combined with a mountain valley situation dominate the climate. This situation is common to many of the old mining towns situated in the South Wales 'Valleys' region north of Cardiff. Much of this area suffers from severe social and economic deprivation and is receiving significant regeneration funding from the Welsh Government. In 2008 as many as 43% of Blaenau Gwent households were reported to be experiencing fuel poverty[xix] and it is likely this figure would have increased in recent years (Hunt, 2011). As a result, this area has become a focal point for the construction of social housing in the Passivhaus format.

In total, three different sites are examined in order to demonstrate the initial findings of this research in three distinct climatic contexts. Case Study 1 examines the building's original location, the Ebbw Vale site in a mountainous valley in Wales. Case study 2 (London CBD) and 3 (London Docklands) examine the predicted variations existing between two adjacent 5km^2 grid cell data sets in an urban context in central London. All three locations share a common building model, based on the certified Welsh 'Larch' Passivhaus for comparative purposes throughout. It is noteworthy that these three locations all lie within 0.25 of a degree of latitude of one another with case study 1 (Ebbw Vale) 51.760°North[xx],

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[xix] Households are considered by the UK Government to be in 'fuel poverty' if they would have to spend more than 10% of their household income on fuel to keep their home in a 'satisfactory' condition. This is usually defined as 21 degrees for the main living area and 18 degrees for other occupied rooms, in accordance with SAP (Hunt, 2011).

[xx] It should be noted that the latitude and grid cell reference for Ebbw Vale refer to the centre of the UKCP grid cell in which the Larch House passivhaus is located and not to the town of Ebbw Vale which is located in the adjacent grid cell (3200215) to the North.

case study 2 (London CBD) 51.509°North and case study 3 (London Docklands) 51.509°North.

For consistency, it is assumed in all three case studies that climate change progresses broadly in line with a 'Medium' SRES scenario. The same approach may be used to examine any of the three principal (Low, Medium, High) IPCC SRES scenarios as well as to compare the historical baseline data for the 1961–1990 period.

3.3.1 CASE STUDY 1 – RURAL PASSIVHAUS AT EBBW VALE, WALES (UKCP GRID REF 3200210)

In order to compare the influence of the climate data sets in context, the datasets were entered into the PHPP model of a certified Passivhaus at Ebbw Vale. Figure 176 shows the resultant annual space heating demands normalised to the TFA of the dwelling. A clear progression is seen from the historic baseline to future probabilistic levels for the 50th percentile year. The data generated using the WG baseline (1961–1990) appears to correspond well to the mean performance predicted by the Meteonorm software. In contrast, use of the BRE Severn region data (even when corrected for altitude) would lead to a significant (55%) under estimation of the space heating demand, to a level that falls below even the 2080M 50th percentile prediction for this location.

Consideration of the annual (space heating) energy demand and peak load are of considerable importance in the design of Passivhaus dwellings particularly where post air heating is used as the primary source of supplementary heat input.

3.3.2 Case Study 2 & 3 – Urban Passivhaus – London CBD and London Docklands (UKCP Grid Ref 5350185 and 5450185)

The following two case studies provide a contrasting view of the predicted implications for urban sites within Greater London. Case study 2 examines the London CBD, a zone that is likely to see some of the most pronounced effects of climate change due to the Urban Heat Island (UHI) effect (DECC, 2011). Case Study 3 examines the predicted impacts in the Docklands zone located 5 km due East of the CBD (an area that is less affected by the current UHI). Both grid cells (Figure 13) sit within the much larger BRE Region 1[xxi] (Central London) regional dataset shown in Figure 7.

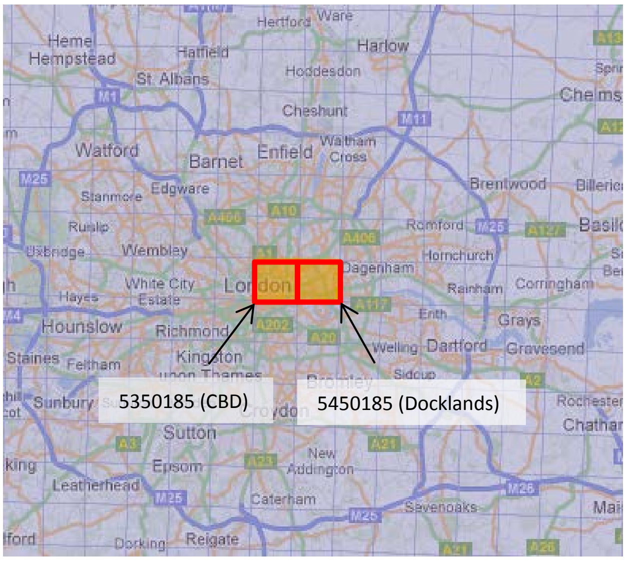

Figure 13 Sub-regional analysis showing location of London CBD (5350185) and Docklands (5450185) 5km grid squares (adapted from DEFRA, 2010)

[xxi] BRE Region 1 originally encompassed much of Greater London, but has more recently (2012) been reduced in size to include only the following 13 Central London Boroughs: Hammersmith and Fulham, Kensington and Chelsea, Westminster, Camden, Islington, City of London, Hackney, Tower Hamlets, Newham, Lewisham, Southwark, Lambeth and Wandsworth.

3.4 RESULTS

3.4.1 ANALYSIS OF DATA GENERATED

Of the climate data required by the PHPP model, the two dominant variables affecting the specific heating demand are the mean ambient air temperature and the solar irradiation. In a quasi-steady state such as PHPP the length of the heating season (H_T)[xxii] and the number of heating degree hours (G_t)[xxiii] are both determined by the monthly mean ambient air temperatures.

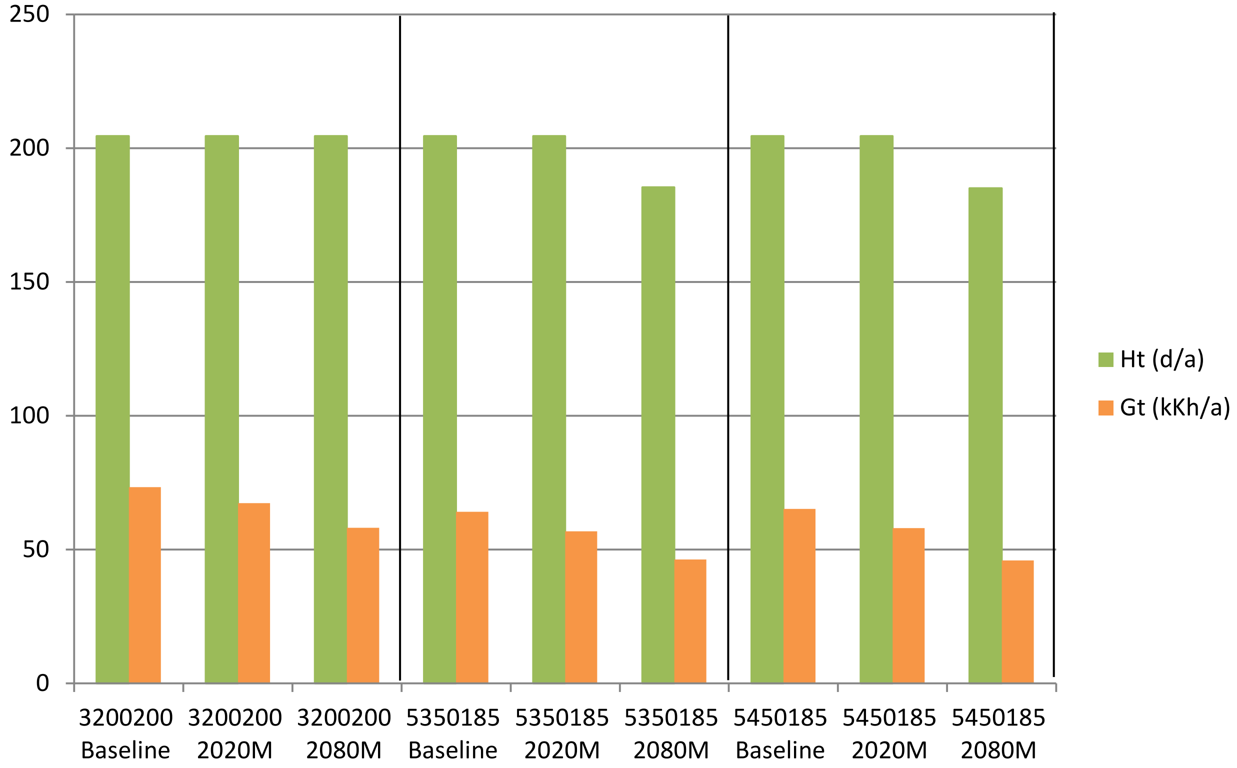

Figure 14 Heating season length (H_T) and heating degree hours (G_t) for Ebbw Vale (3200200) London CBD (5350185) and London Docklands (5450185) under a Medium emissions scenario when assessed at the 50th percentile

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[xxii] In PHPP months where the mean ambient temperature is <10 °C are given a coefficient of 1 (i.e. 100% of the days are included in the heating season). Months where the ambient temperature is >16 °C are given a coefficient of 0 (i.e. all of the days are excluded from the heating season). For months where the mean ambient temperature is >10 °C<16 °C a coefficient is calculated using a fitted quadratic expression (Feist et al., 2012).

[xxiii] The heating degrees hours (G_t) for a given location (or probabilistic interval) are calculated as the time dependent integral of the difference between the ambient air temperature and the internal set point temperature of 20 °C (Feist et al., 2012).

When assessed at the 50th percentile of the CDF the length of H_T is identical in all three locations, at 205 days, under the Baseline and 2020 Medium emissions scenarios. By 2080, under a Medium emissions scenario, H_T is predicted to fall by approximately 10% (to 185 days) for both London locations. The progressive influence of warmer monthly mean ambient temperatures with time can be seen more clearly from the profile of G_t (Figure 14) which is projected, by 2080, to have fallen by 21% (Ebbw Vale), 28% (London CBD) and 29% (London Docklands).

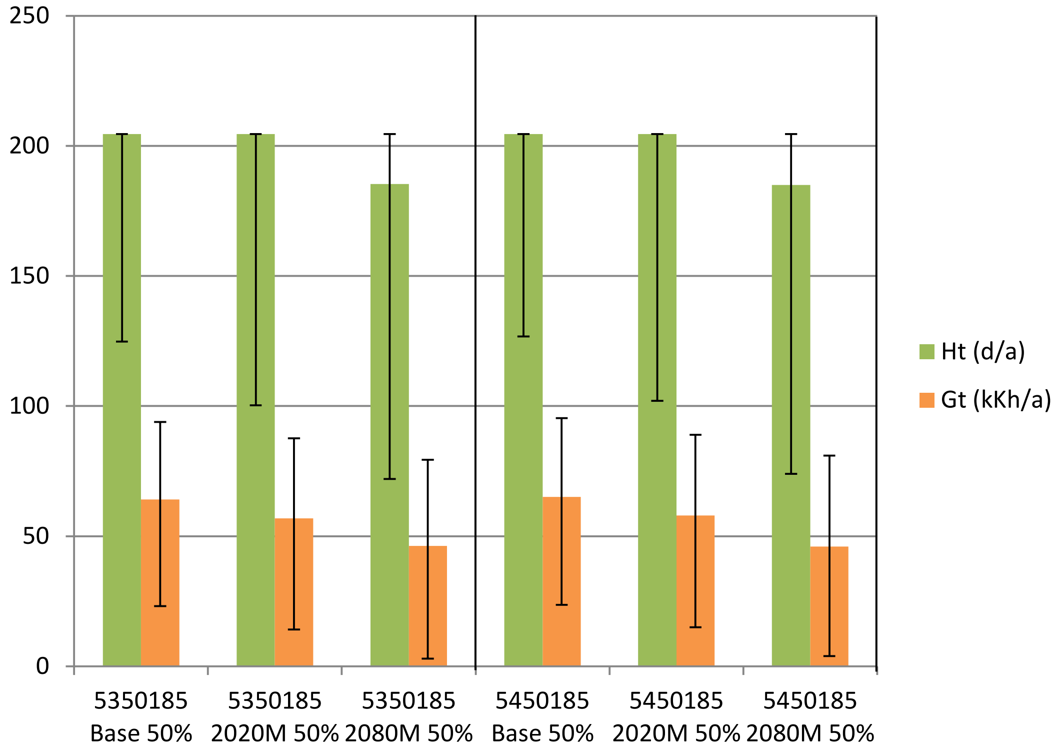

Figure 15 Comparison of heating season length and heating degree hours at 10th (upper bar), 50th and 90th (lower bar) percentile years for London CBD (5350185) and London Docklands (5450185)

A more detailed comparison of H_T and G_t and for the two London locations is shown in Figure 15, where the error bars represent the 10th–90th percentile probability interval. Figure 15 shows that interseasonal variance (as represented by one in ten year extremes) results in far greater variability in both H_T and G_t than occurs as a result of mean climatic change over time. However it is also notable that the variability in the magnitude of H_T is projected to increase over time. This finding implies that whilst on average the length of H_T is contracting over time, under a Medium emissions scenario, it is likely (1 in 10 probability) that there will still be years during the 2080 period (1970–1990) where H_T is as long as during the present day. Conversely there is an equal probability that by 2080 in a warmer than average (90th percentile) year H_T could be reduced by as much as 64% relative to the current (Baseline 50th percentile) H_T.

Under the SRES Medium emission scenario for the Welsh valley location (Ebbw Vale) analysed here, it is likely that by 2080 mean summer temperatures will rise by as much as 4.5 K and winter temperatures by approximately 4 K (McLeod et al., 2011). This evolution of temperatures is not constant however and within any given timeframe, the variation between the 10th and 90th percentile temperatures is significantly greater (+/-7 K), and this remains relatively consistent over time.

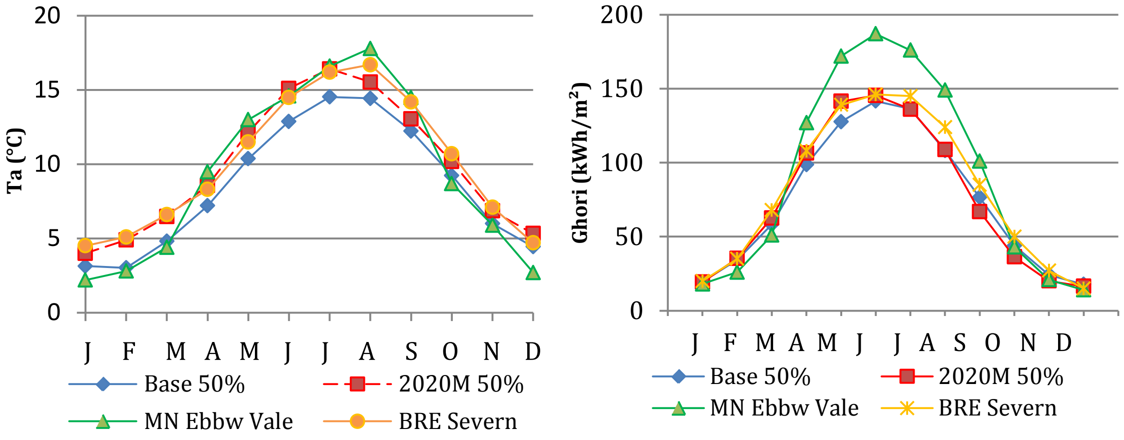

Figure 16 Monthly mean ambient temperature (left) and global horizontal irradiation (right), Ebbw Vale (3200210): comparison of 5km grid Baseline 50th percentile, 5km grid 2020(M) 50th percentile, MN Ebbw Vale (site) and BRE Severn (Region 6)

Comparison of ambient temperatures predicted by different climate data sets and across time periods (Figure 16, left) shows that the Baseline (1961-1990) 50th percentile temperature is consistently lower than the 2020 50th percentile, as might be anticipated through climate change. Notably the Severn data (BRE Region 6), which represents the current regional data set for Passivhaus certification in the location of Ebbw Vale (BRE, 2011), is significantly warmer than the Met Office historical Baseline and exceeds even the 2020 50th percentile temperatures for much of the year. There is good agreement between the datasets for the global horizontal irradiation (Figure 16, right) with the exception of the Meteonorm site-specific data, which predicts significantly higher solar irradiation levels during the summer months.

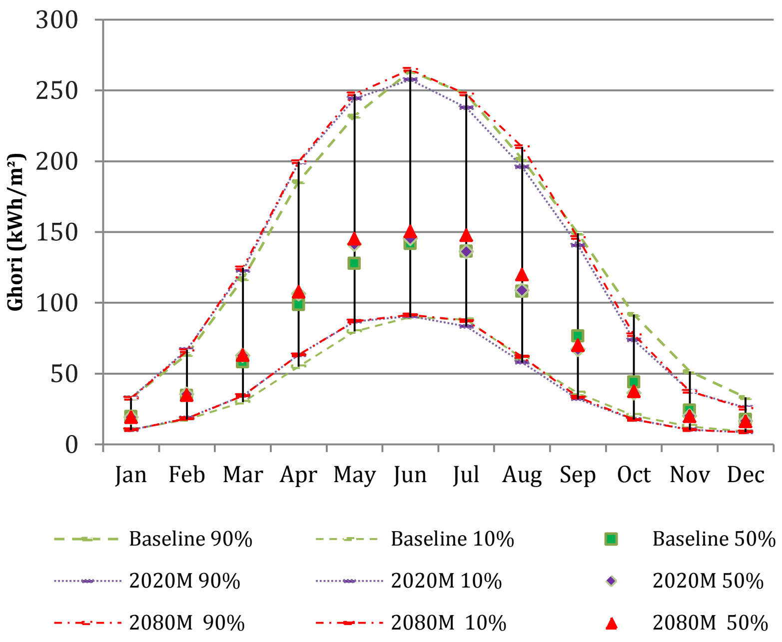

Figure 17 Global horizontal irradiation, Ebbw Vale (3200210): 10th, 50th and 90th percentiles showing 5km Baseline, 5km 2020M and 5km 2080M evolution

Global irradiation is not directly affected by Green House Gas (GHG) concentrations and therefore does not evolve in the same way over time as ambient temperatures (McLeod et al., 2011). Slightly higher levels of global irradiation are seen under the 2080(M) scenario particularly in the summer months however the winter months remain largely unchanged. The changes seen in predicted global irradiation levels are most likely due to changes in the absolute amount of cloud cover and humidity levels. Variation between the 50th and 90th percentile is greater than the variation between the 10th and 50th percentile and this range is more pronounced during the summer months (Figure 177). The variation in irradiation levels occurring at different percentiles during the summer months is likely to have a significant impact on overheating risks when both temperature and irradiation distributions occur above the 50th percentile due to inter seasonal variability.

3.4.2 RESULTS OF DIFFERENT CASE STUDIES

In order to compare the influence of the climate data sets in context, the datasets were entered into a common PHPP model of the certified 'Larch' Passivhaus at Ebbw Vale. Figure 18–Figure 20 show the resultant annual space heating demand normalised to the treated floor area (q_H) of the Passivhaus dwelling. A clear progression from the historic baseline to future probabilistic levels for the 50th percentile year can be seen (dark blue bars).

The current baseline appears to correspond well to the mean performance predicted by the Meteonorm software. By contrast, use of the BRE regional data would lead to a significant (55%) under estimation of the space heating demand, to a level that falls significantly (26%) below even the 2080M 50th percentile projection for Ebbw Vale.

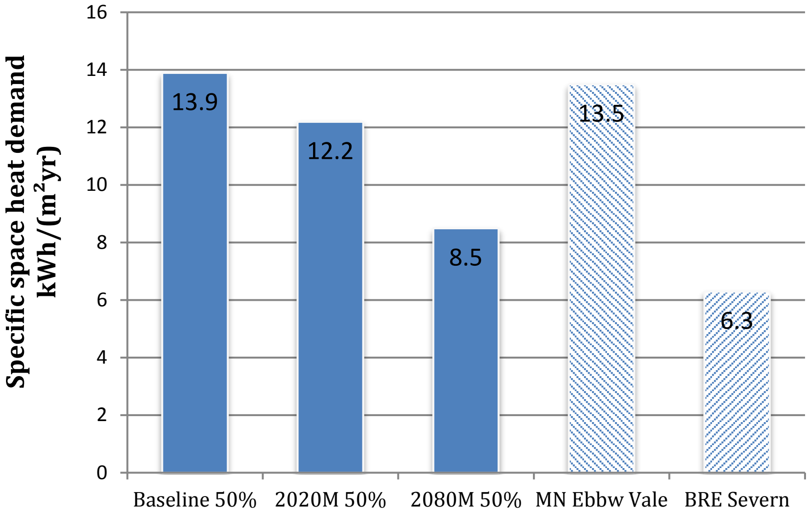

Figure 18 PHPP heating demand, Ebbw Vale: as predicted by 5km Baseline, 5km 2020M, 5km 2080M, MN Ebbw Vale (site), and BRE Severn (Region 6)

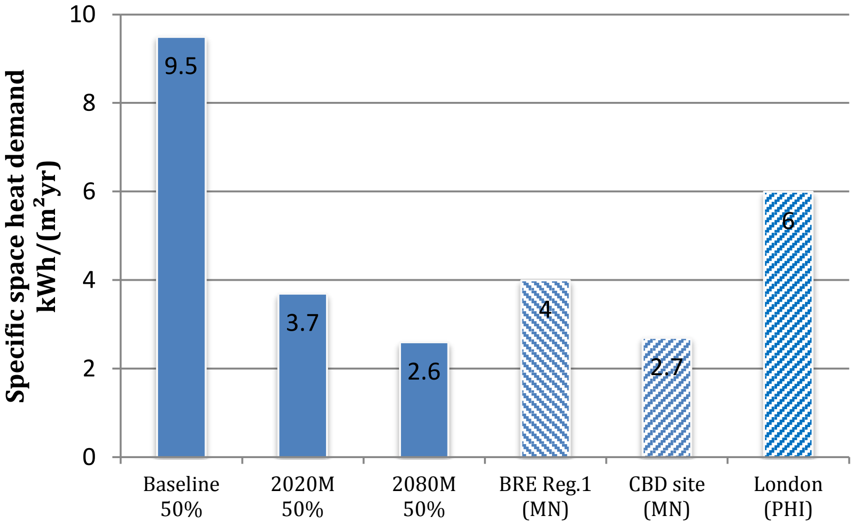

Figure 19 PHPP Heating demand London CBD (5350185) as predicted by 5km Baseline, 5km 2020M, 5km 2080M, MN London CBD (site), BRE Central London (region 1) and original PHI London TRY

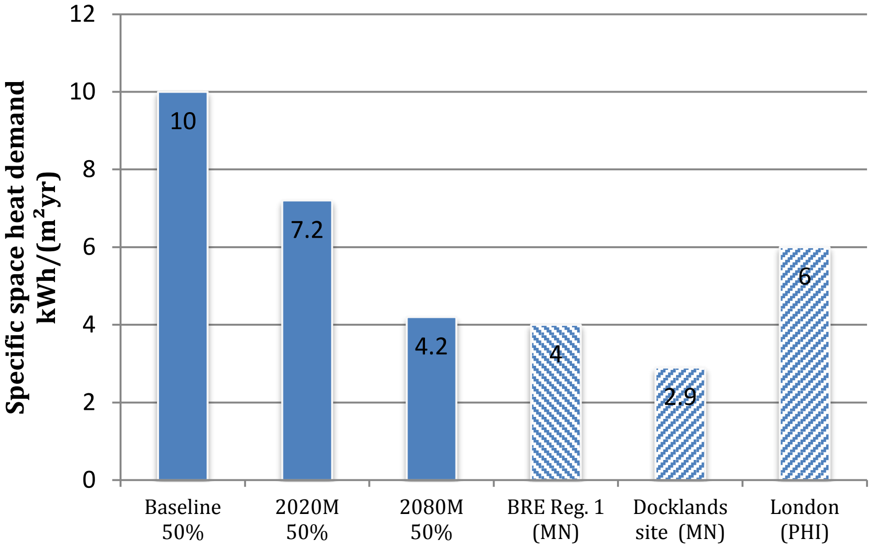

Figure 20 PHPP Heating demand Docklands (5450185) as predicted by 5km Baseline, 5km 2020M, 5km 2080M, MN London Dockland (site), BRE Central London (Region 1) and original PHI London TRY

When comparing the results for both of the London locations for the predicted heating demand, it can be seen that there is a rapid evolution towards fewer heating degree hours. The reduction in heating demand is far more pronounced for the London locations (Figure 19 and Figure 20) than for Ebbw Vale (Figure 18). Consequently, it will become significantly easier to achieve the Passivhaus (q_H) requirement in the future, in all of the regions assessed, and particularly so in areas affected by the Urban Heat Island (UHI).

Analysis of the range of performance predictions here suggests that the application of regional data, in certain microregional contexts, is likely to lead to highly inaccurate design predictions. As a result of using the current BRE regional data set it appears likely that projects modelled outside the London CBD (but within Greater London) may be designed with significant under-prediction of the current day heating demand. This can be seen most noticeably in the case of the London Docklands (5450185) grid cell (Figure 20), where the UKCP data suggests that the current heating demand may be more than 100% higher than the BRE regional data suggests. Paradoxically the use of Meteonorm site-specific interpolation would (in both London examples) lead to an even more pronounced under estimate of the heating demand than the BRE regional data. This is likely to be a result of the location used for the BRE Region 1 interpolation (Latitude 51.517 Longitude -0.117°) (BRE, 2011) which is 1.5 miles due west of the London CBD site specific interpolation point, and therefore further from the influence of the UHI.

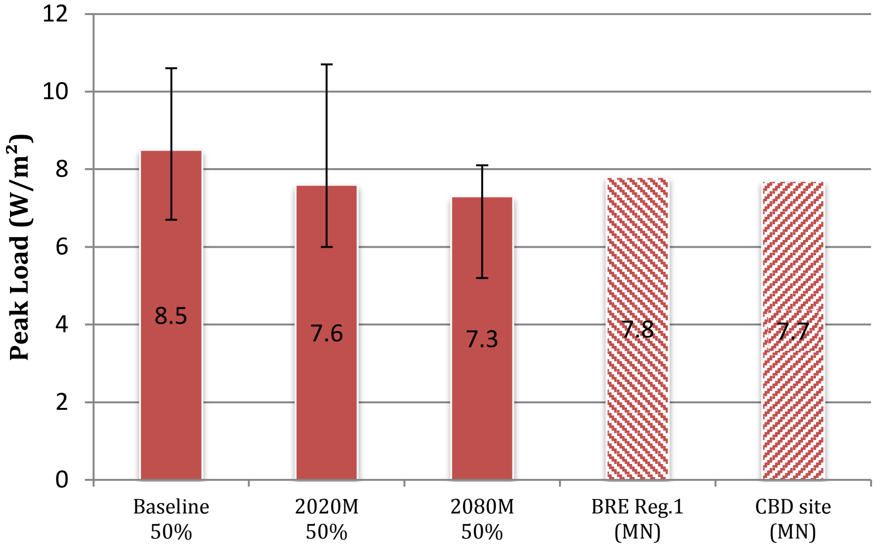

Figure 21 Comparison of peak heating loads, London CBD (5350185): at 50th percentile with error bars indicating the 10th and 90th percentiles

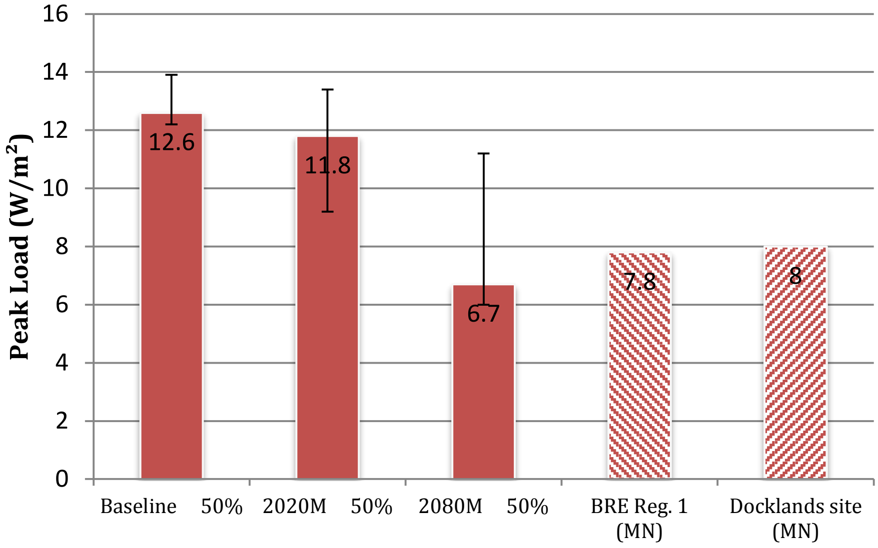

Figure 22 Comparison of peak loads, London Docklands (5450185): at 50th percentile with error bars indicating the 10th and 90th percentiles

Figure 21 and Figure 22 show the results for the peak loads for the two London locations. There is good agreement between the Central London regional data and the CBD 5km 2020M data (Figure 21) at the 50th percentile. However the Docklands 5km data (Figure 22) shows that significantly higher peak loads are predicted just outside the CBD. This marked variance is likely to illustrate the localised influence of the of the UHI effect in the underlying 5km baseline data. Overall these results suggests that the current BRE Central

London (Region 1) data appears to significantly underestimate present day peak loads in Greater London, even allowing for variability predicted between the 10th and 90th percentile ranges.

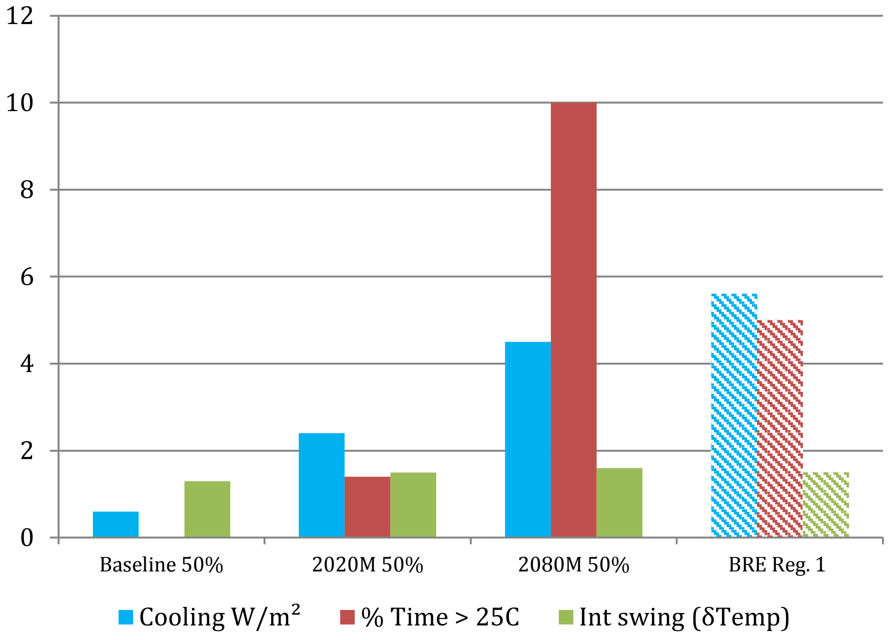

Figure 23 London CBD (5350185) transitional cooling loads and overheating risk

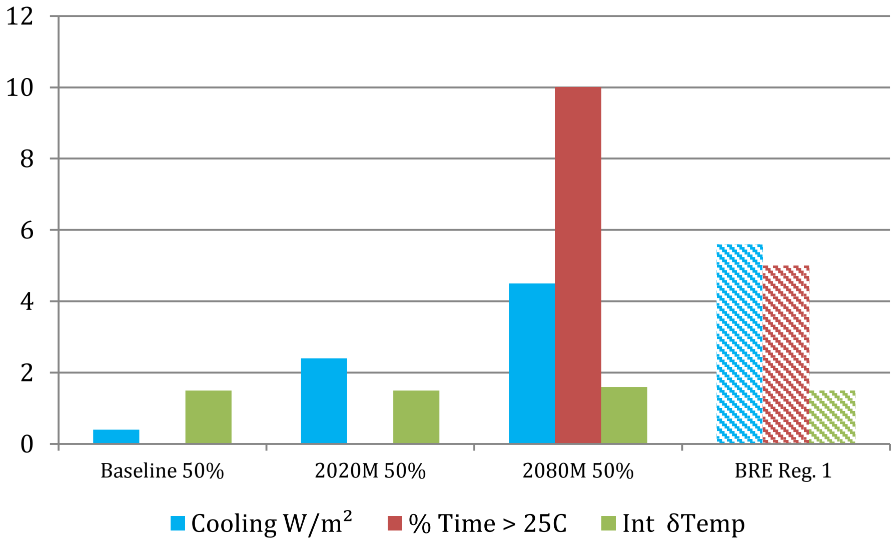

Figure 24 London Docklands (5450185) transitional cooling loads and overheating risk

Figure 23 and Figure 24 illustrate the transitional overheating risks and predicted cooling loads for London CBD and London Docklands. It can be seen that there is an earlier onset of overheating risk in the London CBD location, as might be anticipated by the more pronounced influence of the UHI. In terms of consistency between the data sets, the Central London (BRE Region 1) data seems to significantly overestimate the current day overheating risk when evaluated at the 50th percentile. Overheating risk is however highly dependent upon which percentile the weather year is sampled from, and assessing future overheating risks on a probabilistic basis is an area for further research. By 2080, during a mean (50th percentile) year, even with external roller blinds in place and night purge ventilation operating the building modelled here is likely to overheat for 10% of the year in both of London locations studied. This finding is significant since Rouvel (1997) defines the exceedance of 25 °C for greater than 10% of the year as the threshold at which active cooling is required. The same limiting standard is also applied in the German Wärmeshutz und Energie-Einsparung in Gebauden (2003) standard (DIN 4108-2, 2003). Research by Voss et al (2005), involving post-occupancy evaluation studies of low energy office buildings in Europe, suggests that the 10% threshold above 25 °C represents the upper limit of acceptability. Voss et al (2005) recommend that a lower target of 5% overheating frequency should be the goal of building designers[xxiv].

Some caution is necessary with respect to the future changes predicted by the UKCP09 scenarios in dense urban areas. At the 25 km grid resolution of the HadRM3 RCM the largest urban areas can be seen to exert some influence on the local simulated climate (McCarthy et al., 2009). Since an explicit representation of urban areas was not included in the HadRM3 model the UKCP09 projections cannot fully incorporate the transient effects of the urban areas in the probabilistic predictions (Kershaw et al., 2010). Studies including those carried out by Watkins et al. (2002) have shown that, on average, the UHI effect for London lies between about 2.5–3 °C in summer (Watkins et al., 2002) and 1.0–3.2 °C during winter (Giridharan and Kolokotroni, 2009).

However, according to the UKCP the projections of future climate available from the WG do include the current effects of urbanisation at the 5km grid scale (Kendon, 2012). It follows therefore that if the UHI effect does not change significantly in the future, it is reasonable to add the UKCP09 climate change projections to the observed urban climate in order to

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[xxiv] Overheating risk assessment thresholds are discussed in further detail in Sections 4.1.1 – 4.1.3

generate future urban climate predictions (DEFRA, 2012). Conversely if future changes occur in the amount of energy dissipated in cities (e.g. cooling systems become widespread), or if the density of a city changes then these factors could alter the current UHI effect, and projecting future climates in cities will then require additional techniques to be employed (DEFRA, 2012).

Comparative temperature measurements taken at an inner city location (St. James Park) and a suburban site in Surrey suggest that London's nocturnal UHI has intensified by approximately 0.5 K on average since the 1960s (Wilby 2003), partly as a consequence of increased Human Energy Production (HEP), denser urbanisation, and the changing frequency of weather patterns. It is likely that only a relatively small component of these evolutionary changes are missing from the 5km UKCP baseline data (which was based on data collated over the 1961-1990 period).

Whilst the mean monthly shifts induced by the UHI are reasonably well documented (Kershaw et al., 2010; Wilby, 2003) the local amplitude and temporal profile of the daily UHI effect during heat waves should be carefully evaluated by those attempting to accurately evaluate peak overheating risks under extreme conditions. Data from Graves et al (2001) indicates that the intensity of the nocturnal UHI peak for Westminster, London has occasionally exceeded 7 K during the summer months. Since the most pronounced effects typically occur between 3am – 9am (Wilby, 2003) the timing of this phenomenon will substantially dampen the natural diurnal cooling range, with consequential impacts for buildings reliant on night purge cooling. Generating an improved understanding of the future evolution of localised UHI's is a complex and important area for building simulation, where significant further research is needed.

3.5 CONCLUSIONS

A new method for the generation of current and future probabilistic micro regional climatic data in Passivhaus design is proposed. The approach is based on the use of data generated using the UKCP09 Weather Generator (version 2) which combines historic baseline recorded data with probabilistic outputs from the RCM. Using this methodology data can be generated on a 5km grid basis for the entire UK landmass, across 10-year time intervals spanning from the historic (1961-1990) baseline through to 2080 and for three distinct future IPCC SRES climatic scenarios (Low, Medium and High). For each location and scenario, the data can be interrogated at any percentile of the CFD distribution, allowing the creation of both mean and extreme climate data sets. This approach provides designers with the high resolution data needed to optimise and future proof Passivhaus and low energy designs on a sub-regional basis. Furthermore the ability to group multiple 5km grid cells outputs from the WG creates the possibility to generate spatially representative regional climate data sets underpinned by a common climate model.

The key outputs from the new methodology, when assessed at the 50th percentile, showed generally good agreement with other data sources. When evaluated in the PHPP building model the results showed good correlation with the Meteonorm interpolation software data generated for the same location. When compared with the regional certification data currently used for both the Severn and Central London regions (BRE, 2011) a significant difference was observed in the predicted specific heating demand and peak loads. These preliminary finding suggests that the use of proxy regional data could, in some instances, lead to a significant underestimation of the specific annual heat demand and peak loads. In one example, in the London Docklands region, the UKCP data indicates that the mean present day (2013) heating demand may be 100-150% greater than the BRE regional data suggests (Figure 20). These findings reiterate those of other studies, which have found significant differences between the use of local and regional default data in PHPP design predictions (Oberrauch, 2008; Morehead, 2010). Since the current method of deriving data for Passivhaus design is based on the use of 'nearest neighbour'[xxv] TRY data (which is effectively an historic mean weather year) designers need to be acutely aware of the limitations inherent in this approach particularly with respect to peak loads.

In the context of this study further research is needed in order to establish the robustness of the approach used in terms of predicting peak heating and cooling loads. The approach used here is based on the use of a time constant (Bisanz, 1998) and the sensitivity associated with this approach may require further calibration against empirical studies and established uncertainty analysis methods (Hopfe and Hensen, 2011).

[xxv] 'Nearest neighbour' refers to the practice of using a proxy climate file from the nearest available geographic location for modelling purposes, typically when site specific or sub-regional data is not available.

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CHAPTER 4 | FUTURE PERFORMANCE AND OVERHEATING RISKS IN PASSIVHAUS DWELLINGS

DISCURSUS:

The preceding chapter presented a new method for generating micro-regional current and future probabilistic climatic data for Passivhaus design, which is linked to both the existing Met Office weather station network and the Hadley Centre's Regional Climate Model (RCM). This chapter investigates whether Passivhaus dwellings will continue to provide high standards of thermal comfort in a future characterised by rapid climatic change, or whether the concept is inherently vulnerable to overheating risks.

Section 4.1 discusses previous literature in the domain of overheating risk in Passivhaus buildings (4.1.1), the impact of climate change on buildings (4.1.2), and the relationship between elevated operative temperatures, thermal comfort and human health (4.1.3).

Scenario modelling using probabilistic data derived from the UKCP09 weather generator (WG) in conjunction with a dynamic simulation programme (DSP) and global sensitivity analysis techniques are used to assess the future performance of a range of typical Passivhaus dwellings relative to an identical Fabric Energy Efficiency Standard (FEES) compliant dwelling over a notional future lifespan (Section 4.2).

The emphasis of this chapter is to understand what impact climate change will pose to overheating risks for Passivhaus dwellings relative to the de facto (i.e. FEES) alternative, and which design factors play a dominant role in contributing to this risk. The results show that optimization of a small number of design inputs, including glazing ratios and external shading devices, can play a significant role in mitigating future overheating risks (Section 4.3).

4.1 BACKGROUND

The Passivhaus standard is generally considered to be a low energy building performance standard; characterised by super insulated, airtight envelopes, the use of mechanical ventilation with heat recovery (MVHR) and optimal use of passive solar gains. However, achieving clearly defined thermal comfort criteria are also central to the concept. The functional definition of a Passivhaus, states that:

> “A Passive House is a building in which thermal comfort can be guaranteed solely by heating or cooling of the supply air which is required for sufficient indoor air quality – without using additional recirculated air” (Feist, 2007; iPHA, 2013).

A detailed description of the technical requirements for achieving quality approved Passivhaus status are described in the Passive House Planning Package, Version 7 (Feist et al., 2012). The adoption of the Passivhaus concept in the UK is a relatively recent occurrence, with the first certified Passivhaus buildings being completed in 2010 (iPHA, 2013); as a result only minimal post occupancy data is available to date. Elsewhere in Europe a number of studies that have reported on overheating risks in Passivhaus dwellings and the key findings are summarised in Section 4.1.1. Climate change and heat waves are likely to have significant implications for the future UK built environment and the main findings are summarised in Section. 4.1.2. Thermal comfort and the impacts of overheating on human health are issues which are central to the assessment of future overheating risks, and the main implications are summarised in Section 4.1.3.

4.1.1 OVERHEATING RISK IN PASSIVHAUS BUILDINGS

A number of studies have reported specifically on overheating and the summer performance of Passivhaus buildings in a variety of European climatic zones. A finding common to many of these studies is that the occupants of Passivhaus dwellings often report better thermal comfort in winter than in summer (Berndgen-Kaiser et al., 2007; Danner and Vittar, 2001; Mlecnik et al., 2012; Wagner and Mauthner, 2008 a; Wagner and Mauthner, 2008b) . Contrary to this finding, there are also a number of reports, based on Post Occupancy Evaluations (POEs) and monitoring carried out by the Passivhaus Institute, indicating high levels of occupant satisfaction under summer conditions (Schnieders et al., 2001; Hermelink and Hübner, 2003; Hermelink, 2004; Schnieders and Hermelink, 2006; Feist et al., 2012).

Studies documenting overheating in certified Passivhaus buildings located in Northern Europe warrant further investigation since they are of considerable relevance to the UK climatic context. In Skibet, Denmark, Larsen and Jensen (Larsen and Jensen, 2011) carried out data logging of the internal environment of 10 certified Passivhaus dwellings. The Skibet development is located at 55.7 North (a latitude which is slightly south of Glasgow, UK). They recorded data for dry bulb temperature (T_{db}), relative humidity (RH) and CO_2 levels in multiple locations from 2008 to 2011. The data recorded in this study was then compared to the criteria set out in category B of DS/CEN/CR1752 (2001) , which specifies an acceptable summertime dry bulb range from 23–26 °C. The results for the month of July for the 2009 interval show that this criterion was exceeded 40% of the time. In 2010 the same criteria was exceeded 60% of the time, resulting in severe overheating (Larsen and Jensen, 2011). One factor contributing to the difference in the duration of overheating was attributed to different occupant ventilation patterns and another to different weather patterns experienced over the two summer periods. What is notable is that such a prolonged overheating risk was not predicted by the PHPP model of the certified dwellings, however it was subsequently replicated by a dynamic simulation programme (DSP) BSim (DBRI, 2013) and also via manual calculation in accordance with SBI instruction 202 (Andersen et al, 2002).

A similar study carried out in Lindås, Sweden showed that mean summer temperatures of 25.2 °C were recorded in a group of 20 terraced apartments built to the Passivhaus standard (Ruud and Lundin, 2004). Significant variability was recorded in the internal temperatures between apartments with some recording acceptable conditions and others reaching internal temperatures of up to 30 °C in summer. Further Post Occupancy surveys carried out in the Oxtorget, Glumslöv and Frillesås districts of Sweden also reported thermal discomfort due to overheating. In the worst case, 56% of the Passivhaus residents in the Glumslöv district reported their indoor temperature as too warm during the summer period (Samuelson and Lüddeckens, 2009).

By examining the performance of Passivhaus dwellings in climatic zones that are already warmer than the present day UK climate, it might be possible to infer the likely impacts of future climatic change. However, few studies have investigated the performance of dwellings built to a full Northern European Passivhaus specification in a Southern European context (primarily, because they are seldom built to the same specification). As part of the Passive-On project, Schnieders (2005) set out to determine the optimal performance characteristics of a cost efficient model of a Passivhaus dwelling located in Marseille. In this study Schnieders used a DSP model (Dynbil) to simulate the performance of an end-terrace Passivhaus, based upon a design previously used in the Hannover-Kronsberg development (Feist et al, 2005) . Four variants of the 'First Guess' Passivhaus were modelled to assess performance differences between the use of a well-insulated fabric U values (≤ 0.15 W/m^{2}K) with a less well insulated alternative U values (circa 0.25 W/m^{2}K). The buildings were modelled with both double (U value 1.19 W/m^{2}K, g value 0.64) and triple glazing (U value 0.71 W/m^{2}K, g value 0.5) options, with and without heat recovery ventilation (μ_{HR} =0.75) using a typical weather year (ASHRAE, 2001) for Marseille. The maximum temperature in this weather year is 34 °C with a summer monthly average of around 25 °C (Schnieders, 2005). The findings of this study are interesting because they show that over the year the dwelling with the lowest annual heating demand resulted from the *least* insulated fabric (U values ≈ 0.25 W/m^{2}K) and in conjunction with double-glazing (U value 1.19 W/m^{2}K, g value 0.64) and no heat recovery system. In terms of overheating mitigation all dwellings were modelled with night purge ventilation and automated external blinds. Despite these interventions the goal of not exceeding the overheating threshold, defined by the PHI as 25 °C for 10% of the year (Feist et al., 2012) was not be met in any of the prototypes. Furthermore, without active cooling, maximum temperatures exceeding 27 °C were recorded in bedrooms. However when cooling was applied to maintain the supply air temperature below 25 °C, the well-insulated triple glazed variant with Heat Recovery ventilation recorded a slightly lower cooling demand than the other variants (Schnieders, 2005).

In a larger study Schnieders (2009) used different thermal specifications, and cooling strategies to examine the feasibility of the Passivhaus concept in twelve different reference locations across Southern Germany, Italy, Southern France and the Iberian Peninsula. Schnieders concludes that the Passivhaus concept is able to provide a comfortable indoor climate, in accordance with EN/ISO 7730 (2006) in all twelve locations exclusively by pre-conditioning (i.e. active cooling of) the supply airflow. Schnieders points out that (in summer) solar control; via external shading, reduction of solar load through opaque elements and minimising internal heat loads are decisive characteristics in maintaining thermal comfort. Night purge ventilation and to a lesser extent ground coupling were considered critical factors in removing heat from the building, with supply air cooling providing the remaining cooling and dehumidification requirement. Carrilho da Graçฺa et al (2012) came to similar conclusions in a comparative study of two Net Zero Energy Home (NZEH) prototypes in a Southern European context (Lisbon). Comparing a conventional highly glazed NZEH (using internal shading) with an almost identical moderately glazed Passivhaus (using external shading) Carrilho da Graçฺa et al (2012) found that the highly glazed house had substantially higher overheating risks, with living room temperatures exceeding 28 °C for more than 46% of the summer season. In contrast, the externally shaded Passivhaus rarely exceeded this threshold.

In addition to the heating and cooling demands being lower than for conventional dwellings Schnieders (2009) found that the peak heating and cooling loads where also less pronounced and internal temperature fluctuations were lower regardless of whether active cooling was applied. From a design perspective, Schnieders cautioned, “it is important to note that the differences in climates and the effects of individual building parameters are so large that a dedicated energy balance must be set up for every Passive House. The use of standard values for different buildings is not appropriate” (Schnieders, 2009, p279). These findings highlight the parametric sensitivity of Passivhaus and ultra-low energy buildings, reinforcing the need to study these issues in context.

Evidence suggests that the overheating risks in Passivhaus dwellings are highly dependent on context, and are strongly influenced by both user behaviour; including ventilation patterns, shading strategies and internal gains (Larsen and Jensen, 2011; Wagner and Mauthner, 2008a; Wagner and Mauthner, 2008b) as well as the building’s thermal specification (Schnieders, 2005; Schnieders, 2009). Notably in almost every case external shading was required to maintain summer thermal comfort. Schnieders DSP modelling in a South West European context was predicated upon automated external shutters closing whenever the ambient temperature exceeded 23 °C (Schnieders, 2009, p268). Relatively little is known about the acceptability of such strategies to domestic occupants. A number of authors (Raja et al., 2001; Nicol, 2001; Inkarojit, 2005; Voss et al., 2005) have suggested that the operation of blinds is determined primarily by visual comfort requirements and not by indoor temperature; however, all of these studies have assessed non-residential buildings. To date full external shading devices have been seldom used in UK residential buildings. A recent post occupancy evaluation of the Welsh, Larch and Lime, Passivhaus dwellings supports the finding that occupant use of external shading devices is driven by visual and psychological comfort criteria and not temperature regulation (Bere Architects, 2012).

4.1.2 A CHANGING CLIMATE AND ITS IMPACT ON BUILDINGS

Observed climatic trends for the UK show that, between 1961 and 2006, maximum summer temperatures across the South East had increased by 2 °C on average and in Greater London by up to 2.7 °C (Jenkins et al., 2007). According to the United Kingdom Climate Projections (UKCP09) even under a Medium emissions scenario by 2080 the summer average temperature (at the 50th percentile) is estimated at 5.4 °C higher than the 1961–1990 baseline (2.2 to 9.5 °C, 10th–90th percentile) in parts of southern England. Summer mean cloud cover is also predicted to decrease over this period by up to -18% (-33 to -2%, 10th–90th percentile) in parts of southern England and Wales, resulting in an extra +16 W/m^2 (-2 to +37 W/m^2, 10th–90th percentile) flux in downward shortwave radiation (Jenkins et al., 2010). These figures suggest that by 2080, during the summer months, some areas of the southern UK could receive up to 10% more shortwave radiation.

Along with the overall warming trend and higher irradiation levels suggested by these probabilistic estimates, the frequency of extreme weather events including heat waves is also predicted to increase. According to the UK Office of National Statistics during a ten-day period in August 2003 more than 2000 excess mortalities occurred in England and Wales as a result of a heat wave (ONS, 2003). Persons over 75 years of age, in London, were the most severely affected group during this period with an excess mortality rate 59% higher than reference levels (Johnson et al., 2005). Although the term ‘heat wave’ does not have a generally accepted definition in the UK, one study proposed a working definition as “a continuous set of days when the average temperature was above 20 °C” (Hajat et al., 2002). Hajet et al (2002) proposed a more precise definition based on the three-day rolling average value (at the 97th percentile value) exceeding 21.5 °C. Whilst the UK Health Protection Agency have defined a heat wave as a period when daily mean temperatures on the current day, and at least the previous two days are above the 98th percentile of the whole year temperature distribution (Vardoulakis and Heaviside, 2012). According to this definition, a present day heat-wave in London would correspond to daily mean temperatures of 22.6 °C or higher occurring for three of more days.

During the 2003 heat wave, maximum daily Central England Temperature (CET) exceeded the baseline (1971-2000) reference values by 8 °C. In London a daily maximum of 37.9 °C was recorded with overnight lows as high as 26–27 °C in some areas (Johnson et al., 2005). In a monitored study carried out during this heat wave Wright et al (2005) compared internal temperatures in four blocks of London flats and one semi-detached dwelling. They found that average internal temperatures were above 27 °C in every room in all of the dwellings throughout the weeklong monitoring period. In one block of flats, the mean internal temperature was recorded as 29.9 °C during this period (peaking at 39.2 °C).

Although the occurrence of 'heat wave' events is currently infrequent, Met Office predictions suggests that by the 2080's daytime summer temperatures might exceed 42 °C in lowland England as often as once a decade, under a 'High' emissions scenario (Wright et al., 2005). As a consequence it is likely that previous maximum temperature records will be more frequently exceeded in a changing climate (Rahmstorf and Coumou, 2011). Met Office analysis (Jones et al., 2008) indicates that by 2040 the heat wave of 2003 could reflect average summer conditions. By 2060 this same event would represent a cooler than average summer under a Medium-high (A2) emissions scenario (Figure 25).

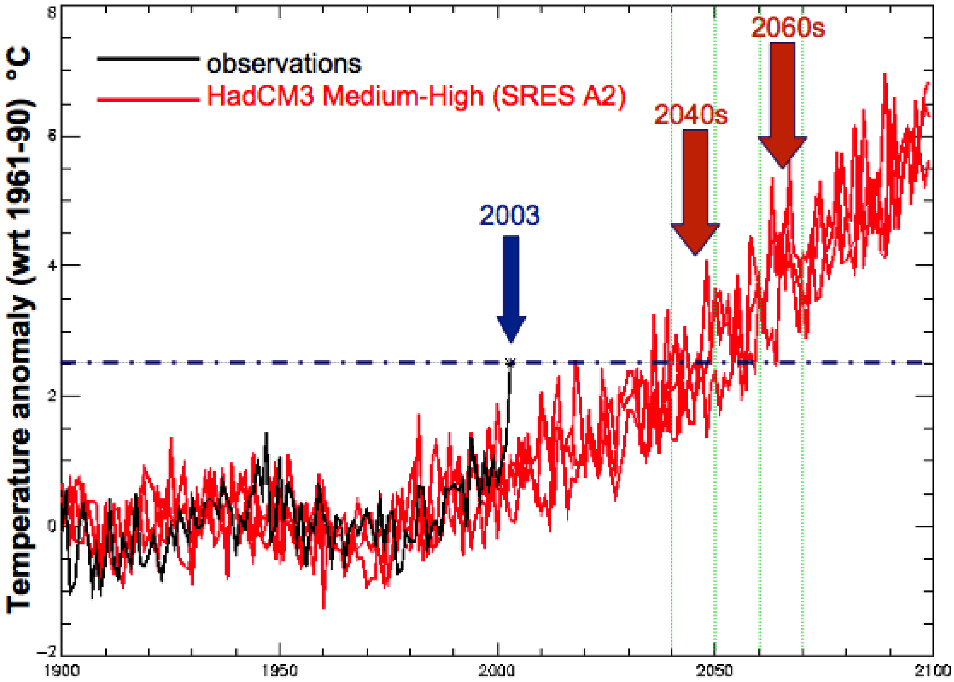


Figure 25 Temperature anomaly of 2003 heat wave in relation to a Medium-High emission trend (Met. Office, Crown copyright)

In a future characterised by significantly warmer summer temperatures and an increase in extreme climatic events (Jenkins et al., 2010; Wilby, 2003) active cooling may become necessary to maintain thermal comfort and even to safeguard life (Ostro et al., 2010). The use of domestic air conditioning in the UK is estimated to be rising by 8% per year (Littlefair, 2005), a phenomenon which could result in an additional six million tonnes of CO_2 emissions by 2020 (Rodrigues et al., 2013). Unless they are extensively subsidised, the ownership of cooling systems is likely to reflect socioeconomic inequalities. O'Neill et al (2005) noted that the prevalence of central air-conditioning amongst black households, in four US cities, was less than half that of white households; resulting in greater vulnerability to heat related mortality. Ownership of an air conditioning system does not guarantee immunity from heat related health affects however, since major power blackouts have historically occurred during periods of high heat stress (Ostro et al., 2010). In light of these risks the UK Health Protection Agency have suggested that "Passive cooling options (building orientation, shading, thermal insulation, choice of construction materials, etc.) implemented at the design stage of urban developments may be equally effective as active cooling in reducing the health burden of heat and would be environmentally sustainable options" (Vardoulakis and Heaviside, 2012, p47).

The precise point at which overheating occurs and active cooling is required is central to the assessment of risk, and yet there is no precise or accepted definition of overheating in the UK (NHBC, 2012a, p7). To date much of the building performance literature has been concerned with the contiguous issue of thermal comfort; whilst the thresholds at which overheating contributes to elevated health risks have been largely ignored. How thermal comfort and overheating risks are defined will strongly influence the outcome of any overheating investigation and these issues are addressed in the Methodology (Section 4.2). The question of whether the Passivhaus concept can delay the onset of overheating and is inherently less vulnerable to heat related risks (in comparison to a conventional dwelling) is highly relevant to adaptation planning, as well as wider mitigation strategies. Faced with a contiguous increase in both economic and social risk factors, including de-rated electricity supply margins (DECC, 2011; Ofgem, 2012) and an aging population (ONS, 2012); this question is likely to become increasingly relevant.

4.1.3 THERMAL COMFORT AND HEAT RELATED IMPACTS ON HUMAN HEALTH

From the perspective of evaluating thermal comfort in relation to overheating, an overheating metric and comfort range are typically defined. The two most widely adopted thermal comfort models are the Heat Balance model, found in EN 7730 (2006) as developed by Fanger (1970), and the Adaptive model, found in ASHRAE 55 (2004) and EN 15251 (2007) as presented in the work of de Dear et al (1997), Nicol et al (1999) and Humphreys and Nicol (2002). Berglund (1978) provides an overview of some of the main mathematical models used for predicting thermal comfort.

From a practical perspective Nicol et al (2009, p355) acknowledge that where, "the adaptive criteria is determined by both the building category and the mean external dry bulb temperature for a number of previous days, then the measurement and ultimate determination of overheating becomes more complex." Many building performance studies have used consistent indices of thermal comfort in preference to running means (Schnieders, 2009; Rodrigues et al., 2013; Coley et al., 2012; Lomas and Giridharan, 2012) although many of these authors also acknowledge that there is likely to be a difference between current and future thermal comfort thresholds. In the UK, CIBSE Guide A (2006) states that (in warm summer conditions) 25 °C is an acceptable operative temperature[xxvi] (OT) in the living area of dwellings and 23 °C is acceptable for bedrooms. CIBSE Guide A (2006) defines 'overheating' as occurring when the OT exceeds 28 °C for more than 1% of the annual occupied hours in the living areas of (free running) dwellings or when the bedroom OT exceeds 26 °C for more than 1% of the annual occupied hours (unless ceiling fans are available). This assessment is based on a warmer than average summer, using a DSY dataset. It should be noted that CIBSE TM 36 recommends a slightly lower limit (of 25 °C) should be regarded as the upper limit of acceptability for the temperature of sleeping areas (CIBSE, 2005a) citing evidence from Thomas et al (1998).

CIBSE Guide A (2006) also offers an adaptive method of assessing the acceptable OT using an exponentially weighted running mean of the daily mean ambient air temperature (T_{rm})

[xxvi] Operative temperature (OT), also referred to as dry resultant temperature (DRT), is a commonly used room temperature index combining air temperature, radiant surface temperature and air movement. When air movement is low OT can be derived from the formula $OT= 0.5T_r + 0.5T_{ai}$ where T_r is the mean radiant temperature at the centre of the room and T_{ai} is the average internal air temperature (McMullan, p68, 2002). In practice OT's are measured using a globe thermometer as described in Appendix 1.A2, CIBSE Guide A (2006).

at a rate of 0.33 K per K. The upper and lower comfort bounds are 4 K apart and the prediction is valid in the T_{rm} range of 8–25 °C. EN 15251 (2007) uses a very similar approach to the CIBSE method (although the standard is applicable for T_{rm} up to 30 °C) and defines two categories of thermal comfort. Cat 1 is applicable for spaces inhabited by very sensitive and fragile persons, including the sick, very young and elderly and uses a 4 K upper and lower comfort range (identical to the CIBSE method). Whilst Cat 2 is applicable to normal levels of expectation and is considered appropriate for new buildings and renovations, spanning a 6 K comfort range.

In terms of the upper limit of acceptable internal temperature the CIBSE living area thresholds tend to be higher than those given in EN ISO 7730 (2006) where Category A allows a maximum temperature of 25.5 °C, whilst category B allows 26°C (at a relative humidity of 60%). These comfort categories are further defined in relation to maximum fluctuations in the OT, whereby a Predicted Percentage Dissatisfied (PPD) of <6% is required for Category A and <10% for Category B. The overheating threshold used in the Passive House Planning Package (PHPP) (Feist et al., 2012) originated from the German DIN 1946-2 (1994) upper limit of 25 °C. Based on this threshold Rouvel (1997) established the criterion for active space cooling as occurring when the 25 °C limit was exceeded for more than 10% of the period of annual usage. For a Passivhaus dwelling this is interpreted as being 10% of the year, since continual occupancy is assumed (Feist et al., 2012). In the context of energy efficient office buildings, post occupancy research by Voss et al. (2005) suggests that the acceptable duration of overheating above 25 °C should be reduced to 5% or less. Contrary to Voss et al.'s recommendation however the recent DIN 4108-2 (2013) incorporated a more adaptive approach, defining a series of three limiting temperatures (25, 26 and 27 °C) that cannot be exceeded for more than 10% of the occupied period depending on the monthly ambient temperature of the region (below 16.5 °C, below 18 °C and above 18 °C respectively). Deutscher (2000) argues that this slackening of overheating limits in the German standards is attributable to the fact that the original targets were too difficult to implement in some German regions without necessitating the use of external shading devices.

Irrespective of whether a deterministic or adaptive approach is used, the criteria which currently define 'overheating' in dwellings have largely evolved from occupant studies of thermal comfort; many of which were carried out in offices and commercial buildings. As a result 'overheating' has been defined as occurring at a point, or range, above which occupants experience discomfort. Dengel and Swainson (NHBC, 2012) suggest a counterproposal to this approach is needed, stating that by definition the existing approach is not based on occupant health but is grounded in the concept of 'thermal preference'. Dengel and Swainson's view is supported by the World Health Organisation (WHO) guidance for air temperatures in dwellings (WHO, 1987; WHO, 1990) which is aimed at protecting health, particularly that of those vulnerable to extremes of temperature, and not at sensations of satisfaction with the ambient temperature (Ormandy and Ezratty, 2012). WHO research, suggests that there is minimal risk to the health of sedentary people, including the elderly, in dwellings where the ambient temperature is between 18–24°C (WHO, 1990). In support of this approach there is a body of evidence which suggests that the elderly may report feeling comfortable at temperatures which are not, in fact, healthy for them (Watts, 1971; Collins and Hoinville, 1980; Ezratty et al., 2009).

In order to evaluate health and safety risks originating from deficiencies in dwellings the UK Government introduced the Housing Health and Safety Rating System (HHSRS) in 2005 (ODPM, 2006). Since the HHSRS replaced The Housing Fitness Standard contained in section 604 of the 1985 Housing Act (as amended by the schedule 9 to the 1989 Local Government and Housing Act) judgements regarding the lack of safety defined under the HHSRS are enforceable under this Act (Wilson, 2008). Accordingly, the health effects of 'excess heat' have a statutory definition in the HHSRS, which states that, "High temperatures can increase cardiovascular strain and trauma, and where the temperatures exceed 25 °C, mortality increases and there is an increase in strokes. Dehydration is a problem primarily for the elderly and the very young" (ODPM, 2006, p60).

In a mortality assessment of England &Wales Armstrong et al. (Armstrong et al., 2010) established a heat threshold, by statistical model fit, broadly occurring at the 93rd percentile of the all-year daily maximum ambient temperature distribution within any given region. Similar research carried out by the UK Health Agency has shown that the daily mean temperature (rather than maximum temperature) can equally be used at the 93rd percentile as a threshold above which an elevated risk of heat related mortality occurs. In the present day case of London this would correspond to a mean ambient temperature of 19.6 °C (Vardoulakis and Heaviside, 2012). Whilst regional ambient temperature thresholds and air pollution levels are widely used for epidemiological predictions (Vardoulakis and Heaviside, 2012; Greenberg et al., 1983; NRC, 1991; CDC, 1995; Wainwright et al., 1999), the corresponding building OT and Indoor Air Quality (IAQ) risk thresholds are rarely documented.

Research by Bouchama and Knochel (2002) established that it is the heat stress experienced across day and night that determines the risk of heat related mortality. An improved understanding of the relationship between OT thresholds and exposure periods in relation to morbidity and mortality data is therefore of critical importance to adaptive building design and heat risk prevention strategies.

Basu and Samet (2002a) proposed that the micro-environmental model, widely used in assessing individual exposure to atmospheric pollutants, (NRC, 1991) could be extended to create a micro-environmental time weighted exposure model for the assessment of heat related exposure. Their initial fieldwork in Baltimore, USA established the validity of this approach; whilst also pointing to the need for larger population studies in multiple geographic regions together with a better understanding of effect modifiers (sex, age, body mass, air conditioning use, and other behavioural adaptations) (Basu and Samet, 2002b).

To date little work has been carried out in the UK context to establish a robust correlation between OT thresholds and morbidity rates in dwellings, although CIBSE Guide A notes that sleep may be impaired above 24 °C (CIBSE, 2006). Increased sleep fragmentation has been directly linked to poor health and reduced work place productivity (Buysee et al., 2010) as well as directly impairing the ability to recover from daytime heat stress (Kovats and Hajat, 2008). Changes in skin temperature of as little as 1 K are known to impair the quality of sleep, notably in the elderly (Aries and Bluyssen, 2009; Raymann et al., 2008). In light of these findings the OT's of bedrooms should play an important role in the assessment of overheating risk.

Heat exposure alone is not the sole parameter governing heat related mortality. Johnson et al (2003) note that excess mortality in England and Wales was significantly higher during the 2003 heat wave than the 1976 heat wave (16% compared to 10%) despite the temperatures being broadly similar; a situation which they postulate may be attributed to an ageing UK population. The fact that the elderly (over 75 years of age) are more vulnerable to heat related mortality has been documented in both the UK (Rooney et al., 1998) and elsewhere (Cassadou et al., 2004; Na et al., 2013). Alongside this Rooney et al (1998) and Stedman (2004) have documented that elevated ground level ozone (O_3), PM_{10} (particulate matter <10 μm in diameter) and Nitrogen dioxide (NO_2) played a contributory role in the localised incidence of mortality during the 1995 and 2003 UK heat waves. Despite the relevance of these findings to the urban context a detailed evaluation of these concomitant factors is beyond the scope of this thesis.

4.2 METHODOLOGY

The research presented here expands on chapter 3 by investigating the likely future performance of UK dwellings built to the Passivhaus standard under a series of future probabilistic climatic scenarios.

In the first stage a DSP was used to model a range of individual interventions in order to understand the general evolution of the Passivhaus and FEES dwellings faced with increasingly severe climate change scenarios. In the second stage of the research a Global Sensitivity Analysis technique was introduced in order to examine which design factors, within the designers influence, have the most pronounced impact on the buildings future performance.

Three different variants of a typical Passivhaus dwelling were modelled in order to account for the influence of thermal mass. An additional control model was used throughout the study in order to show the comparative performance between the Passivhaus concept and a similar dwelling built to comply with the proposed Fabric Energy Efficiency Standard (FEES) (ZCH, 2008).

Although extremes of hot weather are likely to become much more common in the future (Jenkins et al., 2007; Jones et al., 2008), climate models predict that extreme cold weather events are still likely to occur even under 21st century warming scenarios (Kodra et al., 2011). In accordance with this finding, the impacts on both overheating and heating parameters were evaluated; in order to assess whether design interventions that may have influenced one parameter positively, had done so at the expense of another.

4.2.1 Simulation Setup and Parameterization

4.2.1.1 Dwelling – Location and Typology

A 5 x 5km grid square centred on Islington, UKCP cell reference 5350185 (DEFRA, 2009) was chosen as the context for this study, in order to include some of the additional affects induced by the UHI within an urban location (see Section 4.2.3.1 for more information).

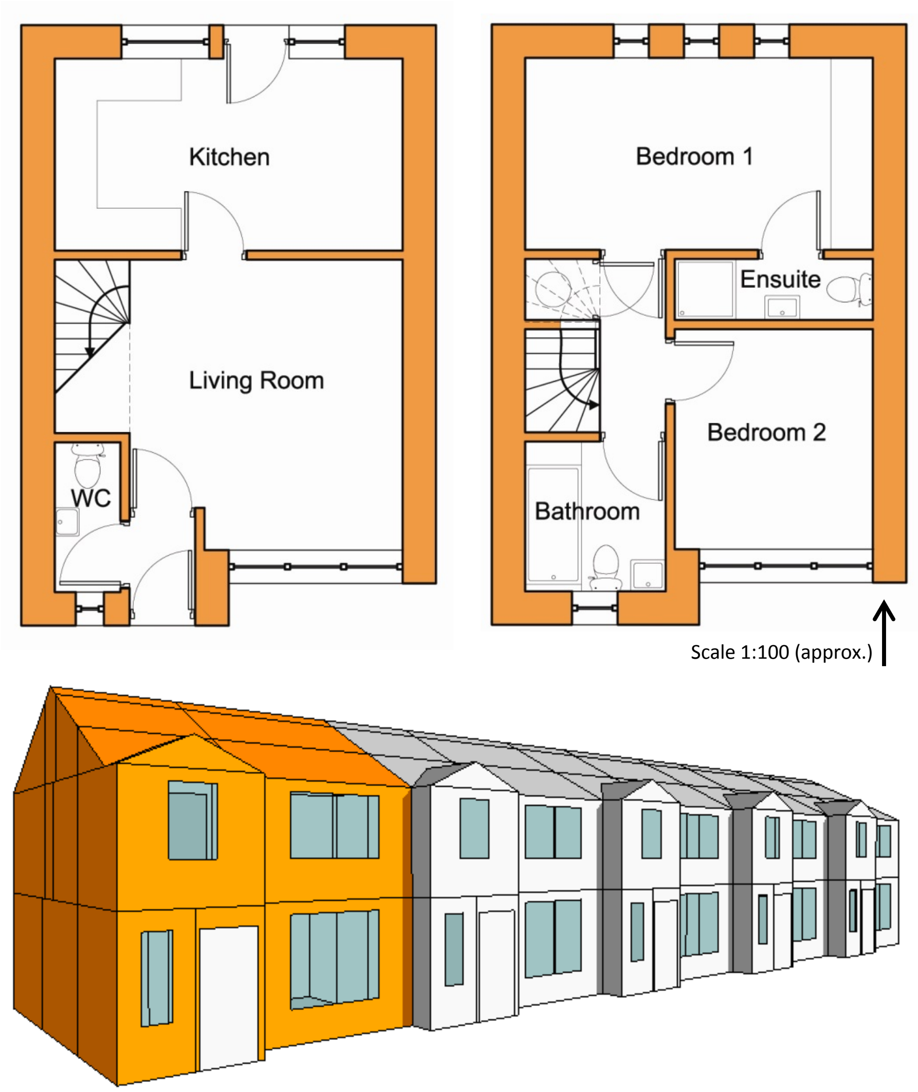


Figure 26 Floor plans and IES model view showing end terrace dwelling (South elevation)

A two bedroom end of terrace dwelling with a gross internal floor area of 70m^2 was used as representative format for this study. A dwelling at the western end of the terrace row (Figure 26) was chosen, consistent with similar studies (Ford et al., 2007; Schnieders, 2009) based on the logic that this unit is most exposed to the influence of solar irradiation during the afternoon when the sun is in the western hemisphere and ambient temperatures peak.

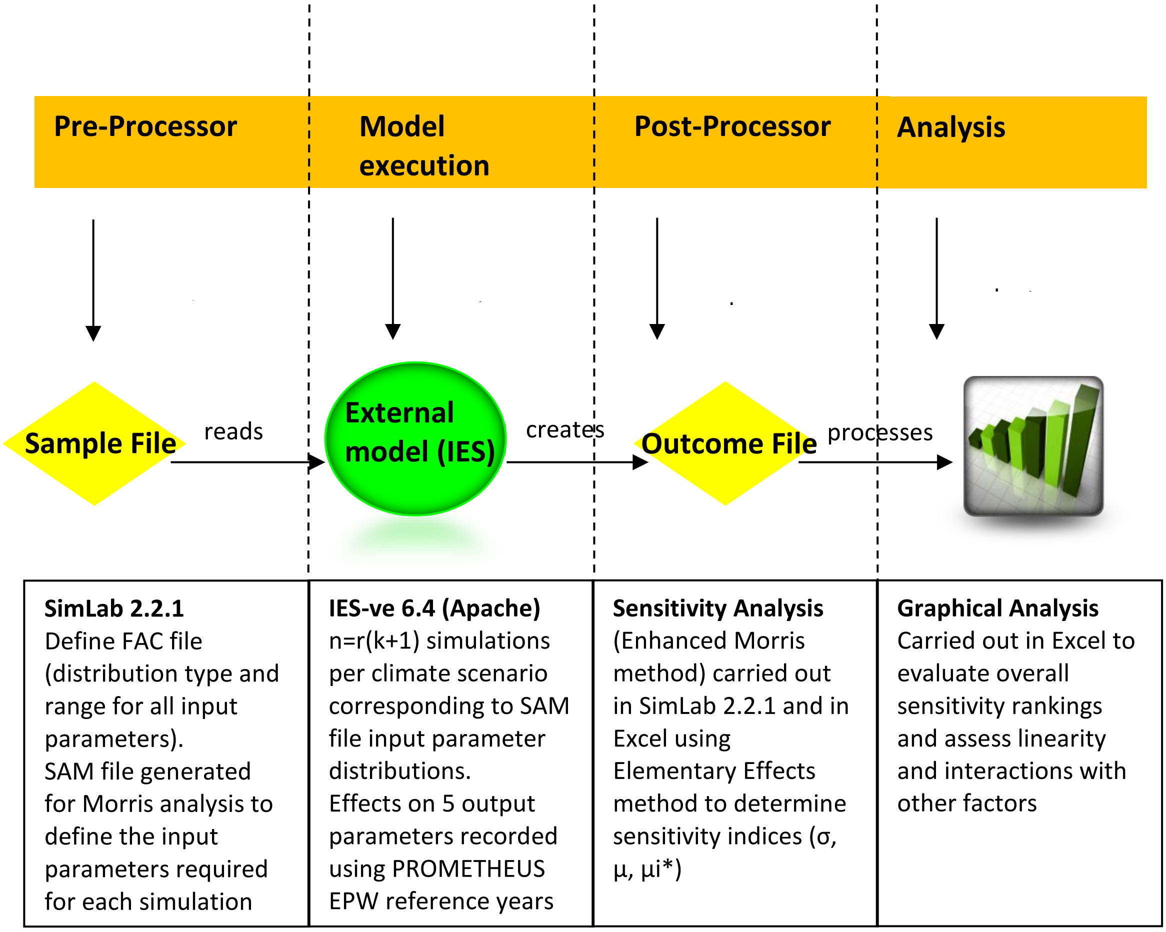
Dwelling typology has been shown to have a significant effect on both heating demand and overheating risks. In comparison to detached dwellings, compact dwelling formats (with reduced external surface areas) are likely to have lower transmission heat losses in winter but conversely may be prone to greater summer overheating risks as a result of reduced external heat exchange surfaces and fewer ventilation openings. Research investigating future overheating in the UK Housing stock by Gupta and Gregg (2012) demonstrated that purpose built flats and mid-terraced houses were at significantly greater risk of overheating in future climatic scenarios than semi-detached or detached dwellings. Porritt et al. (2012) also showed that dwelling orientation plays a decisive role in determining the magnitude of overheating risks, with end of terrace dwellings having less risk of overheating than mid-terrace dwellings when facing West but conversely greater risk of overheating for North, South and East orientations.

The dwellings were orientated to face south, as this is consistent with optimal Passivhaus design in the Northern hemisphere, since it allows the greatest utilisation of passive solar gains during the winter heating season (Feist et al., 2012). The dwellings were assumed to be positioned on a horizontal plane without topographical shading (Figure 26).

Whilst this arrangement is considered to be optimal from a passive solar design perspective, it is acknowledged that a large number of site specific constraints (including shading obstructions, density requirements and access issues) are likely to have a significant influence on the performance of dwellings built in an urban context. For these reasons the findings of this study should be viewed as a comparative analysis of a series of theoretical future scenarios rather than a context specific deterministic study.

4.2.1.2 SIMULATION SOFTWARE

The IES-ve (2012) v6.4 Apache software was used for the dynamic simulations in this study. Apache was developed in the early 1990's and is a widely used DSP both in the UK and internationally. Apache has an extensive validation history which was documented using the CIBSE Applications Manual AM 11 (1998) Appendix B protocol (CIBSE, 1998) by McLean in 2006 (IES, 2009). The software performed well in independent Building Energy Simulation Test (BESTEST) (Judkoff and Neymark, 1995) benchmarking assessment carried out by the BRE (IES, 2009) and has been subject to extensive Empirical testing by Lomas et al. (1994) and Gough and Rees (2004). Apache uses a finite difference discretization scheme known as 'hopscotch' whereby explicit and implicit time stepping is applied to alternate nodes in the construction; this approach is thought to provide both accurate and efficient computation (Struck, 2012).



SimLab 2.2.1 Define FAC file (distribution type and range for all input parameters). SAM file generated for Morris analysis to define the input parameters required for each simulation	**IES-ve 6.4 (Apache)** n=r(k+1) simulations per climate scenario corresponding to SAM file input parameter distributions. Effects on 5 output parameters recorded using PROMETHEUS EPW reference years	**Sensitivity Analysis** (Enhanced Morris method) carried out in SimLab 2.2.1 and in Excel using Elementary Effects method to determine sensitivity indices (σ, μ, μi*)	**Graphical Analysis** Carried out in Excel to evaluate overall sensitivity rankings and assess linearity and interactions with other factors

Figure 27 Simulation and analysis procedure

4.2.1.3 Dwelling Specification- Thermal Characteristics, Glazing ratios, Ventilation

Whilst a number of previous studies have addressed the role of thermal mass in relation to overheating risks in UK dwellings (ARUP, 2005; EST, 2005a; EST, 2005b; Hacker et al, 2008; Orme and Palmer, 2003; Rodrigues et al., 2013; Rodrigues, 2009; Rodrigues and Gillot, 2011), none of these studies has investigated the influence of thermal mass in the context of Passivhaus dwellings. In order to evaluate the role thermal mass might play in Passivhaus dwellings in a future UK climatic context three different construction types (light, medium and heavyweight) were selected as representative of a range of UK Passivhaus constructions (Table 5). In order to provide a control study, for comparative analysis, a naturally ventilated FEES compliant dwelling was modelled in a traditional heavyweight construction format (Table 5), in accordance with the FEES specification (ZCH, 2009). The effects of linear thermal bridging were incorporated into the FEES DSP model by adding a y value adjustment factor of 0.05 W/m^{2}K to the opaque U values (ZCH, 2009).

Internal volumes, glazing ratios, external emissivity and solar absorptance coefficients remained consistent between all four dwelling models. In addition to the above criteria, the Passivhaus dwellings were modelled using a common ground floor construction (pre-insulated raft slab) as well as identical: fabric U-values, glazed U-values, g-values, infiltration and ventilation rates (Table 5). All Passivhaus dwellings were assumed to be 'thermally bridge free' in keeping with the criteria set out in the Passive House Planning Package (Feist et al., 2012, p109).

Table 5 Principal performance characteristics of 4 dwelling types (3 complying with the Passivhaus standard and 1 with the FEES Standard)

MODEL CHARACTERISTICS	DWELLING TYPE			
	FEES HEAVY	**PH HEAVY**	**PH MEDIUM**	**PH LIGHT**
Construction type	Cavity wall wet plastered	Full-fill cavity wet plastered	TGI stud double lined	SIPS panel dry lined
U- value walls [W/(m^{2}K)]	0.23Ɨ	0.14	0.14	0.14
U- value roof [W/(m^{2}K)]	0.18Ɨ	0.10	0.10	0.10
U- value ground floor [W/(m^{2}K)]	0.23Ɨ	0.10	0.10	0.10
Thickness walls [m]	0.3569	0.4860	0.3222	0.2383
Thickness roof [m]	0.2545	0.4262	0.4823	0.3882
Thickness ground floor [m]	0.224	0.511	0.511	0.511
Total heat capacity walls [kJ/(m^{2}K)]	293.4	341.6	95.3	65.5
Uninsulated heat capacity walls [kJ/(m^{2}K)]	153.6	154.7	48.2	15.8
Total heat capacity roof [kJ/(m^{2}K)]	60.4	100.7	92.7	72.8
Uninsulated heat capacity roof [kJ/(m^{2}K)]	15.8	15.8	15.8	15.8
Total heat capacity ground floor [kJ/(m^{2}K)]	240.84	511.1	511.1	511.1
Uninsulated heat capacity ground floor [kJ/(m^{2}K)]	37.2	501.2	501.2	501.2
Total heat capacity internal walls [kJ/(m^{2}K)]*	157.2	157.2	81.7	31.7
Total heat capacity internal floor [kJ/(m^{2}K)]	185.84	185.84	91.43	31.4
U_w value whole window [W/(m^{2}K)]	1.4	0.7942	0.7942	0.7942
U_g value glass [W/(m^{2}K)]	1.4053	0.8017	0.8017	0.8017
g value [EN 410]	0.721	0.618	0.618	0.618
Infiltration [effective ac/h]	0.152	0.035	0.035	0.035
Efficiency of MVHR Unit [-]	-	85%	85%	85%
Mechanical supply air flow rate	-	30m^3/pp.h	30m^3/pp.h	30m^3/pp.h
Natural vent strategy	see profile	see profile	see profile	see profile
Psi value or y-value incorporated	Y value incl.	bridge free	bridge free	bridge free
Ground coupling integrated	via EPW	via EPW	via EPW	via EPW
Cooling coil used	see scenario	see scenario	see scenario	see scenario
Humidity control for cooling	see scenario	see scenario	see scenario	see scenario

Ɨ Includes y value adjustment of 0.05W/(m^{2}K) (ZCH, 2009) * assumes internal walls have two exposed sides

According to CIBSE Guide B in the UK a CO_2 level of 800 -1000 ppm (equating to a fresh air ventilation rate of approximately 8 l/s per person) is widely used as an indication that the ventilation rate in a building is adequate (CIBSE, 2005b, p15). CO_2 is often used as a proxy indicator of Indoor Air Quality (IAQ) in general (Taylor and Morgan, 2011) and concentrations above 5000 ppm CO_2, for more than 8 hours, are considered to represent the upper limit of acceptability in the UK (CIBSE, 2005b).

In both the FEES and Passivhaus dwellings, CO_2 concentrations were used as a proxy indicator of IAQ, with the goal of maintaining an upper threshold ≤1000 ppm above ambient levels. Supply air ventilation in the Passivhaus dwellings was provided via Mechanical Ventilation with Heat Recovery (MVHR) and a summer heat exchanger bypass system was modelled whenever the outside temperature exceeded 20 °C. In contrast the FEES control dwelling utilised natural cross ventilation via ramped window opening profiles to maintain the 'supply air quality' (Table 6). In order to control overheating risks, an identical purge ventilation strategy was used in both the FEES and Passivhaus dwellings in accordance with the 'purge ventilation' profile strategy (Table 6). Maximum window opening angles were limited to 10 degrees in all dwellings in keeping with the use of window restrictors. Such devices are a standard safety feature in new build social housing in the UK in accordance with guidance from the Royal Society for the Prevention of Accidents (RoSPA, 2005).

Table 6 Ventilation profiles according to dwelling type

DWELLING TYPE	VENTILATION REQUIREMENT	VENTILATION PROFILE
FEES model	Indoor air quality	Windows ramp open for ventilation when CO_2 >1000ppm with window opening threshold limited to 10%. If CO_2 >2000ppm then the opening threshold is increased to 50% to maintain air quality. Windows are closed when CO_2 ≤1000ppm or outside air temperature ≤ 5 °C or wind speed is >7 m/s
	Purge ventilation	When the internal temperature >22 °C and the internal temperature is > external temperature the windows open progressively (using ramped profile) with maximum opening of all windows when the internal temperature reaches 26 °C. Window opening restrictors are assumed to limit the maximum opening angle to 10°
PH models	Indoor air quality	If the outside temperature is ≤20 °C then the ventilation air is provided via the heat exchanger operating at 85% efficiency at a constant flow rate of 30 m^3 per person per hour. If the outside temperature is >20 °C the heat exchanger is bypassed and the same flow rate is supplied at the ambient temperature
	Purge ventilation	(As per FEES model)

In order to model the ventilation profile of the FEES and Passivhaus dwellings in accordance with the above guidance two independent window opening profiles were used. In the FEES model, the first ventilation profile was defined by CO_2 concentration and the second by the requirement to 'purge' excess heat. In the Passivhaus model IAQ is maintained by mechanical ventilation via the MVHR unit and additional 'purge' ventilation is modelled as a cooling strategy using the same (restricted) window opening profile as for the FEES model (Table 6).

4.2.2 INTERNAL GAINS AND OCCUPANCY PATTERNS

The occupancy patterns and internal gains profiles used were common amongst all four dwellings.

4.2.2.1 INTERNAL GAINS

The Passive House Planning Package (Feist et al., 2012) uses a default assumption of 2.1 W/m^2 with respect to the effective residential internal heat gains (IHG's). This figure is then rounded upwards to 2.6 W/m^2 (as a safety margin) in the PHPP model for the purpose of assessing summer overheating risk. The derivation of these figures is based upon assessments carried out in German Passivhaus dwellings using a default occupant density of 35 m^2 per person and actual appliance schedules (Feist, 1994). The 'effective' IHG figures used in PHPP account for both the internal heat gains (including occupants) as well as the internal heat losses (e.g. cold water entering cisterns, evaporation) (Feist et al., 2012). A detailed breakdown of this calculation procedure can be found in Schnieders (2009, p75).

For the purpose of this study the standard residential IHG figures of 2.1 W/m^2 used in PHPP (2012) was adjusted using the PHPP 'Internal Gains' worksheet (see Appendix A1) in order to reflect the higher UK social housing occupant densities (and smaller TFA). Using this approach the appliance and services IHG's based on 3 occupants (but excluding the occupant gains) are: 180 W (total) – 132 W (occupant gains) = 48 W (appliance and services gains). Scaling this to the 70 m^2 treated floor area the resulting (appliance and services) specific internal gains are 0.69 W/m^2. Using occupant gains from CIBSE Guide A (CIBSE, 2007) based on three occupants (assuming two adults and a mature child) the total internal sensible heat gains are: 48 W + (3*70 W) = 258 W. Adjusting this to the 70m^2 treated floor area the total specific internal gains are 3.69 W/m^2 (when the dwelling is fully occupied).

In order to assess the sensitivity of the key outputs relative to the internal gains assumptions, in the second part of this study, the influence of low and high IHG figures were assessed. Based on the assumption that the figures currently specified in the PHPP software (Feist et al., 2012) are likely to reflect the use of very energy efficient appliances and moderate electricity consumption profiles the above figure was taken as a the basis for the 'low IHG' profile. Assuming that IHG's could be elevated by a factor of up to 3, in some households (Henderson, 2009; Schnieders, 2009) the 'high IHG' appliance and services gains were estimated as 3 x 48 W, thus the specific (appliance and services gains) would be 144 W/ 70 m^2 = 2.06 W/m^2. Using occupant gains from CIBSE Guide A (2006) based on three occupants (assuming two adults and a mature child) the total internal sensible heat gains are: 144 W + (3*70 W) = 354 W. Scaling this to the 70 m^2 treated floor area the total 'high' (non-occupant related) internal gains are 5.05 W/m^2 (when the dwelling is fully occupied).

4.2.2.2 OCCUPANT DENSITY AND PATTERNS

In order to create a realistic occupancy profiles for the purpose of this study occupant numbers were modelled as a whole number. A larger than average household size based on 3 occupants was chosen in order to err on the side of higher occupant density and internal gains. Occupancy schedules were created to reflect UK household survey statistics (DECC, 2012b). Occupant gains were then assigned to the IES model based on sub-hourly activity data recorded in the UK Time Use Survey (ONS, 2005) with occupant gains data according to activity from CIBSE Guide A (CIBSE, 2007). The weekly occupancy profiles were assigned to the model based on sub-hourly activity profiles created for the 3 occupants. Weekly profiles were created for a 'working adult', a non- working 'houseparent' and a 'student'. Maximum occupancy was assumed at weekends in order to test the influence of higher than average internal heat gains during these periods.

4.2.3 FUTURE CLIMATE DATA AND SCENARIOS

4.2.3.1 FUTURE CLIMATE DATA AND THE URBAN CONTEXT

The UKCP09 grid location 5350185 (DEFRA. 2009), centred on London Islington, has been selected as the reference location for this study. London's urban context is known to create a pronounced micro climate: with one of the consequences being that temperatures are at times significantly higher than surrounding rural areas. Research by Graves et al. (2001) demonstrated that nocturnal ambient temperature peaks for Westminster, London, have occasionally exceeded 7 K (relative to the rural surrounding temperature) during the summer months. The temperature difference between an urban area and its rural surroundings is commonly referred to as the urban heat island (UHI) effect, and is typically most pronounced at night (Kershaw et al., 2010). This localised phenomenon results primarily from the heat generated by human energy production (HEP) being retained in an area of high thermal mass; much of which also has a relatively low albedo, or surface reflectivity (Graves et al., 2001; DEFRA, 2013). One of the main challenges for overheating risk prevention in urban dwellings occurs as a result of the magnitude and the timing of the peak intensity of the UHI, which in inner London locations can occur between 11 pm and 8 am (DEFRA, 2012; Wilby, 2003). The resultant dampening of the diurnal temperature range has implications for the cooling of naturally ventilated buildings, as it compromises the effectiveness of strategies using night-time ‘purge’ ventilation to cool thermal mass. For this reason it is important that any synthesised or predictive weather data used in an urban modelling context accurately reflects the localised influence of the urban micro climate.

Some caution is necessary with respect to the future climatic changes predicted by the UKCP09 scenarios in dense urban areas, since an explicit representation of urban areas was not included in the HadRM3 model (Kershaw et al., 2010). In a large urban conurbation such as Greater London the effects of the existing UHI are captured in the UKCP Weather Generator (WG) model by virtue of the fact that a number of the climate stations used for the interpolation process are situated within the UHI (Kendon, 2012). At the 25 km² resolution of the HadRM3 model the largest urban areas can be seen to exert some influence on the local simulated climate (McCarthy et al., 2009). It follows therefore, that if the UHI effect does not change significantly in the future, it is reasonable to add the UKCP09 climate change projections to the observed baseline (5 km²) urban climate in order to generate future urban climatic predictions at this scale (Kendon, 2012). Conversely if future changes occur in the amount of energy dissipated in cities (e.g. cooling systems become widespread), or if the density of a city changes then these factors could alter the current UHI effect, and projecting future climates in cities will then require additional techniques to be deployed (Kershaw et al., 2010).

In relation to the temporal evolution of the UHI, comparative temperature measurements taken at an inner city location (St. James Park) and a suburban site in Surrey suggest that London’s nocturnal UHI has intensified by approximately 0.5 K since the 1960s (Kendon, 2012), partly as a consequence of increased HEP, denser urbanisation, and the changing frequency of weather patterns. Since the 5 km² baseline data is based on measured data collated over the 1961/1990 period it is likely that only a relatively small component of these evolutionary changes are missing from the UKCP09 projections (McLeod et al., 2012). The main limitation of the UKCP09 WG projections is that the current model does not fully incorporate all of the highly localised effects of the UHI (Kershaw et al., 2010); significant discrepancies may therefore be anticipated when attempting to predict the performance of buildings at a higher resolution than the current 5 km² grid allows.

Generating an improved understanding of the future evolution of localised UHI's is a complex and important area for building simulation, where significant further research is needed. For more information on the implications of the London UHI for micro regional assessments of building performance, refer to McLeod et al. (2012) Kershaw et al. (2010) Graves et al. (2001), Watkins et al. (2002) and Wilby (2003).

4.2.3.2 ASSESSING RISK- EMISSIONS SCENARIOS AND PROBABILITY

In order to represent both a mean weather year and a warmer than average (one in ten) year both the 50th and 90th percentile Test Reference Year (TRY) datasets were used to assess future climate change impacts. An alternative procedure, to assess warmer than average future weather years, would be to use Design Summer Years (DSYs) - which are also available from the PROMETHEUS database (Eames et al., 2012; Coley et al., 2012). DSY years are intended to represent the third warmest summer (April–September period) in a twenty year period (Levermore and Parkinson, 2006), however the statistical basis under-pinning their selection is considered to be unreliable. Coley et al. (2012) remark that some of the current DSY's, generated from observed data, are in fact cooler than the TRY datasets for some UK cities.

The WG is capable of generating probabilistic weather files for each future decade from 2020 to 2080 sampled from any percentile of the Probability Density Function (PDF). Whilst the underlying Met Office grid data for the period 1961- 1990 is used to create a control dataset, reflecting the historical 1970's baseline (Met Office, 2011). In studying the temporal evolution of climate change the UKCP09 data leaves a large gap (50 years) between the historic control period (1970's) and the near future (2020's). In order to fill this gap and to model current day climatic conditions the CIBSE London 2005 TRY and DSY climate files were used in this study.

4.2.4 PERFORMANCE CRITERIA - THERMAL COMFORT AND OVERHEATING THRESHOLDS

In this study the frequency of living area operative temperatures >25 °C (OT_{25}) was assessed in keeping with the Passivhaus assessment criterion (Feist et al., 2012), WHO guidance (WHO, 1990) and the HHSRS assessment criteria (ODPM, 2006). In addition a higher threshold was used to assess the frequency of living area operative temperatures >28 °C (OT_{28}) in accordance with CIBSE Guide A (2007) and CIBSE TM36 (2005). The absolute maximum internal operative temperature (OT_{max}) was also recorded (as an indicator of heat related mortality risk) for comparative purposes (Basu and Samet, 2002b; Hajat et al., 2002; Hales et al., 2000; Larsen 1990; Nakai et al., 1999). Since the impacts of warmer operative temperatures in bedrooms requires special consideration, the frequency of bedroom operative temperatures >26 °C ($BedOT_{26}$) during occupied hours (11pm–7am) was assessed in relation to the CIBSE Guide A threshold (2007) and the Predicted Percentage Dissatisfied (PPD) (EN ISO 7730, 2006). Bedroom overheating risks are considered to be particularly important in relation to performance criteria in an urban context due to the timing of the peak intensity of the UHI (as discussed in section 4.2.3.1)

4.2.5 SENSITIVITY ANALYSIS

For reasons of computational economy, most building simulation studies are based on a limited number of deterministic scenarios. As a result, in some cases, the dependence of performance outcomes upon key input parameters and their possible interactions may remain unknown. Sensitivity Analysis techniques enable designers to understand which input factors have the most important influence on outputs, and the use of Sensitivity Analysis has been extensively documented in relation to building simulation (Burhenne et al., 2010; Hopfe and Hensen, 2011; Struck 2012; Garcia Sanchez et al., 2012).

4.2.5.1 ELEMENTARY EFFECTS METHOD

Morris (1991) developed an efficient screening method for determining which input factors have important direct and indirect effects on an output. Morris' method, also known as the Elementary Effects (EE) method, is considered to be a Global Sensitivity Analysis (GSA) technique because it samples the entire space over which the input factors may vary. The method uses an individually randomised one- factor at- a-time (OAT) sampling method, to assess which parameters are: i) non-influential or negligible ii) linearly influential iii) non-linearly influential (or influential by interaction with other parameters) (Campolongo et al., 2007; Saltelli et al., 2004). The Latin hypercube (LH) sampling technique (McKay et al., 1979) is often used to create the starting points for the OAT sampling. LH divides each factor into *r* stratified intervals of equal probability, which are then sampled OAT.

Morris' method has undergone further enhancement by Campolongo et al. (2005) and has been validated against qualitative variance based methods (such as the method of Sobol') by a number of researchers (Wang et al., 2006; Campolongo et al., 2007; Donatelli et al., 2009; Confalonieri et al., 2010). One of the main advantages of the Morris method is the low sample size required to evaluate the effect of each factor. The number of model executions required is $r(k$+1), where k is the number of factors and r is a predetermined number of sampling intervals. In comparison the widely used Sobol' method requires in the order of 500(k+2) evaluations (Campolongo et al., 2007). As a result the enhanced Morris method is well suited to studies which have either a large number of input factors or require expensive computation.

Mathematically the building simulation model can be represented as the function $y(x)$ where y is the output variable of interest and x is a row vector composed of real input variables with k input coordinates (x_1, x_2, x_3, ... x_k). Each input variable is defined within a given interval ($x_{min} - x_{max}$) and the input variables are then scaled into dimensionless variables in the interval [0, 1], such that $x_i^{'}$ = ($x_i - x_{min} / x_{max} - x_{min}$). The region of interest (Ω) is defined by the domain of the vector x which can be visualised as a k dimensional unit hypercube (H^k) which is composed of *p* discrete grid levels.

A number of different sampling strategies have been proposed in order to optimize the scanning of the input space (Garcia Sanchez et al., 2012; Campolongo et al., 2007; Saltelli et al., 2008). The sampling strategy results in the construction of r different random simulation trajectories in Ω, where each trajectory corresponds to $(k + 1)$ model executions and each sampling point differs from the proceeding point by a single, randomly permutated, coordinate. Thus for a given trajectory r each input parameter (k) changes only once in accordance with a pre-defined step size Δ_i . The relationship between the number of grid levels (p) in the hypercube and the step size between coordinates (Δ) is critical to ensuring an equal probability of sampling at every level of the input space. For this reason Morris (1991) recommended that p be an even number, and that

Δ= p /[2(p_i – 1)] in order that each sampling point x_i has an equal probability of taking on values from {0,1/(p – 1), 2/(p – 2),..., 1}.

If $x^{(l)}$ and $x^{(l+1)}$ are two sampling points in the nth trajectory which differ only in their ith component then the elementary effect (EE_i^n) of the nth trajectory associated with input factor i is:

$$EE_i^n\left(x^{(l)}\right) = \frac{[y(x^{(l+1)})-y(x^{(l)})]}{\Delta_i} \qquad [17]$$

Where the ith component of $x^{(l)}$ is increased by Δ_i (Eq.17), and conversely:

$$EE_i^n\left(x^{(l+1)}\right) = \frac{[y(x^{(l)})-y(x^{(l+1)})]}{\Delta_i} \qquad [18]$$

Where the ith component of $x^{(l)}$ is decreased by Δ_i (Eq.18)

The function $y(x)$ is re-evaluated at every point in the trajectory by running the simulation model, thereby allowing a coefficient of output variation (or EE) to be computed for each input factor i, for i =1,..., k. Once the EEs for each input factor have been determined, sensitivity statistics can be computed relative to the output distributions: The mean μ provides an indication of the overall importance of an input factor, whilst σ (an estimate of the standard deviation) indicates the magnitude of the higher order effects of a factor (i.e. those which are non-linear and/or result from interactions with other factors).

$$\mu_i = \frac{1}{r}\sum_{n=1}^{r} EE_i^n \qquad [19]$$

$$\sigma_i = \sqrt{\frac{1}{(r-1)}\sum_{n=1}^{r}(EE_i^n - \mu_i\,)^2} \qquad [20]$$

Since EEs with a negative sign can occur where input variables have a non-monotonic response on the output (or are involved in interaction effects) Campolongo et al (2007) proposed the use of the mean of the absolute EEs (μ_i^*) (Eq.21) as a more reliable indicator of the overall influence of the factor on the output.

$$\mu_i^* = \frac{1}{r}\sum_{n=1}^{r}|EE_i^n| \qquad [21]$$

Campolongo et al. (2007) demonstrated that μ^* is a good proxy of the total sensitivity index (S_T). According to Saltelli et al. (2008) the use μ^* also solves the problem of type II errors (failure to identify a factor which has considerable influence on the model). In order to evaluate the respective influence of these sensitivity measures Morris (1991) recommended using a graphical representation of σ vs. μ , this approach also helps in the identification of type II errors since factors with EEs of different signs tend to have a low value of μ but a considerably higher value of σ (Saltelli et al., 2008).

4.2.5.2 SENSITIVITY ANALYSIS OF KEY DESIGN INPUTS – 2050 HIGH EMISSION SCENARIO

The purpose of the sensitivity analysis is to investigate the influence of key design inputs upon the performance of the Passivhaus dwellings in a future climatic context. A 2050, 90th percentile year is assessed under a High emissions scenario (Islington 5350185 grid cell) in order to reflect a warmer than average mid-century urban climatic context. It is assumed in this assessment that supply and extract ventilation is provided by a whole house MVHR system operating in summer bypass mode (Table 6). In order to evaluate the influence of key input parameters under a ‘worst case scenario’ it is assumed that natural cross ventilation through openable windows cannot be used to cool the dwellings during the summer months - due to factors associated with the urban context (such as noise, air pollution and crime).

In this study a limited number (k=5) of influential building parameters were selected in order to assess their influence upon a range of critical performance characteristics. The parameters evaluated were chosen to reflect factors which might typically be within the designers influence in this particular context. In practice a larger or smaller set of input parameters may be selected depending on computational resources (e.g. whether the sensitivity analysis can be fully automated) and whether the influence of other parameters (e.g. orientation, solar absorptance coefficients etc.) are considered to be of interest. The range through which the designer is realistically capable of influencing these values (on any given project) defines the minimum and maximum (lower and upper bounds) of the parameters. In practice the bounds of the range are almost always context dependent and are likely to be constrained by a number of issues including: site layout, building regulations, planning policies, structural considerations, cost implications, Passivhaus criteria, the contractor’s expertise etc.

For the purpose of this case study the following input distributions are described, either as discrete values or as uniform (min/max) ranges:

1 Thermal mass (Discrete distribution; based on, lightweight (LW), mediumweight (MW) and heavyweight (HW) mass options – see Table 5).
2 Glazing percentage on south side (Uniform distribution; based on percentage of south facing façade area)
3 External shading device transmission factor (Uniform distribution; based on external shutters shading ratio)
4 Airtightness (Uniform distribution; based on normalised n_{50} value in accordance with EN832, assuming a moderate screening, screening coefficient e=0.07)
5 Internal gains (Discrete distribution; based on the non-occupant related effective internal gains component), see section 4.2.2.1

Table 7 Sensitivity analysis parameters

PARAMETER	DISTRIBUTION TYPE	MIN - MAX (OR DISCRETE VALUES)
1. Thermal mass	Discrete	light, med, high
2. Glazing ratio on south facade	Uniform	10 - 60%
3. External shading transmission factor on south facade	Uniform	0 – 100%
4. Airtightness (ach^{-1})	Uniform	0.0042 – 0.042
5. Internal gains (excl. occupant gains)	Discrete	0.69 W/m^2 (low) 2.06 W/m^2 (high)

It should be noted that some authors (Hopfe and Hensen, 2011; Hu and Augenbroe, 2012; Kim and Augenbroe, 2013; Hopfe et al., 2013) argue that internal gains should not be included as inputs in a sensitivity analysis since they are *a priori* scenario dependent, and therefore cannot be regarded in the same manner as other design related parameters. However since the non-occupant component of the effective IHG's are partially influenced by the appliance and building services specification, this component of the IHG's has been included as an input parameter. In order to evaluate the 'relative' significance of the non-occupant related internal gains, two levels of internal gains (low and high) have been included as discrete distributions in the sensitivity analysis (the derivation of these gains is explained in further detail in Section 4.2.2.1).

4.3 RESULTS AND DISCUSSION

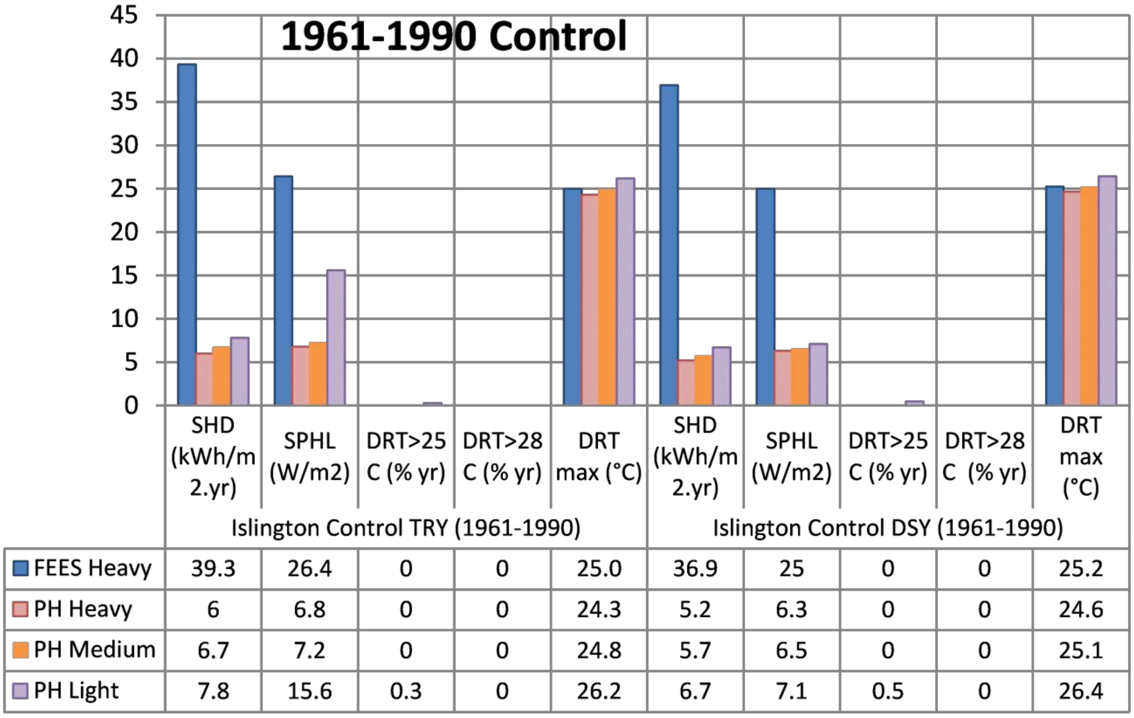
Dynamic thermal simulations were first carried out for a series of base case scenarios in order to establish the overall trend in key performance characteristics between the four dwelling models from the historic (1961-1990) reference period through to 2080, under a High (A1FI) emissions scenario. The purpose assessment was to establish the comparative performance and temporal trends exhibited by the dwellings over a 100 year time period.

The deterministic assessments carried out for the base case scenarios were followed by a sensitivity analysis of the three Passivhaus dwellings for a range of individual interventions (listed in Table 7). The sensitivity analysis was carried out under a 2050 High (A1FI) emissions 90th percentile TRY scenario, in order to determine which design factors would most significantly influence the key performance outputs of the Passivhaus dwellings, at their mid-life stage (under a warmer than average probabilistic climate scenario).

4.3.1 BASE CASE – TRANSITIONAL ASSESSMENT OF 4 DWELLINGS UNDER A HIGH EMISSION SCENARIO (1970 -2080)

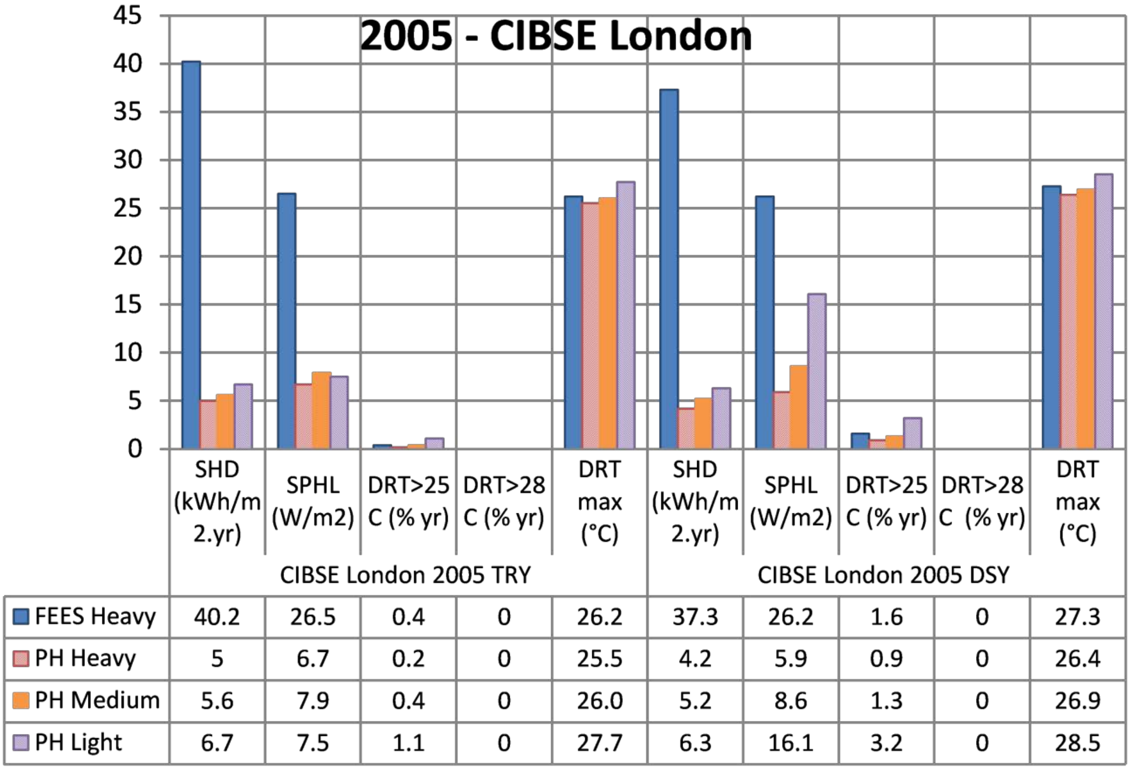
Base case assessments were carried out for the four dwellings with specifications given in Table 5. The purpose of the assessments was firstly to establish whether the models were complying with their respective energy performance standards (FEES and Passivhaus). The base case also provides a comparative indication of the evolution of key performance criteria with respect to time. In order to establish a comparative estimate of performance between a dwelling built to the FEES standard (ZCH, 2009) and dwellings designed to the Passivhaus standard (Feist et al., 2012) identical forms, internal volumes, glazing ratios and purge ventilations strategies (Table 6) were used in all dwellings.

Figure 28 and 29 show that the FEES dwelling is performing in accordance with the limiting SHD criteria, for an end-of-terrace dwelling, of $q_H \leq 46$ kWh/m^2.yr (ZCH, 2009). Similarly all of the Passivhaus dwellings fulfil the SHD criteria of $q_H \leq 15$ kWh/m^2.yr (Feist et al., 2012). The general trends illustrated by Figure 28-Figure 32 shows that SHD will fall significantly in all of the four dwellings under a 'High' (A1FI) scenario, between the historic control period and the 2080's. In the case of the FEES dwellings under a 50th percentile TRY the SHD is predicted to fall by approximately 34%, whilst the Passivhaus dwellings SHD falls by 63% on average.



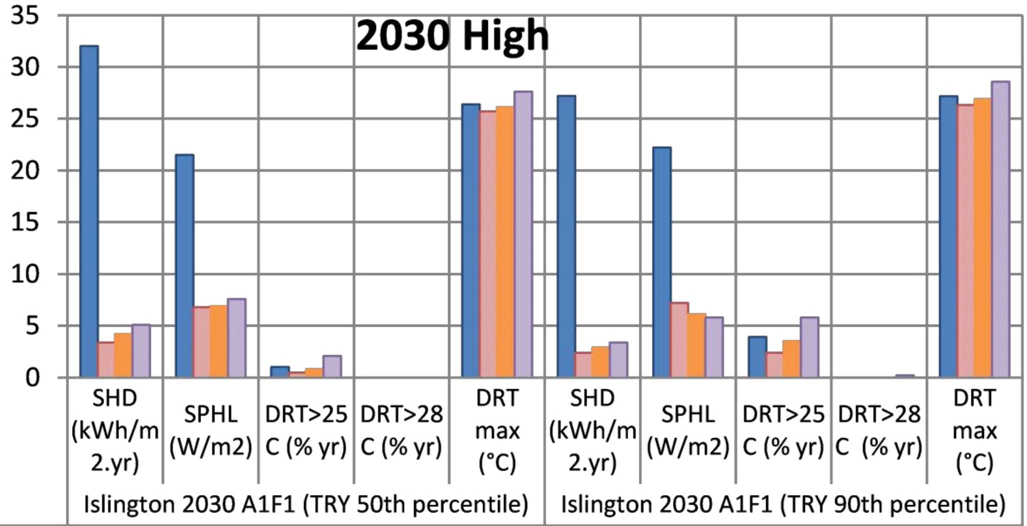
	Islington Control TRY (1961-1990)					Islington Control DSY (1961-1990)				
	SHD (kWh/m2.yr)	SPHL (W/m2)	DRT>25 C (% yr)	DRT>28 C (% yr)	DRT max (°C)	SHD (kWh/m2.yr)	SPHL (W/m2)	DRT>25 C (% yr)	DRT>28 C (% yr)	DRT max (°C)
🟦 FEES Heavy	39.3	26.4	0	0	25.0	36.9	25	0	0	25.2
🟥 PH Heavy	6	6.8	0	0	24.3	5.2	6.3	0	0	24.6
🟧 PH Medium	6.7	7.2	0	0	24.8	5.7	6.5	0	0	25.1
🟪 PH Light	7.8	15.6	0.3	0	26.2	6.7	7.1	0.5	0	26.4

Figure 28 Key outputs 4 dwellings (Islington, 5350185), TRY and DSY control scenario (1961-1990)



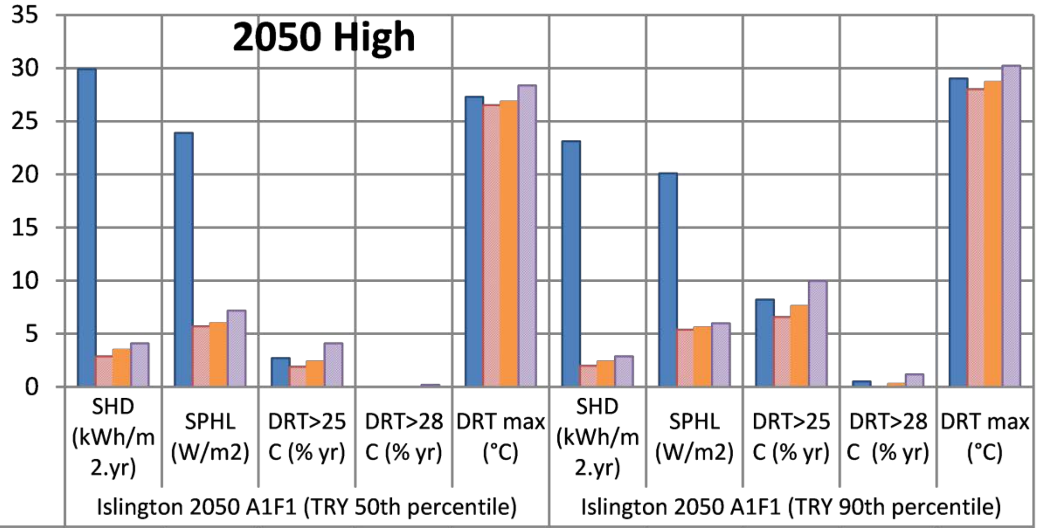
	CIBSE London 2005 TRY					CIBSE London 2005 DSY				
	SHD (kWh/m2.yr)	SPHL (W/m2)	DRT>25 C (% yr)	DRT>28 C (% yr)	DRT max (°C)	SHD (kWh/m2.yr)	SPHL (W/m2)	DRT>25 C (% yr)	DRT>28 C (% yr)	DRT max (°C)
🟦 FEES Heavy	40.2	26.5	0.4	0	26.2	37.3	26.2	1.6	0	27.3
🟥 PH Heavy	5	6.7	0.2	0	25.5	4.2	5.9	0.9	0	26.4
🟧 PH Medium	5.6	7.9	0.4	0	26.0	5.2	8.6	1.3	0	26.9
🟪 PH Light	6.7	7.5	1.1	0	27.7	6.3	16.1	3.2	0	28.5

Figure 29 Key outputs 4 dwellings (London Weather Centre), TRY and DSY current day scenario (CIBSE 2005)



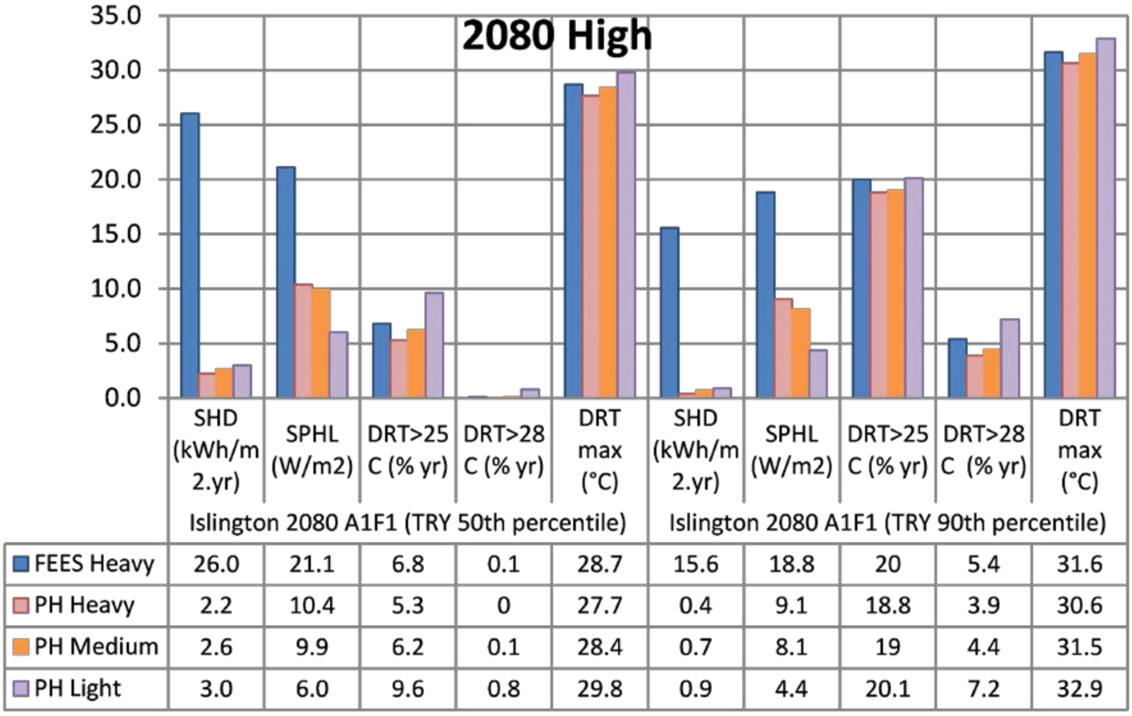
	Islington 2030 A1F1 (TRY 50th percentile)					Islington 2030 A1F1 (TRY 90th percentile)				
	SHD (kWh/m 2.yr)	SPHL (W/m2)	DRT>25 C (% yr)	DRT>28 C (% yr)	DRT max (°C)	SHD (kWh/m 2.yr)	SPHL (W/m2)	DRT>25 C (% yr)	DRT>28 C (% yr)	DRT max (°C)
🟦 FEES Heavy	32	21.5	1	0	26.4	27.2	22.2	3.9	0	27.2
🟥 PH Heavy	3.4	6.8	0.5	0	25.7	2.4	7.2	2.4	0	26.3
🟧 PH Medium	4.2	6.9	0.8	0	26.1	2.9	6.1	3.5	0	26.9
🟪 PH Light	5.1	7.6	2.1	0	27.6	3.4	5.8	5.8	0.2	28.6

Figure 30 Key outputs 4 dwellings (Islington, 5350185), TRY50th and TRY90th percentile (2030 High)



	Islington 2050 A1F1 (TRY 50th percentile)					Islington 2050 A1F1 (TRY 90th percentile)				
	SHD (kWh/m 2.yr)	SPHL (W/m2)	DRT>25 C (% yr)	DRT>28 C (% yr)	DRT max (°C)	SHD (kWh/m 2.yr)	SPHL (W/m2)	DRT>25 C (% yr)	DRT>28 C (% yr)	DRT max (°C)
🟦 FEES Heavy	29.9	23.9	2.7	0	27.3	23.1	20.1	8.2	0.5	29.0
🟥 PH Heavy	2.9	5.7	1.9	0	26.5	2	5.4	6.6	0	28.0
🟧 PH Medium	3.5	6	2.4	0	26.8	2.4	5.6	7.6	0.3	28.7
🟪 PH Light	4.1	7.2	4.1	0.2	28.4	2.9	6	10	1.2	30.2

Figure 31 Key outputs 4 dwellings (Islington, 5350185), TRY50th and TRY90th percentile (2050 High)

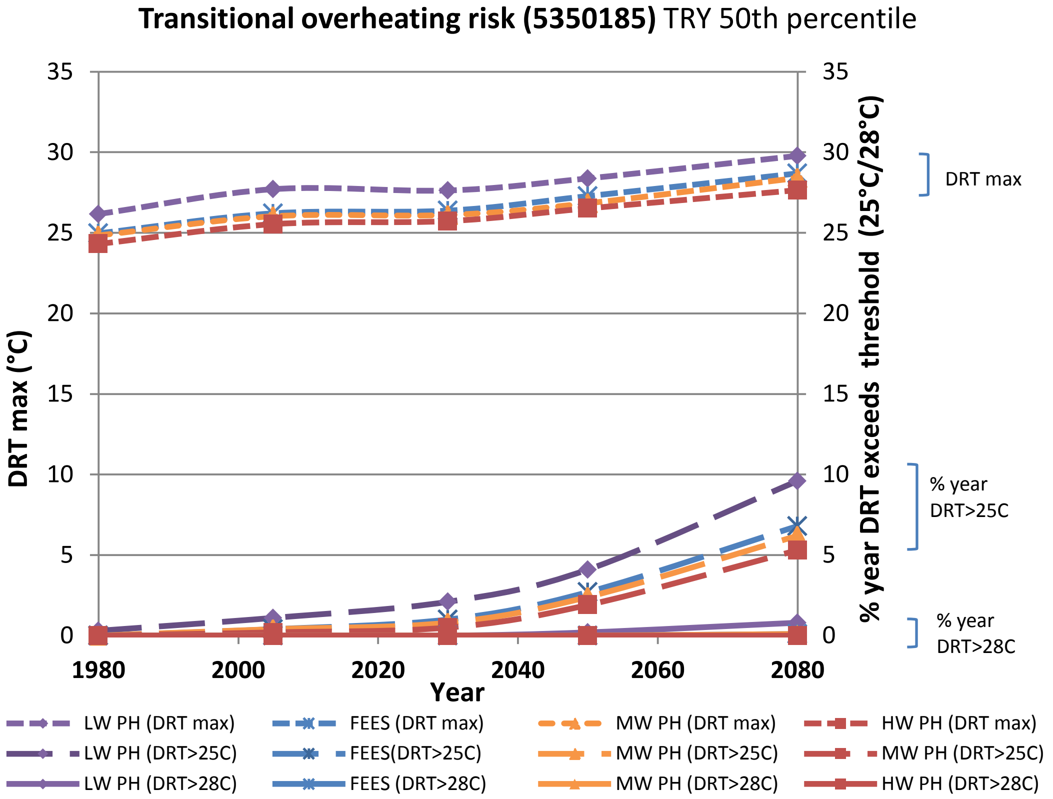


	Islington 2080 A1F1 (TRY 50th percentile)					Islington 2080 A1F1 (TRY 90th percentile)				
	SHD (kWh/m2.yr)	SPHL (W/m2)	DRT>25 C (% yr)	DRT>28 C (% yr)	DRT max (°C)	SHD (kWh/m2.yr)	SPHL (W/m2)	DRT>25 C (% yr)	DRT>28 C (% yr)	DRT max (°C)
FEES Heavy	26.0	21.1	6.8	0.1	28.7	15.6	18.8	20	5.4	31.6
PH Heavy	2.2	10.4	5.3	0	27.7	0.4	9.1	18.8	3.9	30.6
PH Medium	2.6	9.9	6.2	0.1	28.4	0.7	8.1	19	4.4	31.5
PH Light	3.0	6.0	9.6	0.8	29.8	0.9	4.4	20.1	7.2	32.9

Figure 32 Key outputs 4 dwellings (Islington, 5350185), TRY50th and TRY90th percentile (2080 High)

The overall trend in Specific Peak Heating Load (SPHL) (Figures 28-32) is far less pronounced than the evolution in SHD, suggesting that whilst the overall climatic trend is warming significant cold periods will continue to exert an influence on peak heating loads in all of the dwellings through to 2080. Beyond the present day (CIBSE 2005) period, the SPHL in all Passivhaus dwellings remained ≤10 W/m^2 even when assessed at an hourly time step. By contrast the SHL in the FEES dwelling fell slightly over the same period but remained above 20 W/m^2.

In contrast to falling heating demand, the risk of overheating rose in all dwellings from the control period through to 2080. The transition towards an increased risk of overheating under both a 50th and 90th percentile TRY as predicted by three performance indicators ($OT_{25,}$ OT_{28} and OT_{max}) is illustrated in Figure 32.



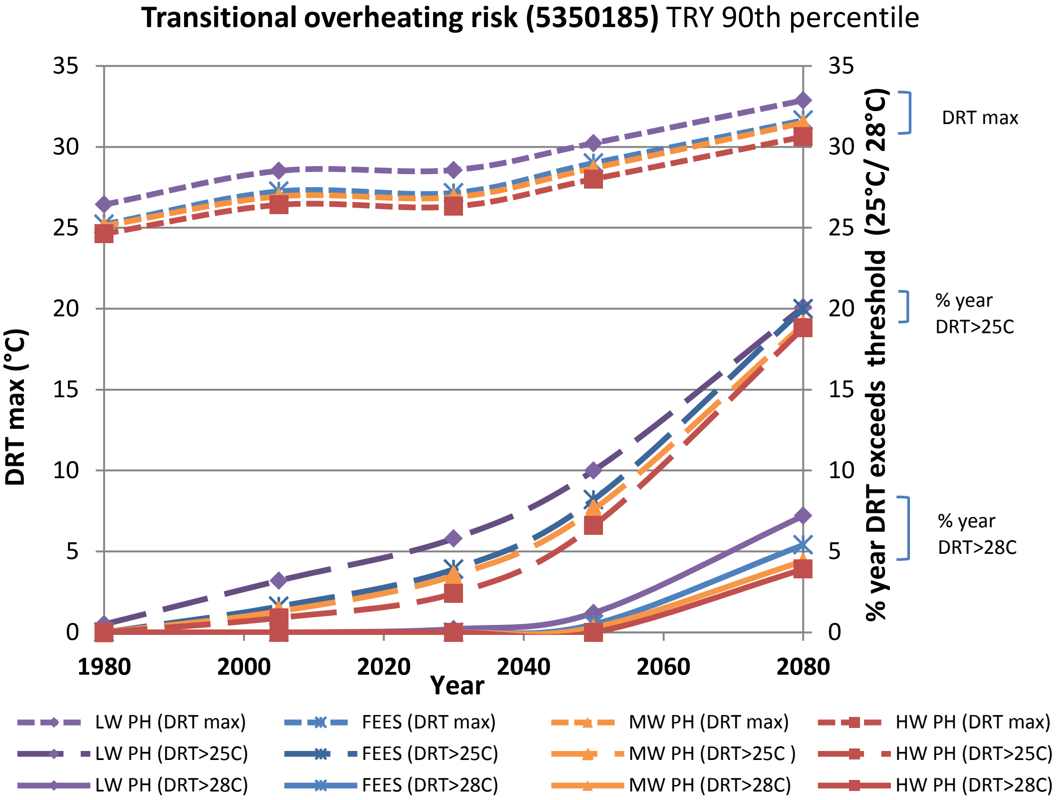


Figure 33 (top) Transitional overheating risk for 4 dwellings at 50th percentile TRY and (bottom) 90th percentile TRY under a High emissions scenario (1980-2080)

In terms of overheating risk it is notable that the FEES (heavyweight) dwelling performed only slightly worse than the MW Passivhaus overall. This finding suggests that the Passivhaus concept (without additional shading or cooling systems) offers only a slight advantage over the more conventional FEES dwelling typology in respect to overheating risk mitigation (assuming comparable design strategies).

It can be seen (Figure 33) that by 2050 under the 90th percentile TRY scenario all of the dwellings are exceeding both the HHSRS criteria (ODPM, 2006) and Voss's 25°C criteria (Voss et al., 2005) for more than 5% of the year, with the LW Passivhaus also exceeding the PHI 10% overheating criteria at this stage. By 2050 the LW Passivhaus has also exceeded the CIBSE 28°C threshold for more than 1% of the year, and by 2060 all of the dwellings are predicted to overheat beyond the CIBSE 28°C threshold for more than 1% of the year. Under a 50th percentile TRY scenario the same overheating frequencies are not likely to occur until 2080. By 2080 even in an average (50th percentile) year all of the dwellings will be at risk of overheating beyond 25 °C for more than 5% of the year.

For the period up to 2050 these findings are in agreement with the findings for overheating risks in dwellings published in CIBSE TM36 which suggests that "buildings with very good control of solar shading, ventilation and internal heat gains can meet targets until the 2050s" (CIBSE, 2005a, p.1). However where CIBSE TM36 states, "In living areas, use of high mass construction enabled the performance targets to be met into the 2080s" (CIBSE, 2005a, p.1). This study found that the same performance targets could not be met in the 2080's by any of the dwelling typologies analysed (even under the 50th percentile TRY scenario). It is notable however that the TM36 (2005) assessments were based on earlier UKCIP02 Medium-High emission scenario climatic predictions, in comparison to the UKCP09 High emission scenario used in this study.

In practical terms these findings suggest that, even with moderate areas of south facing glazing (33 % by internal façade area), restricted natural ventilation strategies (see section 4.2.1.2) alone are unlikely to provide sufficient means of eliminating the risk associated with prolonged periods of overheating in any of the low energy dwelling types.

In living areas it is apparent that thermal mass appears to offer some benefit both in terms of reducing the frequency of overheating and also the amplitude of the maximum internal temperature (by approximately 2 K on average). By 2080, as the duration of warmer temperatures become more prolonged, the benefits of thermal mass in reducing the frequencies of temperatures above 28 °C appears to diminish (Figure 33).

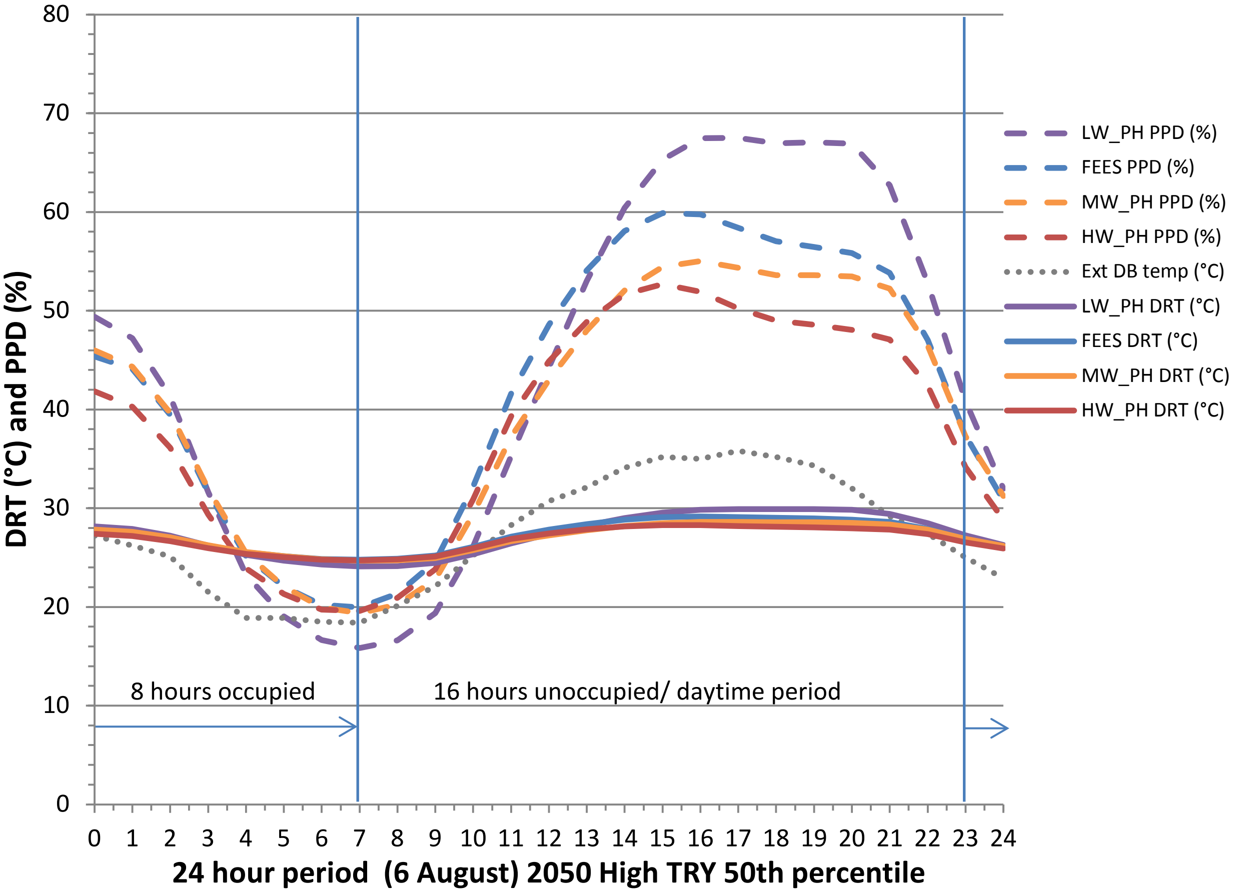


Figure 34 24 hour cycle showing Bedroom Dry Resultant Temperatures (°C) and Predicted Percentage Dissatisfied (%) during the hottest period of 2050 High (TRY 50th percentile) year

In the bedrooms the benefits of thermal mass in reducing overheating risks are less obvious. Despite higher daytime temperatures the lightweight Passivhaus cools more rapidly during the night-time period than the heavier weight dwellings (Figure 34). As a result for approximately half of the occupied period (11 pm -7 am) the lightweight Passivhaus achieves a lower Predicted Percentage Dissatisfied (PPD) vote than the other dwellings. The precise point at which the dwellings begin to cool is affected by the thermal inertia of the building and the timing of the peak external dry bulb temperatures. In an urban context the duration and intensity of the afternoon temperature peak may be strongly influenced by the magnitude and the timing of the peak intensity of the UHI effect (section 4.2.3.1), and hence it is essential to assess the benefits of thermal mass in a context specific manner. Whilst thermal mass can be seen to play a useful role in dampening maximum internal temperatures it can also delay the rate and extent of night-time cooling (Figure 34). Overall these finding suggests that the benefits of thermal mass in reducing the frequency of overheating during prolonged overheating spells may diminish in urban contexts during the latter part of this century and warrants further investigation.

4.3.2 SENSITIVITY ANALYSIS RESULTS – 2050 HIGH EMISSION SCENARIO

The results of the EE sensitivity analysis are shown as scatter plots (Figure 37 a-f) where each point represents the influence of a single individual input variable (i) upon the selected output. The input variables and input variable ranges are shown in Table 7. For clarity the number of input variables has been limited to 5 in this initial analysis, although in theory consideration of an unlimited number of variables is possible given sufficient computational resources. The *x*-axis in the scatter plots (Figure 37 a-f) represents the absolute mean (μ_i^*) of the EE's, a measure of the absolute importance of the input factor (i). The *y*-axis represents the standard deviation (σ_i) of the EE's, a measure of the extent which the effects are non-linear or result from interactions with other factors.

The ratio (σ_i/μ_i^*) can thus be seen as an indicator of linearity for the input factor (i), where a true linear response would occur in the case that $\sigma_i/\mu_i^* = 0$, since $\lim_{\sigma i \to 0}\left(\frac{\sigma i}{\mu i*}\right) = 0.$ According to the theory of normal distribution, where the EE's take the form of a general normal distribution then 95% of the EE dispersions will lie within the range of $\mu_i \pm 1.96\ \sigma_i$ (Montgomery and Runger, 2011). Thus if $\sigma_i \leq 0.1\ \mu_i$ then 95% of the EE's will lie in a range $\mu_i \pm 20\%$. Where the ratio $\sigma_i/\mu_i \leq 0.5$, most EE's (95% with a normal distribution) will have the same sign and the model response can be considered monotonic with respect to the input variable *i* (Sanchez Garcia et al, 2012).

In the context of building simulation models, the distribution of elementary effects for a given input factor is unlikely to follow a theoretical normal distribution, a scatter plot analysis of the relationship between (σ_i/μ_i^*) vs. $\sigma_i/abs(\mu_i)$ (Figure 35) is therefore a useful diagnostic method for identifying monotonic behaviour in the model (Garcia-Sanchez et al, 2012). The monotonic interval is found where the ratio (σ_i/μ_i^*) vs. $\sigma_i/abs(\mu_i)$ scatter points are located on or near the bisector, which can be seen to extend slightly beyond (σ_i/μ_i^*) ≤ 0.5 in Figure 35. Highly scattered EE's occur where $\sigma_i/abs(\mu_i) > 1$ indicating factors where marked non linearity and interactions with other factors are taking place, this occurs in the interval (σ_i/μ_i^*) ≥ 0.5 , with highly scattered EE's occurring at (σ_i/μ_i^*) ≥ 1.0 (Figure 35) . The delineation of slope gradient lines at $\sigma_i/\mu_i^* = 0.1$, 0.5, and 1 thus provides a useful framework for the subsequent assessment of the linearity of the EE's associated with each input variable in Figure 37 a –f.

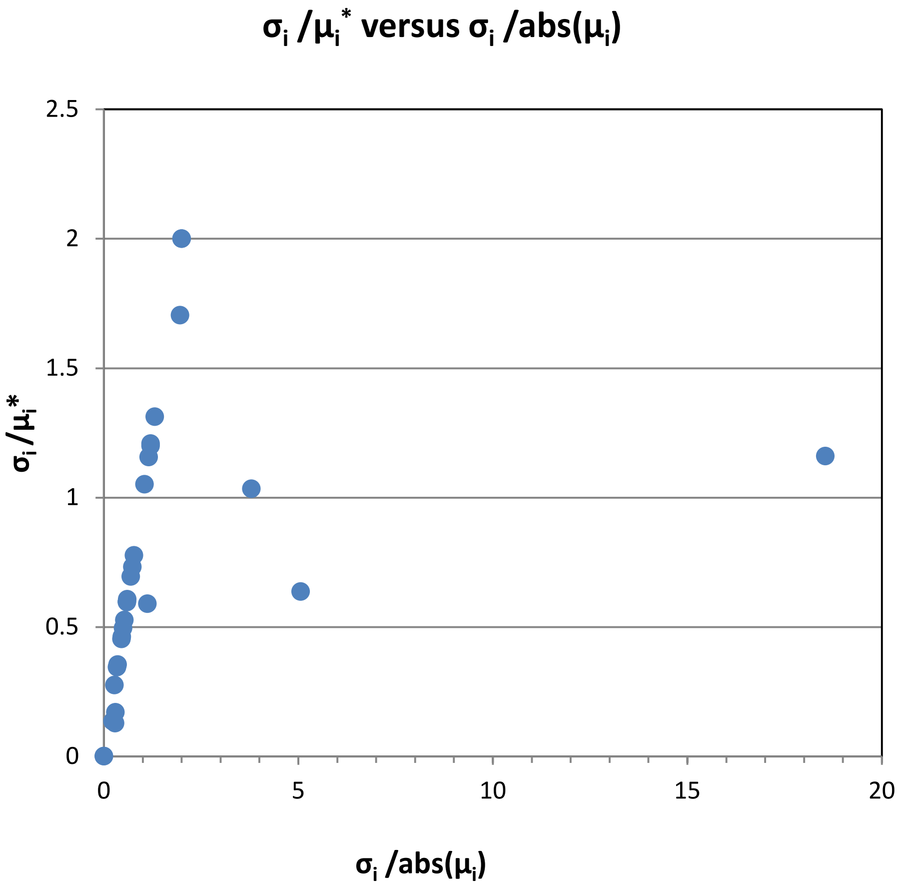


Figure 35 Relationship between σ_i / μ_i^* and σ_i /abs(μ_i) for a combination of 30 elementary effects

The far right hand outlier (Figure 35) is the output for the frequency of the DRT>28C in response to the internal gains input factor, which indicates that *abs(μ_i)* is significantly smaller than μ_i^*, for this factor. This finding suggests that the internal gains are having a non-monotonic effect on the frequency of the DRT>28°C (in contrast to the linear effect of the internal gains on the frequency of the DRT>25°C). This finding is unexpected and is likely to be a result of interactions with other factors, which could only be revealed through an analysis of the second and higher order effects.

The mean of the absolute EE's (μ_i^*) for each input factor (i) is considered a good proxy of the total sensitivity index (S_T) (Campolongo, 2007; Saltelli et al, 2008). Figure 36 ranks input/output sensitivity for a combination of 6 outputs in relation to 5 inputs factors.

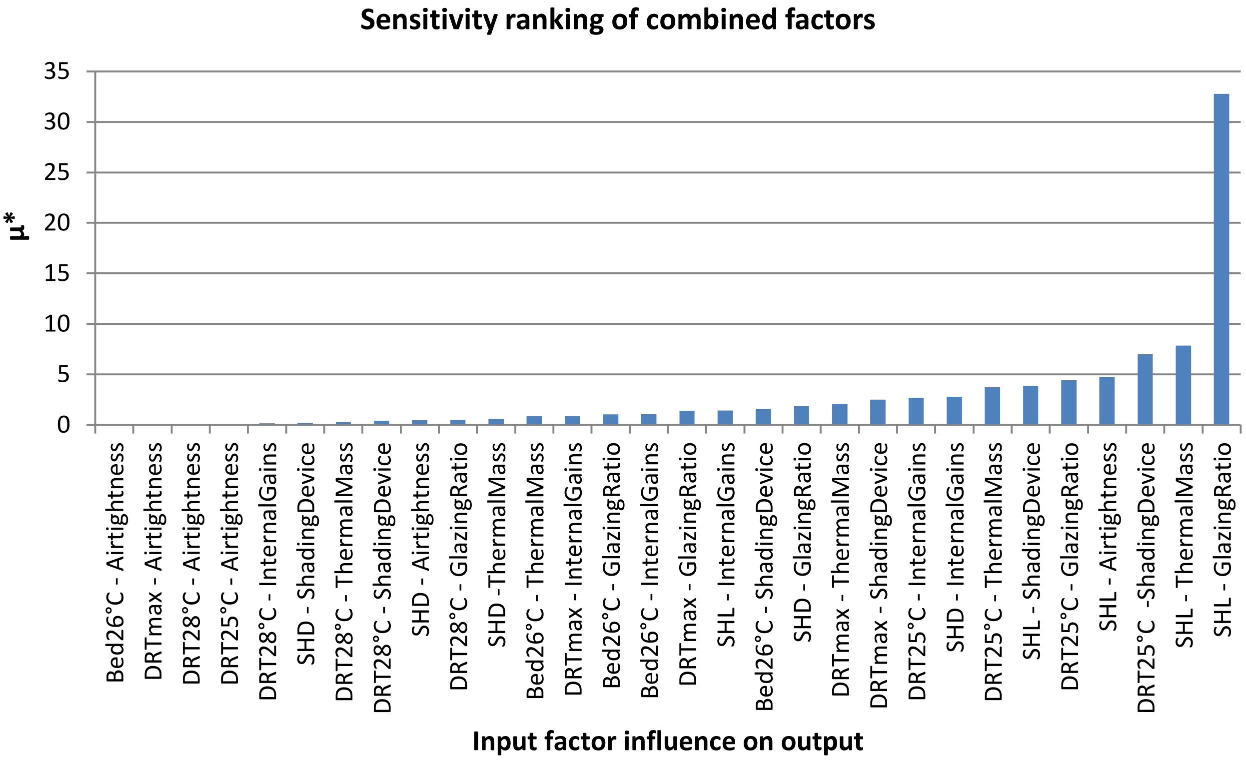


Figure 36 Ranking of output factor sensitivity - combined measures

The output factor sensitivity ranking shown in Figure 36 provides useful information at the conceptual design stage. For example the ranking illustrates that the SHL is highly sensitive to the glazing-to-wall ratio used in the model, and that this factor is four times more important than the dwelling's thermal mass in influencing the SHL (in relation to the ranges assessed in Table 7). This information is particular relevant in the planning process where either the SHD ≤15 kWh/m^2.yr or SHL ≤10 W/m^2 criteria may be used to comply with the Passivhaus certification criteria (Feist et al, 2012).

The ranking of the overheating variables (Figure 36) provides a useful hierarchy for minimising the future overheating risk. It can be seen from this analysis that the influence of the external shading device has the greatest potential effect upon the frequency of internal temperatures above 25 °C, followed by the (south facing) glazing-to-wall ratio (within the ranges assesses in Table 7). At the opposite end of the scale improving airtightness (beyond n_{50} ≤0.6 h^{-1}) can be seen to have negligible impact upon any of the overheating parameters. In practice the use of hierarchical ranking also exposes optimization synergies. For example it can be seen (in Figure 36) that designs optimized in relation to the SHL shows a better correlation with factors that will also result in reduced overheating risks, than designs optimized in favour of the SHD.

In a first order analysis, the value of an elementary effect for an individual input variable (i) corresponds to the output variation when the input i moves from the minimum scalar function (0) to the maximum (1). By averaging the EE's of r random trajectories the dependence on a single sampling point is removed and μ_i^* becomes a good proxy for the mean output variation corresponding to the input i. By plotting μ_i^* against σ_i (Figure 37 a–f) it is possible to graphically identify factors which are almost linear (below $\sigma_i/\mu_i^* = 0.1$), monotonic ($0.1 < \sigma_i/\mu_i^* < 0.5$), almost monotonic ($0.5 < \sigma_i/\mu_i^* < 1.0$), and factors with which are highly non-linear or interacting with other factors ($\sigma_i/\mu_i^* > 1$) (Figure 37 a –f).

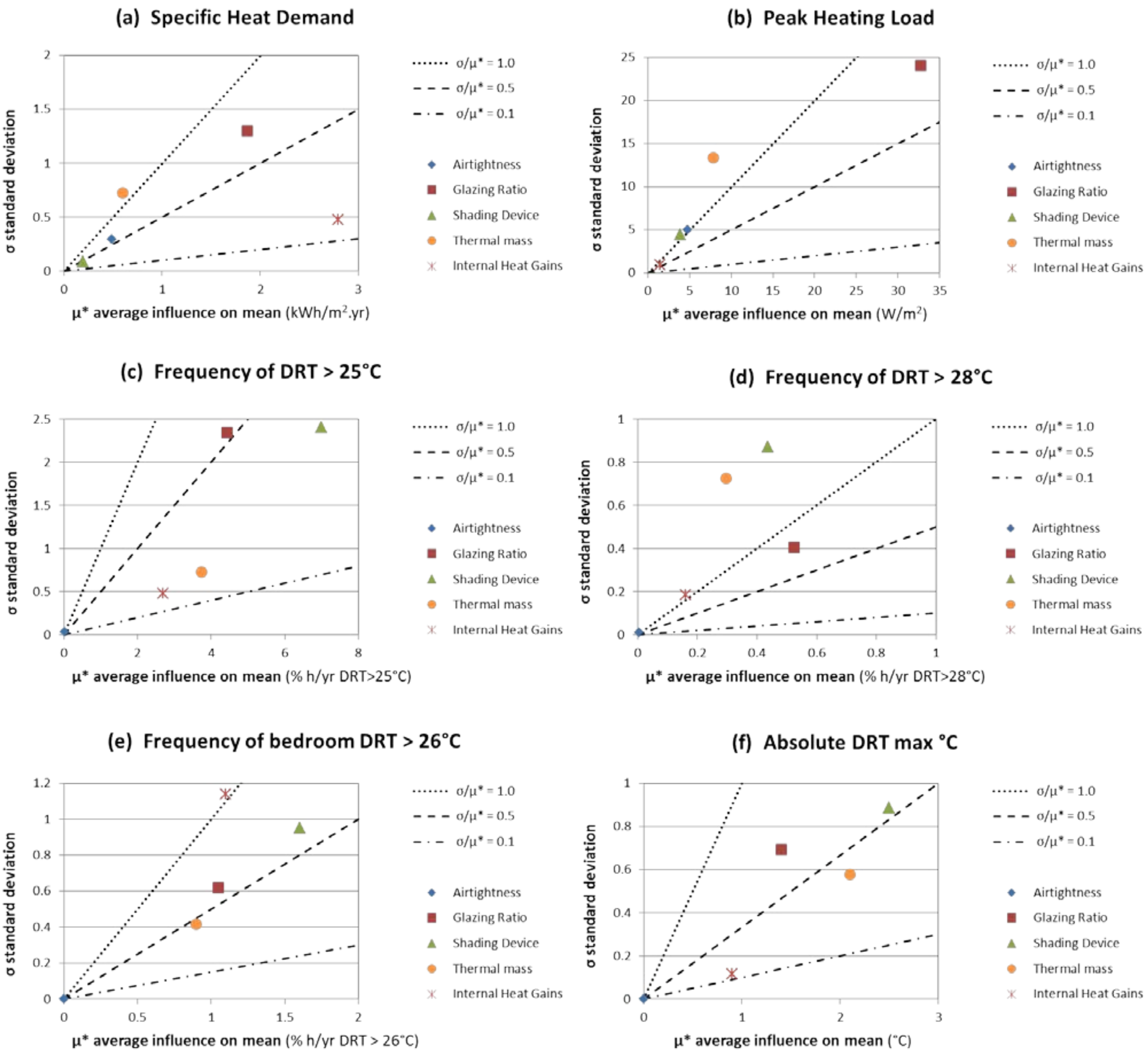


Figure 37 Enhanced Morris analysis of absolute mean (μ^*) and standard deviation (σ) of first order elementary effects for (a) space heating demand (b) peak heating load (c) living area DRT above 25 °C (d) living area DRT above 28 °C (e) bedroom DRT above 26°C and (f) living area maximum DRT

Figure 377a shows that internal gains have a significant and monotonic effect on the SHD, yet play only a small role in influencing the SHL. The SHL (Figure 377b), is most strongly influenced by the glazing ratio (as shown by Figure 36) in an almost monotonic manner. In contrast thermal mass also exerts a significant influence on the SHL (Figure 37b), however its influence is highly non-linear suggesting that possible interactions with other factors are occurring.

In terms of the overheating parameters the most pronounced influence of the input parameters can be seen on the frequency of the OT_{25} (Figure 377c), since the influence of all passive design factors diminishes as the overheating threshold is elevated (Figure 377d,e,f). The shading device has the most pronounced influence upon the frequency of OT_{25} and also the frequency of $BedOT_{26}$. Interestingly internal gains appear to play a more significant role in influencing the frequency of $BedOT_{26}$ (Figure 37e) than in the combined living area overheating parameters. One possible explanation of this finding is that internal sources of heat are likely to contribute to internal air temperature stratification which will be experienced more strongly in the first floor bedrooms due to the buoyancy effect.

Overall the SHL (Figure 377b) sensitivity analysis is better correlated with the overheating parameters than the SHD (Figure 37a). This finding suggests that there are likely to be less parameter conflict in a Passivhaus dwelling that is optimized for low SHL and low overheating risks than for a dwelling designed for low SHD and low overheating risks.

4.4 CONCLUSIONS

Evidence suggests that Passivhaus and super insulted dwellings are already at risk of overheating in the UK, Ireland and Northern Europe. In the rapid transition to zero carbon building in the UK, designers of Passivhaus and low energy dwellings are currently at risk of pursuing ultra-low space heating targets at the expense of whole life thermal performance. According to the results of this study by 2050 a warmer than average summer could see average internal temperatures (in some Passivhaus and FEES low energy dwellings) in London exceeding 25 °C for between 5-10% of the year. Beyond 2050, in warmer than average summer conditions, the duration of mean internal temperatures above 28 °C rises sharply in all of the dwelling types studied. Unless there is a move towards whole life design optimization based on minimising future overheating risks, active cooling systems may become a de-facto requirement in urban Passivhaus and low energy dwellings in the UK within the next 30-40 years.

If global GHG emissions continue to follow a ‘High’ (A1FI) emissions scenario trajectory then the average SHD of Passivhaus dwellings in London is likely to fall considerably (by approximately 40%) by the middle of this century, whilst at the same time the SHL is likely to remain substantially unchanged. In relation to overheating risk factors, the Passivhaus concept (when used without active cooling systems) appears to provide only slight additional protection in comparison to an almost identical naturally ventilated FEES dwelling.

The performance of the Passivhaus dwellings in this study was shown to be highly sensitive to a small number of design inputs. In particular the risk of overheating (OT frequency above 25 °C) was shown to be highly dependent upon the solar transmission reduction provided by a full external shading device, as well as the glazing to wall ratio on the South façade. Glazing to wall ratios also played a dominant role in relation to the peak heating load. It follows therefore that design optimization in relation to the SHL, as opposed to SHD, is likely to produce better outcomes in relation to overheating risk reduction.

Thermal mass played a clear role in reducing the overall duration of overheating in the Passivhaus dwellings, and was also correlated with a reduction in the SHL. In relation to reducing the SHD however, thermal mass had only a minor effect. Further detailed investigations regarding the effects of thermal mass in relation to the timing of the dampening effect (decrement delay) during prolonged heatwaves (where night purge ventilation possibilities are limited) is needed. The results here suggest that the use of thermal mass may be counter indicated in relation to overheating risks in bedrooms in some cases. More sophisticated systems involving the use of displaced thermal mass (via earth air heat exchangers) or Thermally Active Building Systems (TABS) may overcome these problems and is worthy of further investigation.

Careful attention must be paid to the design assumptions and assessment criteria used to evaluate future overheating risks. The methods currently used to prepare TRY and DSY datasets involve the use of a statistical filtering procedure (the Finkelstein Schafer statistic) a process which tends to smooth out extreme day to day variability in the creation of 'representative' weather years. As a result heat wave events are not reliably modelled by the use of these climate files regardless of the percentile of the CDF which is used. The use of additional procedures to model extreme weather events is therefore advised.

In urban contexts, the possibilities of purge ventilation through opening windows may be limited or non-existent and internal gains in a UK social housing context may be significantly higher than PHPP defaults suggest. Clearer guidance on acceptable overheating criterion with respect to morbidity and mortality risks as a function of OT's and IAQ is urgently required.

Further research is also needed to establish the full extent of the future overheating risk in a broad range of Passivhaus dwelling typologies and urban contexts. This work is particularly important in relation to dwellings housing vulnerable occupants (including apartments and care homes); where a combination of high internal gains, large glazed areas and reduced purge ventilation possibilities are likely to co-exist. Simple sensitivity analysis techniques, used in conjunction with probabilistic scenario modelling, provide a means of facilitating transient design optimization in the face of rapid climatic change.

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CHAPTER 5 | HYGROTHERMAL IMPLICATIONS OF LOW AND ZERO ENERGY STANDARDS FOR BUILDING ENVELOPE PERFORMANCE

DISCURSUS:

The preceding two chapters have addressed methods to improve the resolution and quality of the climatic data used for Passivhaus design, and the implementation of that data in predictive modelling of energy and thermal performance criteria. This chapter addresses the hygrothermal issues that arise out of the interaction between the external micro-climate and internal boundary conditions, in relation to the moisture response of Passivhaus and ultra-low energy building envelopes.

Moisture is a major cause of damage and deterioration in the fabric of buildings and plays a significant role in surface mould growth and the internal air quality (IAQ) in buildings. In the rapid transition to achieving ultra-low energy and zero carbon targets in the UK, relatively little attention has been placed on the hygrothermal implications of designing super-insulated dwellings in a predominantly maritime climate.

This chapter sets out to evaluate some of the key issues inherent in current UK policy and praxis, in relation to adapting existing UK construction typologies to meet Passivhaus and ultra-low energy performance standards in the face of changing hygrothermal boundary conditions (Section 5.1). The Glaser method is a widely used stated-state method for the calculation of vapour pressure difference in buildings envelopes which has become the de facto assessment method in many UK condensation risk assessment tools. The limitations of this approach are explored in the context of examining the challenges imposed by the upgrading of the existing building stock and the compounding implications for building envelope performance (Section 5.2). The specific implications for fully filled and retrofitted cavity wall constructions are evaluated in Section 5.3. Concluding remarks and recommendations for more robust approaches to hygrothermal assessment are summarized in Section 5.4.

5.1 UK BUILDING REGULATIONS AND CURRENT PRACTICE IN HYGROTHERMAL ASSESSMENT

5.1.1 CURRENT PRACTICE – EVOLUTION OF THERMAL PERFORMANCE STANDARDS IN THE BUILDING REGULATIONS (PART L1A)

The 1985 Building Regulations were the first to include the UK's modern system of Building Control. Under the 1984 Building Act provision was made for future changes to technical specifications using a system of Approved Documents (England & Wales) and Technical Standards (Scotland and Northern Ireland) (Killip, 2005).

Despite the addition of Approved Document L to the UK Building Regulations, which was designed to promote the conservation of fuel and power, there is currently only limited legislative scope for its application in partial refurbishment work (HM Government, 2010a). Alongside this, demolition and replacement rates in the UK housing stock are extremely low, with figures suggesting that the existing housing stock is currently being replaced, on average, once every 1300 years (Boardman, 2007). This situation means that only a very small percentage of the UK building stock would comply with modern (post 1985) building regulations.

Even when new dwellings are built a number of reports suggest that there is often a large discrepancy between the design performance mandated by the Building Regulations and what is actually constructed. A BRE client report by Doran (2001) showed that out of a sample of 200 newly completed UK dwellings, more than one third would have failed to comply with the then current Part L requirements. Similarly in an unpublished 2005 report, produced by Sustainable Energy Authority of Ireland (SEAI) (Irish Times, 2011), it was revealed that out of a home inspection survey of 52 Irish dwellings built between 1997 and 2002, none complied with the State's building and energy regulations. The report pointed out that "92 per cent of the houses failed to meet minimum insulation levels", whilst "42 per cent did not (even) meet minimum ventilation standards" (Irish Times, 2011) which are considered necessary to reduce surface condensation risks, dampness and problems associated to human health. Furthermore studies highlighting a marked difference between what building energy models predict and the reality of what is built are not uncommon (Norford, 1994; Olivier, 2001; Bordass et al, 2004; EST, 2004; Sanders and Phillipson, 2006).

In response to these findings, the UK Parliamentary Environmental Audit Committee (EAC) stated that they were "alarmed at the apparent ease and possible extent of non-compliance with Part L of the Building Regulations" (House of Commons, 2005, p45 item 116). The EAC found that, "The fact that compliance with Part L of the Building Regulations is not covered by new buildings insurance, combined with a lack of post-completion inspections by Building Control bodies, provides little incentive for developers to carry out work to a standard that ensures proper compliance with energy efficiency requirements" (House of Commons, 2005, p45, item 117).

The recently revised Approved Document (AD) L1A 2010 for new build dwellings provides current guidance on the conservation of fuel and power in UK homes, and aims to reduce CO_2 emissions by 25% over Part L1A 2006 (HM Government, 2010b). Part L1A is largely based on demonstrating that whole building carbon emissions comply with the method set out in the UK Standard Assessment Procedure (SAP) 2009. Approved Document L1A (2010) also provides limiting (worst case) fabric U-value for external walls to ≤0.3 W/m^2K and ≤2.0 W/m^2K for windows (HM Government, 2010b, p15), whilst Part F (2010) regulations address issues relating to ventilation. In order to harmonise these two standards, recent revisions have been made to improve the control of background air leakage from UK dwellings. Currently Part L1A (2010) specifies that air leakage should not exceed $10m^3/m^2.h$ at 50Pa (HM Government, 2010b, p15). In practical terms this level of airtightness is equivalent to allowing a hole the size of a twenty pence coin in each square meter of the building envelope (BRE, 2012). New legislation was also implemented in Part F (2010) to ensure that more airtight dwellings ($<5\ m^3/m^2.h$ @ 50Pa) had adequate trickle ventilators or mechanical ventilation systems due to concerns regarding reduced Indoor Air Quality (IAQ) standards in airtight dwellings.

In order to tighten operational emissions from new build housing, the UK government intend to incrementally reduce the Target CO_2 Emission Rate (TER)[xxvii] via Part L of the

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[xxvii] The Target CO_2 Emission Rate (TER) is defined by the PartL of the Building Regulations as the minimum energy performance requirement for a new dwelling and is expressed in terms of $kgCO_2/m^2$ of floor area per year, emitted as a result of the provision of the specified fixed building services for a standardised household when assessed using approved calculation tools based on the current Standard Assessment Procedure (SAP). The target uses a 'notional' building design and sets

Building Regulations every three years between 2010 and 2016. The key targets of these new standards are:

- to achieve a reduction of 25% in new build carbon emissions in 2010 over the previous standard (2006) (CSH Energy Level 3),
- followed by proposals for a 44% reduction in 2013 (CSH Energy Level 4), and then
- in 2016, all new homes will be defined as 'zero carbon' (CSH Energy Level 5).

In terms of the building fabric, under the revised definition of 'zero carbon', the Fabric Energy Efficiency Standard (FEES) would provide a national minimum energy efficiency specification for 'zero carbon' homes (ZCH. 2009b). This performance specification has significant implications since it effectively defines a national minimum insulation and airtightness standard as well as having implications for the climate change adaptation and the mitigation potential of the UK's future housing stock (see Section 2.4.3).

The proposed FEES standards mandates limiting the specific heat demand (SHD) of detached, semi-detached and end terrace 'zero carbon' dwellings to 46 kWh/m^2.yr and for apartments and mid-terraced dwellings to 39 kWh/m^2.yr (ZCH. 2009) based on the SAP(2009) methodology (see Section 2.4.3.4). Modelling carried out by the ZCH suggests that, in order to comply with the FEES standards, fabric standards will have to meet or exceed those set out in Table 8.

Table 8 Fabric performance values required to meet FEES standards (adapted from ZCH, 2009b)

	DWELLING TYPE			
	4 STOREY APT. BLOCK	MID-TERRACE	END TRCE/ SEMI	DETACHED
Target FEES standard (kWh/m^2.yr)	39	39	46	46
Wall U value (W/m^{2}K)	0.18	0.18	0.18	0.18
Roof U value (W/m^{2}K)	0.13	0.13	0.13	0.11
Window U value (W/m^{2}K)	1.4	1.4	1.4	1.3
Air permeability (m^3/m^2.h @50 Pa)	3	3	3	3
Thermal bridging 'y' value (W/m^{2}K)	0.05	0.05	0.05	0.04

It should be noted that the SAP calculation takes account of thermal bridging, at junctions between elements and around openings. If linear thermal transmittance psi-values (ψ) are

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'improvement factors' for the developer to demonstrate that their designs are within the targets. The 2010 edition uses the 2006 level with an improvement factor of around 25%.

available for these junctions, they can be multiplied by the length of the junction concerned, and the total added to the one dimensional transmission heat transfer coefficient, as shown in equation 22.

$$\mathrm{U} = \mathrm{U}_0 + \frac{\sum_{i=1}^{n}(\psi\mathrm{L})_i}{\mathrm{A}} \qquad [22]$$

where U is the resultant U-value after the two-dimensional linear thermal bridging transfer coefficients are added. The three-dimensional point bridging chi-value (χ) effects of fastenings and wall ties are normally included as adjustment factors in the U_0 calculation in accordance with EN6946 (2007). If specific values for linear thermal bridges are not known, an approximation is permissible by including a notional 'y-value' allowance of 0.15 W/m^{2}K based on the total exposed surface area (SAP, 2009).

It should be noted that the use of a y-value in accordance with the UK SAP (2009) convention involves a notional adjustment to the elemental U value in order to incorporate the area weighted influence of linear thermal bridges (ψ). A y-value is therefore the product of (ψL) for all junctions divided by the total area of external elements, including all exposed elements but not party walls (DECC, 2011, p78), as shown in equation 23.

$$y = \frac{\sum_{i=1}^{n}(\psi L)_i}{A_{exp}} \qquad [23]$$

where A_{exp} is the total area of external elements.

The assumption in the FEES standard is that the non-repeating thermal bridging can contribute to worsening the overall elemental U_0 values by 0.04 W/m^{2}K for a detached house and 0.05 W/m^{2}K for all other dwelling types (ZCH, 2009b). As such the y-values permissible under the FEES standard allow for a worsening of the stated backstop elemental thermal transfer coefficients by approximately 25%.

Whilst the FEES standards are likely to be mandated as defining the minimum fabric efficiency standards permissible under PartL1A (2016), it is notable that they fall significantly short of the energy savings achieved by internationally established low energy standards including the German Passivhaus standard (Feist, 2012), the Canadian R2000 standard (NRCAN, 2012) and the Swiss Minergie-P standard (Minergie, 2012).

5.1.2 CURRENT PRACTICE - IMPLEMENTATION OF THE BUILDING REGULATIONS IN EXISTING DWELLINGS (PART L1B)

As previously discussed in Section 2.2 , achieving deep CO_2 emission cuts of 80 % from the total UK housing stock by 2050 (UK Parliament, 2008) represents an enormous technical and logistical challenge (Boardman, 2007). Historically low stock replacement rates in the UK means that the majority of dwellings built between the present day and 2050 will create additional stock that simply adds to the emissions problem (McLeod et al, 2012a). The scale and anticipated lifespan of the UK housing stock (Boardman, 2007) coupled with the generally poor standard of energy efficiency amongst the existing stock (DCLG, 2007c) (Olivier, 2001) suggests that a re-emphasis towards deep retro-fitting of the existing stock is likely to achieve far greater energy and carbon savings in the short to medium term.

In terms of legislation affecting the thermal upgrading of existing buildings, Part L1B applies to the removal and reinstatement of existing dwellings as well as upgrading the existing envelope (BR ADL1B, 2010). A large number of buildings in the UK are exempt from Part L1B legislation however, due to their conservation status (BR ADL1B, 2010). In England alone there are 374,081 listed building entries (English Heritage, 2012). Although listing is not a preservation order, Listed Building Consent is required to make changes to the fabric of a listed building and this includes common replacement works such as changing windows and doors as well as any work affecting the building fabric (English Heritage, 2012). In buildings with Grade I or Grade II* status, substantial thermal upgrading may not be permissible.

According to L1B, in the case where existing thermal elements are retained, the individual element limiting U-value for walls should not exceed $0.7W/(m^2{\cdot}K)$. Although such backstop (or worst case) U values are specified in both Part L1A and L1B, they are rarely enforced. Part L compliance is typically evidenced via a ‘whole building’ carbon emission methodology (see footnote xxvii) based upon the outputs from a SAP calculation. As such, the predicted CO_2 emissions reductions - relative to a ‘notional’ building of the same format with a fabric specification designed to meet the previous Part L standards and with boundary assumptions derived from the National Compliance Methodology (NCM) - has become the defining standard. If a 25% CO_2 reduction is made against this ‘notional’ dwelling then the Dwellings Emission Rate (DER) will be less than the Target Emission Rate (TER) and the dwelling is deemed to comply with Part L. In reality, no thermal upgrade may be needed to achieve compliance in this manner since simply switching from a conventional gas heating system to an equivalent biomass pellet heating system would effectively reduce the heating fuel CO_2 emission intensity by a factor of 7 (SAP, 2009, p199), thus far exceeding a notional 25% improvement in the DER. Therefore contingent upon the fuel type, building format, heating system or installed Low and Zero Carbon Technologies (LZCTs) used to reduce the SAP regulated carbon emissions anything from a nearly Passivhaus standard envelope down to something that could have been the default elemental standard 10 years ago may still be permissible for Part L compliance.

5.1.3 HYGROTHERMAL IMPLICATIONS FOR PASSIVHAUS (NEW BUILD) AND ENERPHIT (REFURBISHMENT)

The first certified Passivhaus projects in the UK were completed in 2010 and as a result it is still too early to assess whether significant hygrothermal issues will arise as a result of the construction methods used to achieve this advanced thermal standard. In the majority of cases it seems likely that the use of external insulation and internal vapour barrier layers are likely to reduce the risk of interstitial condensate forming within the structural elements of the building. However, several of the projects completed in the UK to date have adapted more conventional construction methods including the use of cavity wall constructions and lime based pointing and renders.

The risk of cracking of parge coatings to masonry blockwork and the tearing of membranes in timber frame construction is always possible and carries an associated risk of introducing approximately 360g of water vapour per day in to the building fabric, through a 1m crack length (x 1mm wide) (BRE, 2012). Similar studies by the Fraunhofer Institute of Building Physics, Stuttgart, have shown that under standard occupancy conditions as much as 800g of moisture can be convected through a 1m x 1mm crack per day when exposed to a pressure differential of 20Pa across the building envelope (IBP, 1989). Where vapour diffusion[xxviii] to the outside is possible the risks associated with localised construction

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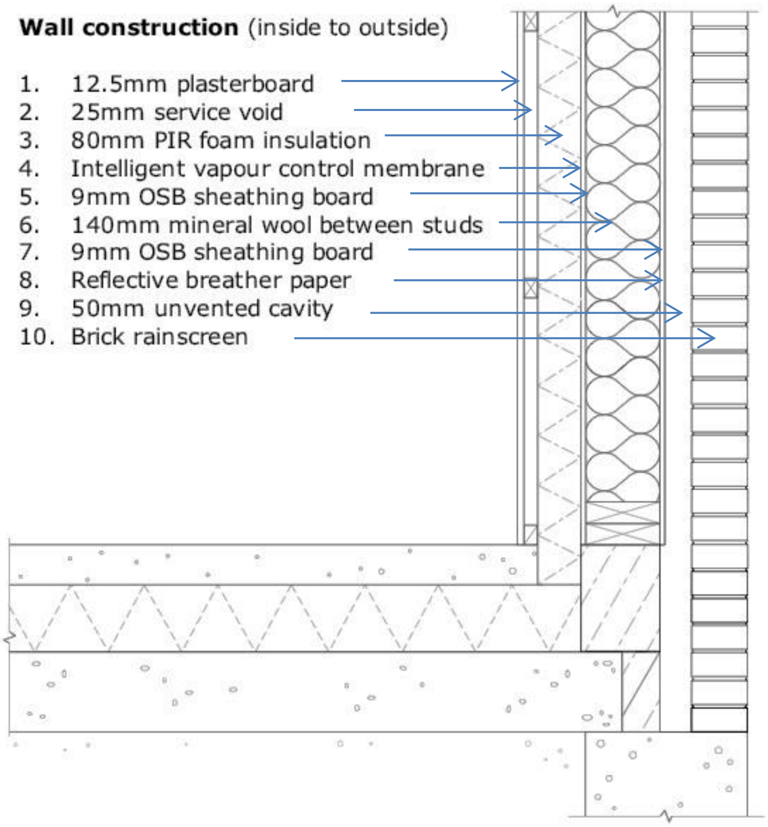
[xxviii] Vapour diffusion describes the movement of single water vapour molecules, caused by their own thermal movement and collisions (Brownian motion). Vapour diffusion is driven by vapour pressure differences across a building element. The direction of water vapour movement is driven by the temperature differential across a building component (from warm to cold) or according to relative humidity (from moist air to dry air). Vapour diffusion occurs in the air and also in porous building components. The more impermeable a material is, the greater its diffusion resistance. The vapour diffusion resistance factor (μ_{VR}) is a dimensionless quantity which indicates the factor by which a

defects may be reduced. However, such risks need to be carefully evaluated in their specific context particularly in constructions where synthetic renders, render boards, and other rain screen materials are applied externally without a vented cavity.

According to Quirotte (2004) constant cavity cycling poses a risk in well-sealed cavities due to the pressure fluctuations inside the cavity driven by variations in external air pressure. This cyclic phenomena occurs when the external air temperature drops (at night) drawing warm moist air in to the cavity from the inside of the building, where it is likely to condense. During the day in the presence of substantially warmer sol-air temperatures the air pressure flux within the cavity may be reversed, thus creating a 24 hour cycle. This phenomenon poses a potential future risk in the UK where sealed unvented cavities are increasingly specified in an attempt to improve the thermal resistance of cavity walled buildings. Figure 38 shows an example of a ‘partially filled’ timber frame and brick veneer cavity wall construction that is unvented (Cae Gleishon passivhaus).



Wall construction (inside to outside)

1. 12.5mm plasterboard
2. 25mm service void
3. 80mm PIR foam insulation
4. Intelligent vapour control membrane
5. 9mm OSB sheathing board
6. 140mm mineral wool between studs
7. 9mm OSB sheathing board
8. Reflective breather paper
9. 50mm unvented cavity
10. Brick rainscreen

Figure 38 Cross section showing the Cae Gleishon Passivhaus wall construction

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material’s diffusion resistance differs in comparison to a reference value. Air is typically used as the reference value as it offers the least resistance to water vapour (μ_{VR}=1).

According to the ideal gas law, the relationship between pressure, volume and temperature can be described by the following equation[xxix]

$$PV = nRT \qquad [24]$$

where P is the absolute pressure (Pa), V is the volume of gas (m^3), n is the chemical quantity of gas molecules (moles), T is the temperature of the gas and R is the ideal, or universal, gas constant.

and

$$P_1 V_1/T_1 = P_2 V_2 /T_2 \qquad [25]$$

where P_1 and P_2 are the absolute air pressure before and after temperature change (Pa), and T_1 and T_2 are the initial and resultant air temperatures during a cycle (K), and V_1 is the free air volume of the cavity (m^3) and ΔV is the displaced air volume (m^3).

Since the cavity volume is constant then,

$$V_2 = V_1 + \Delta V, \qquad [26]$$

and the volume of displaced air is,

$$\Delta V = (P_1 V_1 T_2/T_1 P_2) - V_1 . \qquad [27]$$

Thus, for a given change in sol-air temperature or barometric pressure the displaced air volume of the cavity can be calculated. According to Quirouette (2004) this phenomenon is widely documented during winter months in Northern Latitudes. In practice the severity of this phenomenon is proportional to the extent of the temperature change and the duration of each cycle, and will only occur when the outer leaf of the cavity is well sealed.

Where more traditional constructions such as cavity walls have been constructed in a fully filled manner such as in the Denby Dale Passivhaus (Figure 39) (GBS, 2010) or BedZED (Lazarus, 2002) further investigations may also be warranted. Of possibly greater

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[xxix] Since water vapour behaves almost like an ideal gas this equation can equally be applied to determine the changes in the partial pressure of the water vapour in the air mix.

significance than the diffusion and convection driven interstitial condensation risks outlined above, are the potential problems associated with driving rain entering an unventilated cavity, particularly one which is not properly drained. The influence of driving rain on unvented cavity constructions where the outer layer is constructed from a porous stone material or brick (which may also be prone to cracking at the joints) has not been extensively researched in the UK.

Figure 39 shows a cross section of the Denby Dale Passivhaus wall construction, an example of a fully filled undrained passivhaus cavity wall which is faced in porous sandstone with a lime based pointing. Although water repellent mineral fibre has been used as a precaution in this construction (Butcher, 2012), there is no egress for trapped water or condensate. As a result moisture accumulation in the cavity could lead to saturation of the lower course of facing stone over time.

Figure 39 Fully filled 300mm cavity wall construction with sandstone facing (courtesy of Green Building Store).

Ice expansion damage can result in structural cracking when rainwater seepage freezes in poorly drained cavities (Figure 40). The risk of trapped water freezing in the outer layer of a cavity or rainscreen is elevated in super insulated Passivhaus and EnerPHit wall constructions as a consequence of the high temperature gradients across the construction.

Figure 40 Ice expansion damage to the bottom of a poorly draining cavity wall (courtesy of J.Morehead)

Where sol-air temperatures fall below freezing point (at night) on the outside of super insulated buildings following spells of driving rain are likely to lead to spalling and frost damage where trapped moisture freezes and expands within the outer layer of porous or sorbtive material (Figure 41). Modern bricks are predominantly frost resistant but it is important to consider this issue before post filling existing cavity walls.

Figure 41 Spalling damage to a brick facade caused by driving rain and subsequent freezing

Super-insulated timber frame constructions are also vulnerable to this phenomenon. Transient hygrothermal analysis accounting for the directional dependence of localised driving rain is recommended before the use of hygroscopic cladding materials, such as lime based renders, are specified as a surface coating to sorbtive materials such as woodfibre board, as for instance in the Lime Passivhaus at Ebbw Vale (Figure 42).

Figure 42 Lime rendered South facade of the Lime Passivhaus, Ebbw Vale

Further, the presence of air also alters moisture flow at the micro-scale (Descamps, 1997). Once a material is wet, the capillary sucked water displaces air out of the material's pores until only enclosed air bubbles are left (Hens, 2012). This phenomenon is known as the capillary moisture content and basically states that the value of the moisture uptake is sometimes limited to a value well below saturation.

None of these relationships are linear and as the air temperature increases, the Saturated Vapour Pressure (SVP) also increases exponentially (Tetens, 1930; Murray, 1967). This relationship has implications for the phenomenon of reverse diffusion or summer condensation, where the moisture flux is reversed.

Buxbaum et al (2007; 2008) have demonstrated that there is a risk of moisture vapour entering the vapour permeable outside layers of some passivhaus constructions and condensing on the external face of the internal vapour barrier. For this reason Buxbaum (2007) recommends that internal vapour retarders with high Sd-values[xxx] should not be used in timber construction, and that vapour permeable materials such as OSB-3 or

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[xxx] The Sd-value is a measure of the vapour diffusion resistance of a material and is the product of the vapour diffusion resistance factor (μ) and the thickness of the material (d).

intelligent membranes offer a better solution. The high external temperatures and humidities needed to drive a strong reverse vapour pressure differential are relatively rare in the UK, however inward diffusion of moisture vapour may readily occur as a result short wave radiation absorption warming external surfaces saturated by driving rain (Quirouette, 2004; Kuenzel and Zirkelbach, 2011). Climate change projections indicate that increasingly warmer and wetter summers are likely for much of the UK (Jenkins et al, 2007), this suggest that pre-cautionary assessment of this risk is advised, particularly where the structural elements of timber frame or steel constructions may be at risk.

The EnerPHit standard was launched by the Passive House Institute, in 2010 as a trial standard for use in retrofitting existing properties that would otherwise be too difficult or costly to refurbish to the full Passivhaus standard (PHI, 2010). Where insulation can be applied externally in a continuous manner, the EnerPHit standard is unlikely to present challenges from a hygrothermal perspective (except where water is trapped in the construction during installation).

The EnerPHit standard specifies that the overall thermal transmission coefficient of internally insulated walls must be <0.35 W/m^2K (Feist, W., 2012a). In the case of internally insulated floors, the thermal transfer coefficient multiplied by the ground temperature reduction factor (f_t) should be <0.15 W/m^2K (PHI, 2010). The guidance documents also state that the construction of the ground floor covering must result in an internal floor surface temperature of at least 17 °C for the design conditions (assuming an indoor set point temperature of 20°C) (PHI, 2010). Assuming a typical annual ground temperature reduction factor range in the UK of 0.62 (Central London) to 0.75 (Outer Hebrides) (Feist, 2012), then this would imply that the actual U values for the floor build up should be no greater than 0.2 - 0.24 W/m^2K, depending on the location. This would be equivalent to adding approximately 14cm (or more) of XPS insulation ($\lambda = 0.035$ W/mK) to the warm side of an un-insulated concrete slab.

Such targets are necessary if radiant surface temperature asymmetry is to be minimised within the limits of acceptability set out in EN ISO 7730 whilst achieving an overall specific heating demand of $q_H \leq 25 kWh/m^2.yr$ (Feist, 2012a). Implementation of the EnerPHit standard can presents significant technical challenges where ambitious energy reduction targets are imposed in contexts where thermal bridging issues and interstitial condensation problems are likely to be exacerbated. When internal insulation is applied the temperature gradient across the wall/ floor or roof element will become more pronounced and existing structural elements will be at much lower temperatures in winter. This will reduce the drying potential of saturated walls and could also lead to significant frost damage where temperatures fall below freezing point.

Thermal bridges are likely to be exacerbated where internal insulation is used, particularly at junctions where the insulation is not continuous. Careful detailing around all junctions (including window reveals, party walls etc.) is needed to ensure that localised internal surface temperatures do not fall below a minimum threshold of 12.5°C (Pfluger, 2006). This guidance is based on the assumption that with an internal air temperature of 20°C the dewpoint temperature will occur at 12°C (with an internal RH of 60%). In such situations two and three-dimensional analysis of thermal bridges and transient hygrothermal modelling will almost certainly be required to determine whether long term damage is likely to occur either via mould growth or moisture accumulation.

Thermal bypass poses another serious risk where internal insulation is used. Warm air convected around or through internal insulation due to a breach in the airtight barrier (or an internal cavity) can lead to air with a high vapour pressure condensing on cold surfaces deep within the construction. Problem areas include window frame junctions and the ends of timber joists in floors and ceilings. Internal insulation must therefore be installed in an airtight manner; Pfluger (2006) suggests that a target q_{50} (air infiltration) value below $0.6m^3/m^2.h$ should be maintained for this reason. A detailed study of the long term performance of 14 different internal insulation approaches (including capillary active insulation materials) used in conjunction with different types of vapour retarders across a range of driving rains zones can be found in AkkP 32 (2005).

The EnerPHit guidance was amended in 2012 to define a new standard ‘EnerPHit^{+I}’ which applies to situations where more than 25% of the opaque external wall area is to be internally insulated (Feist et al, 2012a). Although internal insulation is often the only acceptable route to refurbishing dwellings in the UK that are subject to conservation or planning restrictions, the risks inherent in this process cannot be neglected. In practical terms a comprehensive survey of the existing building fabric and services should be carried out before internal insulation is specified. Potential risks such as: inhomogeneous materials and voids, heating pipes embedded in the outer wall, air leakage paths at critical junctions, thermal bridges and convective bypass routes must be carefully assessed before internal insulation is installed. Altering the hygrothermal behaviour of an outer wall which is acting as a rain screen or buffering system could have significant consequences for the long term durability of the building fabric.

The revised EnerPHit guidance states that: for interior insulation proof of suitability must be provided by means of an expert report, based upon accepted testing procedures (e.g. hygrothermal simulation) (Feist, W., 2012a). This is the first time that an energy performance standard adopted in the UK has mandated third party indemnity procedures with respect to hygrothermal risk assessment.

5.1.4 UK LEGISLATIVE GUIDANCE (PART C2 AND EN 13788)

Although rarely referred to, the UK Building Regulations Approved Document C (ADC) (BR ADC, 2010) addresses site contamination (Part C1) and moisture for new build construction (Part C2). Amongst other information ADC2 provides additional information for different wall constructions, insulation types and finishes or cladding to be specified appropriate to the regional driving rain location in the UK (see Figure 43).

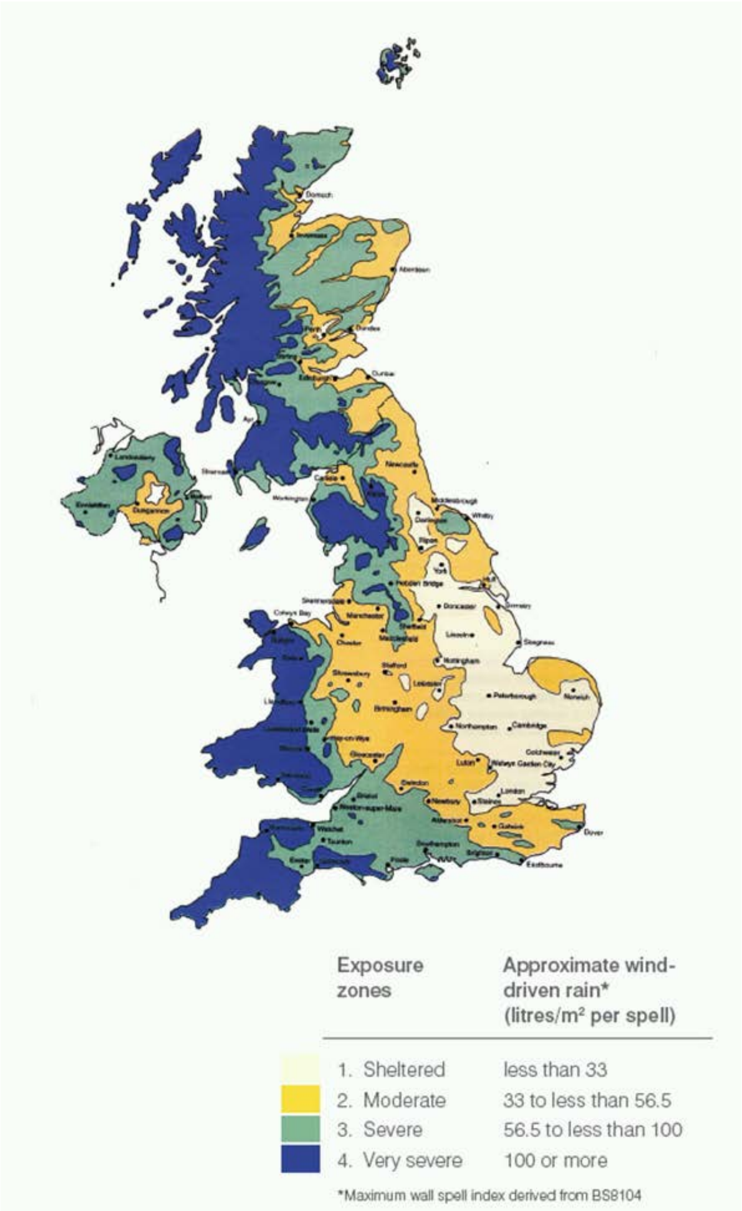

Figure 43 Impact of driving rain in the UK (Sterling, 2002)

For example, it is stated that in the regions prone to severe driving rain (zone 4) either an impervious rain screen or complete rendering of the facing masonry is advised (BR ADC, 2004, p35). Such guidance stands in significant contrast to what has actually been implemented in much of the recent UK building stock where brick walls, often with recessed pointing, are found in regions with 'severe'(zone 3) and 'very severe'(zone 4) driving rain exposure (Figure 43).

However, although Part C is an Approved Document and part of the UK building regulations, this section is considered to be 'guidance' rather than an enforceable requirement.

Moisture content has an important impact on the building performance. These effects range from modification of the thermal performance of insulation, through to structural collapse of buildings and chronic health issues. Moreover according to (Hens, 1990) there are serious risks of surface mould formation if the inside of the building envelope reaches equilibrium at 80% RH (relative humidity). Not only is building performance affected by moisture but indoor air quality (IAQ) and hygienic conditions become less favourable as moisture levels rise above an optimum threshold. Mould and dust-mite allergens are closely correlated to indoor Relative Humidity (RH) levels above 45% RH (Emenius et al. 2004; Franchimon, 2009) and are directly attributed as a causal agent of allergies and asthma (Pulimood et al., 2007). The UK has one of the highest rates of asthma in the world (Covey, 2004) and its regional prevalence is closely correlated to areas of high rainfall and fuel poverty (Asthma UK, 2008).

5.2 HYGROTHERMAL CONSEQUENCES OF HIGH INSULATION VALUES

5.2.1 APPLICATION AND LIMITATIONS OF THE GLASER METHOD IN PRACTICE

The Glaser method (BS EN ISO 13788, 2002[xxxi]) assesses the moisture balance of a building component by considering vapour diffusion transport from its interior. Developed during the late 1950's the Glaser method was originally conceived as a means to evaluate interstitial condensation on freezer walls (Glaser, 1959). Nevertheless, it became one of the most common tools used to analyse the moisture balance of building components, and is commonly referred to as the 'dew-point method' in the USA (ASHRAE, 1993). It was subsequently upgraded by including the effects of capillary action and by the incorporation of more realistic indoor and outdoor boundary conditions (Hens, 2012).

Although it has become a commonly adopted method, it cannot always be relied upon to give a reliable indication of vapour diffusion and moisture behaviour through the building structure due to its simplified steady state assumptions. In reality dynamic simulation tools that are capable of accounting for: thermal and hygric inertia (sorption/desorption), for capillary moisture movement, as well as taking into account variations in non-homogenous material property values, whilst allowing consideration of wind-driven rain, building

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[xxxi] Note since the time of writing BS EN ISO 13788: 2002 has been replaced by BS EN ISO 13788: 2012, which was published in January 2013.

moisture sources etcetera are more likely to produce reliable predictions. BS EN 15026 (2007) was the first European and British standard to address the transient hygrothermal performance of building components, using numerical simulation. However, despite the existence of this standard and the availability of transient hygrothermal software packages conforming to it, the Glaser method remains the most commonly used moisture analysis method in the UK construction industry. The fact that the Glaser method is relatively simple to use and is incorporated in a number of widely used in building energy models and U-value calculators (including BuildDesk Energy, IES-ve, Hevacomp, JPA Designer, amongst others) may explain its popularity as a tool for the determination of surface and interstitial condensation phenomena and the ancillary risk of mould growth.

The Glaser method essentially proposes that it is possible to calculate the vapour pressure evolution through a building component in a similar manner to which one determines the temperature evolution through layers of a building component. According to the Glaser method, condensation will appear on or within a layer where the calculated vapour pressure exceeds the saturation vapour pressure at a given temperature (i.e. the dew point temperature is reached). Generally, the overall moisture response is more pronounced in winter, as the vapour pressure gradient across a construction element is higher at this time due to lower external temperatures which limit the absolute moisture content (and hence saturation vapour pressure) of the external air.

Since interstitial condensate typically accumulates at the interface between construction materials or within a porous material layer, the consequences of this moisture accumulation may not be visible at the internal surface of the building for several years. In some circumstances, such as inside cellulose based insulation materials or structural timbers, the condensate may have caused irreversible damage at this point. Theoretically, the amount of interstitial condensate forming in winter and the amount of evaporable water in summer can be evaluated using the Glaser method as well. If the materials are able to seasonally absorb and desorb the same amount of moisture without creating long term build up (Künzel, 2000) there is, in theory, no problem. The Glaser method assumes that a given amount of built-in water will dry out during the summer period based on the steady state boundary conditions used, however this method does not take into account a number of important physical phenomena (including the transient nature of boundary conditions) and consequently the method is applicable only to structures where these effects are negligible. The application and limitations of the method have been described in BS EN 13788 (2002).

According to Künzel (2000) in one study comparing the interstitial condensation predictions in roof constructions, the Glaser method and the dynamic simulation software (WUFI) gave fairly similar results. However, Künzel points out that evaluating short time step variations in the boundary properties using the Glaser method are limited and that is why it is, in some cases, essential to use dynamic simulation tools. One example might be the effects of solar and long wave re-radiation on sol-air boundary temperatures or, perhaps more importantly in a UK context, the influence of prolonged spells of driving rain or melting snow which may affect the moisture conditions but are neglected in steady-state calculations.

In the United Kingdom where large regions (such as Northern Ireland, and the Western coasts of Wales, Scotland and the SW) are confronted with severe driving rain (Figure 43), the use of dynamically coupled heat and moisture simulation becomes increasingly important.

In a study conducted by May (2009), the difference of three different wall constructions, of approximately similar *U* values, located in two different climate zones is shown. One is modelled under a moderate climate in London and the other one being located in Swansea/ Wales facing severe driving rain. May's (2009) study illustrates the failure of conventional insulation materials such as using PU foam insulations by demonstrating the moisture content rising in the wall construction over time and reaching its critical failure point after only 2 years' time in the relatively sheltered London location; even worse, the same construction is predicted to fail within the first 9 months if located in a more severe climate such Swansea.

In contrast to the Glaser method, dynamic hygrothermal simulation, incorporating transient heat, air and moisture (HAM) transport in one and two-dimensional assemblies, introduces the possibility of more realistic modelling of material properties. Some material properties are easy to measure (density, dry thermal conductivity, the sorption isotherm, vapour permeability and air permeability) (Hens, 2012). Others however, for instance moisture diffusivity and thermal moisture conductivity demand complex and time-consuming tests (Roels, 2008; Hens, 2012).

5.2.2 MODELLING UNCERTAINTY IN MATERIAL DATA AND OUTPUTS

Hens (2012, p30) points out that despite such advances limitations still exist in dynamic modelling due to, "too simple material modelling and uncertainty in material properties". Figure 44 (Hens, 2012) shows the results of a series of dry cup vapour resistance factor measurements on 30 facing brick samples from the same production batch in order to demonstrate the problem of non-homogeneity in building materials.

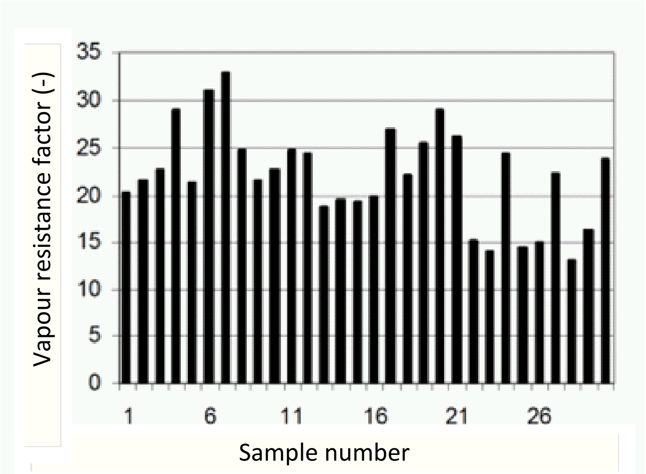

Figure 44 Dry cup vapour resistance value measured on 30 samples of bricks from a single production batch (Hens, 2012)

Building materials are heterogeneous by nature; however natural variation in material data creates uncertainty in modelling parameters which cannot be resolved in a straight forward manner. In a study by Woloszyn and Rode (2008) it was shown via several whole building design calculation methods that relying upon the assumption that heat and moisture transfer can be neglected produces significant uncertainty in the outcome. This uncertainty increases even more when air and moisture transfer is taken into account. Blind inter-model comparison of the results produced by a thirteen HAM models when benchmarked against BESTEST case 900 (Judkoff and Neymark, 1995), showed variations of up to 370% (Woloszyn and Rode, 2008). More recently researchers such as Costola (2011) have attempted to reduce this modelling uncertainty by developing new external coupling methods to integrate building energy simulation with heat and moisture simulation.

Physical uncertainties are mostly identifiable as the standard input parameters in energy, thermal comfort or heat and moisture simulation. Physical uncertainties refer to physical properties of materials such as thickness, density, thermal conductivity, or the hygrothermal properties of wall, roof and floor layers. Due to the manufacturing processes and random variations occurring in natural materials such uncertainties are always present, and thus inevitable (Hopfe, 2009; Hopfe and Hensen, 2011).

Obtaining sufficient information about specific variations in material properties is not always straight forward; especially in the case of natural materials such as sheep wool, cork, hempcrete and strawbale. Information about the physical properties of such materials is often either very limited or differs significantly according to different sources and measurement techniques (Table 9) (e.g. Adensam et al., 2005; Christian et al., 1998; Hens, 2012). The introduction of new harmonised European product standards EN 13162 to EN 13171 (amongst others) is intended to establish a level European playing field for all commercially manufactured insulation materials. This has led to the adoption of what is known as the λ90/90 assessment method for insulation materials, whereby the 90/90 fractile is the compliance criterion for the product group. In other words the declared product λ-value represents the 90th percentile confidence level being achieved by 90% of production output (Figure 45) (BBA, 2012). The use of the performance benchmark λ-value derived from a manufacturer's λ90/90 assessment is now the accepted method used for generating the thermal values used in PHPP modelling. What may be more helpful in assessing the uncertainty in hygrothermal performance analysis would be to have information regarding the range of individual key parameters available as model inputs within an appropriate confidence level.

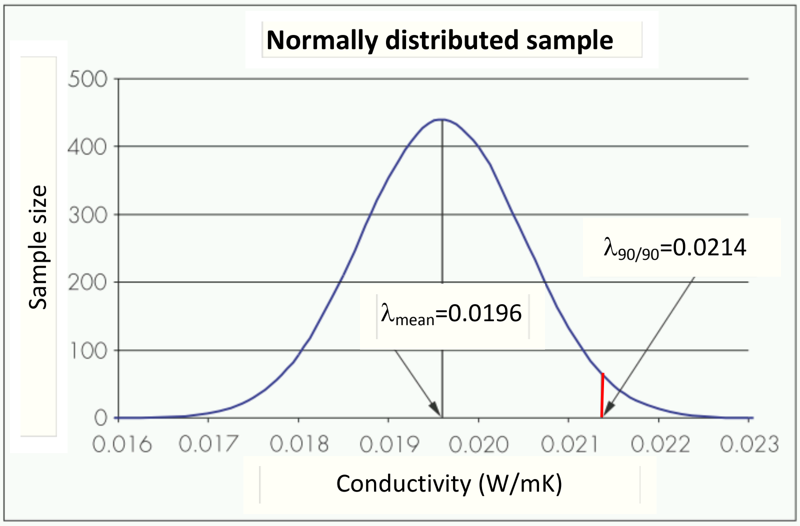

Figure 45 Example showing the λ90/90 assessment method (adapted from BBA, 2012)

Variations or uncertainty regarding material moisture content or specific hygrothermal properties as well as variations in the sources or heat and moisture within the building envelope will in reality significantly affect the thermal and hygric performance of the building. If for example an insulation material becomes wet, the thermal conductivity of the insulation material will increase, which consequently affects the buildings energy consumption. Taking these compounding uncertainties into account is ultimately related to quality assurance. Despite the designer's best attempts at quality assurance there will always remain a degree of uncertainty that they have no influence upon. In the case of strawbale for example, Sutton et al (2011) recorded changes in density varying from 100-130 kg/m3 and thermal conductivity in the range of 0.05-0.065 W/mK. Organic materials such as straw, cork, etc. are strongly hygroscopic and therefore have non-linear vapour permeability characteristics.

The influence of such transient material properties is likely to be underestimated in current data (even that used in dynamic simulation) when considering the in-situ behaviour in high humidity regions such as the UK. Most material databases do not yet contain such data in relative humidity ranges and literature reviews often provide incomplete information. An example showing variations in the measured physical properties (bulk density, thermal conductivity and water vapour diffusion resistance) of strawbale as measured by different researchers is shown in Table 9.

Table 9 Bulk density, thermal conductivity and water vapour diffusion resistance for strawbale according to literature

REFERENCE SOURCE	ρ_{bulk} (kg/m^3)	λ_{dry} (W/mK)	μ (-)
Munch-Andersen and Moller Andersen (2008)	75-90	0.052-0.057	
Haus der Zukunft (2000)	100	0.038	
Christian et al. (1998)	62-81	0.057-0.082	
McCabe (1993)	150	0.048-0.06	
Acton (1994)	90	0.05-0.06	
Hemke (2009)		0.052-0.08	
Sutton et al. (2011)	110-130	0.055 – 0.065	
Goodhew and Griffiths (2005)	60	0.067	
Danielewicz et al. (2008)	100	0.045	1.3
DIBt (2006)		0.052-0.08	2
Adensam et al. (2005)			1
Fuehres (1996)			2-5

5.2.3 WEATHER DATA UNCERTAINTY

The UK is a nation of varied micro-climatic contexts, and a diverse existing building stock. The adoption of dynamic hygrothermal simulation, if correctly implemented, can be seen as a step forward in both the diagnostic recognition of typological problem areas and the prevention of future damage to individual buildings.

Accurate in-situ prediction of moisture problems in buildings requires boundary data sets which reflect the internal and external conditions that the building is likely to face. The key parameters needed to model the climatic influences on a building include the following (IBP, 2010; Künzel, 2006; Künzel and Zirkelbach, 2011):

- rain load vertically incident on the exterior surface (l/m^2h)
- solar radiation vertically incident on the exterior surface in (W/m^2)
- temperature of the exterior air (°C)
- relative humidity of the exterior air (0-1)
- temperature of the interior air (°C)
- relative humidity of the interior air (0-1)
- barometric air pressure (hPa).
- long-wave atmospheric counter-radiation (W/m^2), if night time radiative cooling is to be accounted for

Rain load and radiation are directionally dependent quantities, however in conventional weather station measurements they are usually only recorded on horizontal surfaces. With knowledge of the vertical rain load and the wind velocity and direction it is possible to compute the directionally dependent driving rain. Likewise the amount of radiation incident upon any given surface tilt angle or orientation can be determined from knowledge of the global and diffuse radiation components incident on a horizontal surface for a given latitude and time (Muneer, 2004). WUFI performs these directional conversions automatically and will recognize data files in .WAC, .WET, .TRY, .DAT or .IWC format. In some cases an additional file (.AGD) is needed to supply geographical data regarding the climate location (IBP, 2010). Although data is available for a wide number of locations worldwide using the ASHRAE IWEC data (.IWC) caution is advised as this does not typically contain quantitative rainfall data (IBP,2010).

By integrating the dynamic hygrothermal capabilities of WUFI with the quasi steady state energy model PHPP, the Fraunhofer Institute has developed WUFI-Passive (IBP, 2012). This integrated design tool was originally developed for the U.S. Passivhaus market where issues of cooling and dehumidification are more pronounced than in central Europe. The WUFI-Passive software avoids the double entry of common data from the building energy model to the hygrothermal model ensuring that valuable hygrothermal outputs are now available to designers at the early stages of design.

Currently the WUFI software does not contain any default climate data for the UK and this may be a factor in limiting its adoption by less experienced practitioners. None-the-less there are a number of options available to obtain suitable hygrothermal weather datasets for the UK. TRY data is readily available from the CIBSE for 14 UK locations. CIBSE is due to release future probabilistic weather files in the form of Test Reference Years (TRYs) and Design Summer Years (DSY) derived from UKCP09 scenarios that cover three time periods, three emissions scenarios, and three probability levels for each of the 14 locations available in the current CIBSE datasets. These future weather files were produced using the morphing method detailed in TM48: Use of climate change scenarios for building simulation (Shamash, 2012).

Several researchers have noted the limitations of using the 'nearest neighbor method' of transposing climatic data from one micro regional context to another in building energy and moisture models (McLeod et al, 2012b) (Morehead, 2010) (Remund, 2010). In order to address this situation and provide a clearer statistical basis for decision making the PROMETHEUS project at Exeter University developed a new method for generating high resolution (5km grid data) in an EPW file format. Using primary outputs from the UKCP weather generator Eames et al (2010) created a series of probabilistic weather files in TRY and DSY format. The weather generator is a stochastic randomly seeded model which combines measured data from the UK Met Office with data downscaled from the Hadley Centre's Regional Climate Model (HadRM3) for various future climate scenarios (DEFRA, 2009). The method used by PROMETHEUS allows the development of current and future probabilistic datasets, following the main IPCC SRES emission scenarios (IPCC, 2000), for use in building programs requiring hourly simulation time steps. A full description of the methodology including that used to derive missing variables such as future wind speed, wind direction and atmospheric pressure can be found in Eames et al (2010).

A further option for deriving data at sites where either measured or synthesized data is unavailable is through the use of the Meteonorm interpolation software. Meteonorm uses interpolation methods (such as 3D inverse distance models for global radiation) to create weather files in almost any output format for any location in the world (Remund, 2010). Although the use of interpolation has been shown to entail a level of inaccuracy (Rawlins, 1984), particularly for Global Horizontal radiation and ambient temperature, Remund (2010, p32) points out that the root mean square errors (RMSE) for this method are typically less than when the 'nearest neighbour' approach is adopted. Analysis carried out by the Fraunhofer IBP suggests that driving rain and wind data produced by Meteonorm can be too homogeneous in its distribution and therefore not always reflective of local conditions (IBP, 2010). In Germany the Holzkirchen climate dataset is commonly used in hygrothermal simulations as a 'worst case' reference location for driving rain. No such location has yet been adopted in the UK as a proxy for 'worst case' analysis, however a number of locations situated within exposure class 4 (very severe) driving rain category (ADC, 2004) would make suitable candidates. EN 15026 (2007) suggests a simplified proposal for the generation of extreme climate years by creating simple shift functions of +2K for a warm year and -2K for a cold year. Such approximations may suffice as part of an initial sensitivity analysis depending on the accuracy and temporal period being considered. Regardless of the climate data used a sound knowledge of the uncertainty inherent in the modeling process and familiarity with the micro climate of the building being modeled are important pre-requisite for interpreting the outcomes of hygrothermal simulation.

Uncertainties in modelling and climate data are just a few of many other limitations in dynamic simulation. To date most commercially available models overlook air and wind intrusion as important factors when looking to the hygrothermal response of wall and roof constructions. Other limitations exist with respect to the modelling geometry of building components (the reality compared to what the tool allows), perfect hydraulic contact conditions, boundary conditions (for instance the randomness and localised pooling of wind driven rain) (Blocken, 2004). Further to this in order to provide comprehensive outputs there is a need to judge indoor air quality, health and durability (Hens, 2012), all of which are challenges yet to be addressed by dynamic simulation models .

5.3 CONSEQUENCES OF RETROFITTED CAVITY WALL INSULATION

A number of UK government funded strategies have been implemented over the past decade in order to reduce fuel poverty and improve the thermal performance of Britain's worst performing housing. The most recent government initiated carbon reduction scheme - Carbon Emissions Reduction Targets (CERT), was targeted towards electricity and gas suppliers to reduce the amount of carbon emissions from dwellings (Ofgem, 2011). The scheme was originally to be run from April 2008 to March 2011, but was extended to end in December 2012 (DECC, 2012). According to Ofgem (2013) the Carbon Emissions Reduction Target (CERT) was the main legislative driver for improving energy efficiency of homes within Great Britain between 2008 and 2012. Figure 46 shows different methods of saving carbon emissions under the CERT scheme, it can be seen that the most popular method was insulation, which included both loft insulation and cavity wall insulation (Ofgem, 2011).

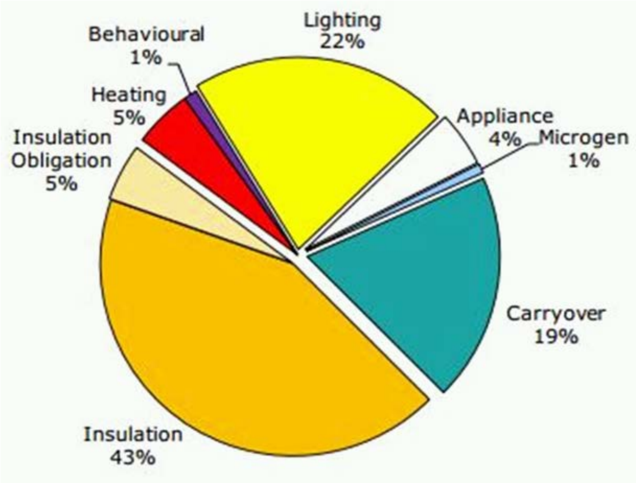

Figure 46 Comparison of achieved carbon emissions by measure type used in the Carbon Emissions Reduction Targets to reduce CO_2 emissions up until August 2011 (Ofgem, 2011)

By the end of the third year of the CERT (2008-2012) scheme, it was estimated to have saved a total of 296.9 Mt CO_2 of emissions from a combination of energy efficiency measures including 75.1 Mt CO_2 of savings which were achieved through measures installed under the insulation target (Ofgem, 2013). The most popular material used for the insulation of the cavity walls under this scheme was mineral wool (Ofgem, 2011).

It is estimated that 69% of dwellings in England have a cavity wall present; of which only 40% have cavity wall insulation (BRE, 2005). A comparison of the regional prevalence of cavity walls and dwellings with cavity wall insulation can be seen from Table 10.

Table 10 Regional distribution of cavity wall insulation in dwellings according to location (adapted from BRE, 2005)

LOCATION IN ENGLAND	DWELLINGS WITH CAVITY WALL	DWELLINGS WITH CAVITY WALL INSULATION
North East	87%	36%
London	43%	29%
South West	71%	38%

The cavity method of wall construction was first introduced in UK during the early Victorian period (English Heritage, 2010) and had become a widely adopted construction method for dwellings by the 1920's, (Energy Saving Trust, 2002). Initially they were introduced to replace solid wall construction in order to reduce construction costs, and also to provide protection from driving rain penetration on the internal envelope (English Heritage, 2010). The concept was considered effective in that it allowed rainwater and moisture to be removed from the building envelope through the cavity area of the wall (Osbourn, 1985).

A number of factors need to be considered before cavity wall insulation material can be retrospectively injected into a dwelling, such as rain penetration (Energy Saving Trust, 2002), location of the dwelling (Smith, 2005) and exposure (Which?, 2011) as well as the type of insulation to be injected (BR ADC, 2004). Inbuilt and Davis Langdon (2010) state that by installing cavity wall insulation in a dwelling, the risk of cold bridging, condensation and frost damage is increased.

It can be seen from Figure 43 that wind-driven rain affects various locations of the UK with differing intensities, from zones less than 56.5 l/m^2 to zones that receive in excess of 100 l/m^2 of driving rain per spell. According to Edwards (2011) no consideration is given to wind driven rain or the buildings location during the pre-assessment for the suitability of applying cavity wall insulation to a specific dwelling, despite guidance in Approved Document C (2010, p35). Dwellings in various locations will all receive different amount of moisture penetrating into the cavity wall area. This observation is confirmed by Gellert

(2010a; 2010b) who believes that the location, latitude and altitude of a dwelling should all be taken into consideration, before the installation of cavity wall insulation is specified.

The Energy Saving Trust (2002) also recommends that the wall construction and condition of dwellings should be taken into account before installing cavity wall insulation. Problems such as leaking gutters may cause the wall to be saturated, therefore potentially exacerbating problems after insulation has been injected into the cavity area. The British Standards Institute guidance on foam filled cavity walls BS 5618:1985 (BSI, 1985) states that any defects that will subsequently affect the cavity wall after the injection of insulation, should be rectified before insulation is installed, and this should form a part of the contract.

5.4 CONCLUSIONS

It was aim of this chapter to illustrate the current challenges facing the practice of hygrothermal assessment in the UK in the context of rapidly evolving building performance standards. The UK is characterised by highly localised climatic conditions and experiences extreme driving rain conditions along much of its Western border. The existing stock is characterised by a high percentage of historic buildings and historically low demolition rates (Boardman et al, 2005); this means that advanced thermal refurbishment measures will need to be applied to a very high percentage of the existing stock if the UK if it is to meet its climate change and fuel poverty abatement targets. Planning, space and aesthetic considerations suggest that a large percentage of the existing stock will need to be internally insulated in order to meet these targets (Boardman et al, 2005; Boardman, 2007; Killip, 2008).

The hygrothermal consequences of attempting to meet advanced thermal performance standards (such as Passivhaus and EnerPHit) and alleviate fuel poverty have been widely overlooked in the race to reduce CO_2 emissions and fulfil the energy efficiency commitments of utility companies. The UK Building Regulations currently provides disparate information on the Conservation of Fuel and Power (Part L) and the provision of Ventilation (Part F). This guidance needs to be harmonised with the inclusion of more robust guidance in Part C2, particularly with respect to post-filling cavity walls and more advanced refurbishment measures, including internal insulation and the use of porous and hygroscopic cladding materials in super-insulated wall constructions.

This chapter has highlighted areas where there is clearly a need for more research to be conducted and demonstrates the evolutionary role that transient hygrothermal modelling will needs to play in the refurbishment and the design of the future UK building stock. Unless accompanied by widespread building physics training schemes, for UK building professionals, it seems likely that achieving deep refurbishment targets may engender serious risks for the moisture response and structural integrity of many UK buildings.

Current de-facto practice of using steady state modelling (Glaser method), and the assumption of homogenous material properties, as a means of condensation analysis has been demonstrated to be unreliable - particularly in advanced refurbishment cases. The widespread adoption of dynamic heat and moisture simulation should form part of the precautionary approach, particularly where significant levels of internal insulation are used and the dew point falls inside the thermal envelope. The development of new tools (such as WUFI-Passive), capable of coupling heat and moisture processes in an integrated platform, offer a potential step change by making reliable hygrothermal information available early in the design process.

As with all building simulation tools the results obtained can only supplement and further assist a detailed knowledge of the existing structure, local weather patterns and careful on-site assessment and implementation; factors that are indispensable to the effective realisation of modelled predictions in reality. Only by better understanding the 'real world' behaviour of the system being modelled and the limitations of the model itself can more robust design predictions be achieved.

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CHAPTER 6 | DISCUSSION AND FURTHER REMARKS

DISCURSUS:

The preceding four chapters have addressed diverse issues and implications inherent in successfully adapting and implementing the Passivhaus standard in the UK. The findings of this research have raised a number of important questions, both for policy and praxis. Before drawing specific conclusions to close this thesis (Chapter 7), this chapter provides a brief discussion and remarks in relation to the wider implications of the research and its relationship with existing research.

6.1 CHALLENGES FOR POLICY

Carbon budgets were introduced in the UK in 2008 in order to ensure a planned and legally enforced decarbonisation trajectory as part of the Climate Change Act (DEFRA, 2007). These budgets are divided in to two sub-sectors: The traded sector, which is based on the UK's share of the EU Emissions Trading System (EU ETS) limit and includes the power and heavy industry sectors; and the non-traded sector includes everything else, including road transport, agriculture and buildings (HM Government, 2013). The first four carbon budgets are set in law and cover the period from 2008 – 2027. The UK is currently on track to meet the first three carbon budgets, however by the time the fourth budget arises (2023-2027) an estimated shortfall of 205 $MtCO_{2\,e}$ is expected to occur (HM Government, 2013). In order to reduce this impending emissions deficit tighter non-tradable emission reductions are needed.

The built environment plays a dominant and expanding role in the total GHG emissions from the non-traded sector. According to the UK Government Environmental Audit Committee substantial measures are needed to prevent a near doubling of the total GHG emissions from the housing sector by 2050 (House of Commons, 2005). Analysis in this thesis (Sections 2.5 and 4.3) shows that adopting the Passivhaus standard as a minimum performance standard for all new build dwellings could make a significantly greater contribution to reducing emissions from the housing sector than the FEES alternative. Furthermore the experience gained from implementing higher levels of energy efficiency in new build housing could help to facilitate the knowledge transition and up-skilling needed to effectuate similar levels of change in the retrofitting of the existing stock.

A number of policy changes are needed in order to facilitate the widespread uptake of the Passivhaus standard in the UK:

- Certified Passivhaus dwellings should be ‘deemed to comply’ with Part L of the UK Building Regulations (2013), in order to avoid the unnecessary need for separate energy modelling and reporting in respect of energy consumption, carbon emissions and Energy Performance Certificates (EPCs).
- More robust guidance is needed in Part C of the UK Building regulations in respect of the moisture risks associated with super-insulated wall, floor and roof constructions. Particularly with respect to the use of fully filled cavity walls and internally insulated wall and floor constructions.
- ‘Allowable solutions’ involving carbon offsetting outside of the immediate development site should not form part of the permitted criteria for meeting the ‘zero carbon’ definition. Since buildings form part of the non-traded sector of the UK’s carbon budgets (HM Government, 2013) it is imperative that emissions are reduced at the level of the built environment where they occur.
- The Passivhaus standard should replace the FEES standard as the minimum level of energy efficiency required to define a 2016 ‘zero carbon’ dwelling in the UK. In addition to achieving greater carbon and energy savings, a single energy efficiency standard would expand the market for higher quality components and drive down the economic costs of delivering ‘zero carbon’ homes.
- The Passivhaus standard Primary Energy targets should be periodically reviewed on a national basis in order to ensure that national emission trajectories continue to be followed, in light of an expanding UK housing stock and increasing domestic electrical energy consumption. Vallentin (2009) suggested that by 2010 the PE target for Passivhaus dwellings (in Germany) should have been lowered to ≤100 kWh/m^2.yr and by 2050 the PE target should be ≤60 kWh/m^2.yr (i.e. half the level of the current Passivhaus standard), in order to follow a decarbonisation pathway similar to the UK’s.

- Further consideration of embodied carbon in UK buildings appears to be an essential next step in order to meet the targets set in subsequent carbon budgets. Research by Stephan et al (2013) has demonstrated that the majority (>70%) of the total carbon emissions associated with dwellings built to the Passivhaus standard lie in the embodied energy content of the materials. It would be relatively straightforward to extend the Passivhaus concept to include an embodied carbon cap, as described by McLeod (2007) and therefore create a framework for true Zero Carbon dwellings.

6.2 CHALLENGES FOR PRAXIS

The successful implementation of the Passivhaus standard, on the scale required to meet the demand for new build housing in the UK, could result in an unprecedented step-change for the UK house building industry. If the Passivhaus standard were to become the minimum standard of energy efficiency required to meet the 2016 ‘zero carbon’ target (or to qualify as a ‘zero energy’ home under the 2019 European EPBD) then substantial facilitation of the Passivhaus design, build and certification process is required. The following practical measures would help to ensure that the role out of the Passivhaus standard can be achieved on a wide scale without a substantial loss of quality control:

- Certified Passivhaus Designer and Tradesperson training courses are available for architects, engineers and tradespeople in the UK. These courses are expensive and remain relatively undersubscribed. Government funding and subsidies would be likely to increase the uptake of these schemes. Further embedding the training offered into university and technical training college syllabuses would also help to accelerate industry wide knowledge transfer.

- The software used to design and certify Passivhaus buildings (PHPP) is currently in Excel format and this limits the possibilities for visualisation, and data exchange with other platforms. Methods for improving data exchange with the PHPP model have been demonstrated, as shown in for instance by Cemesova (2013) and beta prototyping of the Design-PH interface for SketchUp. BIM based data exchange models are advancing rapidly and will ultimately enable better data exchange between multiple tools, as well as reducing the designers’ workload.

- The PHPP model does not currently address moisture transfer related issues, and this situation necessitates the re-entry of building geometries and construction profiles into additional software in order for hygrothermal risk assessments to be carried out. The recently developed WUFI-Passive tool (IBP, 2012) overcomes this limitation; however at the time of writing (July 2013) this software had not been ratified by the Passivhaus Institute as a compliant tool for Passivhaus certification.

- There is already evidence in Part L of the UK Building Regulations, and the revised 'zero carbon' definition, that a shift is taking place away from prescriptive (or elemental) design values in favour of performance based metrics based on defined parametric limits. Struck (2012) argues that a further evolution towards risk based limits as defined by descriptive statistics (such as probability distribution functions) is a logical extension of this process. As such uncertainty propagation and sensitivity analysis techniques are likely to play an increasing role in defining both the performance and optimization of low energy buildings in the future. Practically, this implies that the future development of BPS tools such as PHPP should incorporate uncertainty estimates and sensitivity analysis techniques (as shown in Section 4.3.2)

- Micro-regional and future probabilistic climate data sets need to be made freely available if more accurate modelling procedures are going to be implemented on a wide scale. The methodology presented in this thesis for the creation of such data (Chapter 3) could be encoded into a suitable platform that would make the data readily available in the PHPP format for UK designers.

- Finally, advances in modeling procedures (such as stepping to 'full' hygrothermal modelling) or improved data quality alone will not suffice to refurbish buildings and construct new ones with the assurance of optimal design performance. A profound education in the fundamental concepts of building physics is a necessary first objective for all building professionals.

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CHAPTER 7 | CONCLUSIONS AND FURTHER WORK

The aim of this thesis was to critically examine a number of important issues affecting the implementation of the Passivhaus standard in the UK, and to propose new methods to address these challenges. In response to the original problem statement (Section 1.2) the research was divided into four main themes, with detailed conclusions and recommendations provided at the end of each of the individual research chapters (2, 3, 4 and 5). This chapter begins by recapping the original problem statement (Section 7.1). This is followed by a summary of the main conclusions and findings in response to the original research questions (Section 7.2). Suggestions for further research to build upon this work are then proposed (Section 7.3), followed by some brief closing remarks (Section 7.4).

7.1 THE ORIGINAL PROBLEM STATEMENT

The research in this thesis set out to address four key issues outlined in the original problem statement (Section 1.2), that could pose significant challenges to the widespread adoption of the Passivhaus standard as a template for future low energy and zero carbon housing in the UK. The issues identified were:

- Barriers imposed by UK ‘zero carbon’ policy and the Building Regulations (Part L) calculation methodology.
- Limitations imposed by the lack of micro-regional and future probabilistic climate data required for accurate Passivhaus design and modelling.
- Climate change implications for the future performance of Passivhaus dwellings.
- The limitations of adapting existing UK construction typologies to cope with the hygrothermal implications of super-insulated dwellings.

7.2 CONCLUSIONS

In order to address the four core issues identified in the original problem statement (Section 1.2), and to establish whether the hypothesis (Section 1.3) underpinning this research was valid a series of research questions were presented in Section 1.4. These research questions are repeated below, followed by a summary of the main conclusions that were drawn in response to them.

7.2.1 BARRIERS IMPOSED BY UK 'ZERO CARBON' POLICY AND BUILDING REGULATIONS (RESEARCH QUESTIONS 1–4)

Chapter 2 examined the relationship between the Passivhaus standard and the FEES standards in the context of the revised 'zero carbon' housing definition and overarching GHG mitigation targets set out in the UK Climate Change Act (2008).

1. Is the Passivhaus concept capable of achieving substantially greater CO_2 emission savings than an equivalent Fabric Energy Efficiency Standard (FEES) dwelling?

   Based on normalised comparisons between a detached FEES dwelling and a FEES flat and an equivalent Passivhaus dwelling and Passivhaus flat, the research has shown (in Section 2.5) that the Passivhaus concept is capable of achieving substantially greater (45 –50%) reductions in net operational CO_2 emissions. In terms of the comparative space heating demand savings, the research (Section 4.3.1) showed that the Passivhaus dwellings studied typically required only 15–20% of the useful space heating energy of an equivalent FEES dwelling in a present day climate. This finding stands in contrast to the figures suggested by the ZCH Energy Efficiency Task Group that a Passivhaus (Spec D) dwelling would result in a space heating demand of 23 – 29 kWh/m2.yr when modelled in SAP (ZCH, 2009b, p66).

2. Are methodological differences between the Standard Assessment Procedure (SAP) and the Passive House Planning Package (PHPP) masking a transparent assessment of the energy and carbon savings that can be achieved by Passivhaus dwellings?

   Based on a comparative assessment (Section 2.5) of the methodological assumptions underpinning SAP (2009) and PHPP V7 (2010), it appears that the SAP assessment procedure is masking the full energy and carbon saving benefit achievable from a Passivhaus dwelling. As result the Passivhaus performance figures presented by the ZCH Energy Efficiency Task Group are likely to substantially underestimate the full energy savings potential achievable by dwellings meeting the Passivhaus standard.

3. Can the Passivhaus concept reduce the need for 'allowable solutions and carbon offsetting' mechanisms?

   It follows (from conclusions 1 and 2 above) that due to the higher levels of energy efficiency and carbon emission savings resulting from the Passivhaus standard that the revised 'zero carbon' definition could be met with far less reliance on 'allowable solutions' and carbon offsetting mechanisms. Mandating the Passivhaus standard as the minimum energy efficiency standard for 2016 (in place of the current FEES standard) would provide greater coherence with the UK's overarching objectives in respect of energy security and climate change emission reduction targets.

4. Do the requirements for higher levels of air-tightness and the use of Mechanical Ventilation with Heat Recovery (MVHR) in Passivhaus dwellings pose a potential health risk to occupants?

   A review of the literature (Section 2.5.2) suggests that when correctly installed and maintained the higher levels of air-tightness and the use of MVHR ventilation systems in Passivhaus dwellings is unlikely to pose an annoyance or health risk to occupants. There is evidence to suggest that dedicated ventilation systems may actually slow down the development of some respiratory disorders and prevent the conditions necessary for the growth of a number of allergen producing agents. It is acknowledged that further research from a larger base of monitored projects is needed in a UK context to present conclusive evidence on the overall impact of air-tight dwellings and MVHR ventilation systems in relation to a broad range of IAQ indicators.

7.2.2 LIMITATIONS IMPOSED BY THE LACK OF MICRO-REGIONAL PROBABILISTIC CLIMATE DATA FOR PASSIVHAUS DESIGN (RESEARCH QUESTIONS 5–7)

Chapter 3 proposed a new method for generating high resolution current and future climate date and implemented this approach through a series of comparative case studies, thereby addressing research questions (5-7).

5. Is the current use of 22 regional proxy datasets (BRE, 2013), and the methodology by which these datasets were generated, sufficiently accurate for the design optimization of Passivhaus and ultra-low energy buildings across all of the UK's micro climatic zones?

   The generation of high resolution (5km grid) micro-regional climate data and comparisons with measured site specific climate data and existing TRY datasets has shown that the current use of 22 regional proxy datasets (BRE, 2013), is not sufficiently accurate for the design of Passivhaus and ultra-low energy buildings in all UK micro climatic zones. Significant under prediction of the specific heating demand and peak loads have been shown to occur in multiple regions (Section 3.4.2) using the current regional datasets, in comparison to the use of the higher resolution 5km grid data. Furthermore the current regional datasets do not allow designers to explore the uncertainty associated with climatic scenarios in the way that probabilistic climate data does.

6. Does the UKCP09 Weather Generator (WG) provide a robust basis for the development of more accurate micro regional and future probabilistic climate data for Passivhaus design?

   The UKCP09 Weather Generator (WG) provides a robust and validated basis (Section 3.2.5.3) for the development of more accurate micro regional and future probabilistic climate data for Passivhaus design. The use of established solar geometry algorithms and inter-variable relationship equations (as explained in Section 3.2.6 – 3.2.8) provides the potential for the outputs of the WG to be transformed into PHPP datasets. Thus generatingr in excess of 11,000 grid cell locations across the entire UK land mass and at any percentile of the Probability Density Function (PDF) and for any decade (up to 2080) and for a choice of 3 (High, Medium and Low) future emissions scenarios. As with any source of climatic data used in BPS, users need to be aware of potential sources of uncertainty inherent in the use of the outputs from the WG model (Sections 3.2.4, 3.2.5.3 and 3.4.2).

7. Will the use of higher resolution climate data result in more accurate design predictions, thereby preventing over and under engineering of Passivhaus designs?

   The use of higher resolution (5km grid) climate data is likely to result in more accurate site specific design predictions, which can thereby help to prevent over and under engineering of Passivhaus designs. Over and under engineered buildings carry substantial cost and long term performance implications and can be a significant cause of 'slippage' between design predictions and real world performance. The availability of high resolution probabilistic data, spanning a series of decadal time intervals, represents a significant step forward in improving the designers understanding of the possible range of performance predictions from Passivhaus and low energy buildings. In contrast to the limited information available from the use of a single deterministic data set.

7.2.3 CLIMATE CHANGE IMPLICATIONS FOR THE FUTURE PERFORMANCE OF PASSIVHAUS DWELLINGS (RESEARCH QUESTIONS 8–10)

Chapter 4 addressed the future performance and overheating risk in Passivhaus dwellings.

8. Do Passivhaus dwellings, as currently designed in the UK, offer a robust model in the face of future climatic changes?

   A review of the literature (Section 4.1.1) documenting overheating in European Passivhaus dwellings together with a limited number of first hand occupant reports describing overheating in UK and Irish Passivhaus dwellings, suggests that there is already potential for the risk of overheating to occur under a present day climate. Currently most of the reported overheating relates to highly glazed/ poorly shaded Passivhaus dwellings. In contrast to this Dynamic simulations of an optimized Passivhaus (south facing, moderately glazed with fully automated external shading) in an urban UK context demonstrated (Section 4.3.1) that it is possible to maintain high levels of thermal comfort under present day design conditions without active cooling. By 2050 in a warmer than average summer (in an urban environment) it may no longer be possible to achieve the same thermal comfort criteria without recourse to an active cooling system.

9. Will Passivhaus dwellings perform better or worse than equivalent FEES ‘zero carbon’ dwellings faced with identical future climatic change scenarios?

   Research comparing the projected future performance of FEES and Passivhaus dwellings using a DSP showed that well designed Passivhaus dwellings (i.e. with optimized glazing and shading systems) are capable of mitigating future overheating risks marginally better than an equivalent FEES dwelling.

10. Can the application of Global Sensitivity Analysis (GSA) techniques be used to improve whole life design optimization, by isolating the key design variables influencing the future performance of a Passivhaus dwelling?

    By coupling a GSA technique (the Enhanced Morris Method) with a validated Dynamic Simulation Program (DSP) the key design variables influencing the future performance of a Passivhaus dwelling were isolated and ranked (Section 4.3.2). This technique demonstrated a computationally efficient method of understanding the sensitivity of the dominant design parameters in influencing key performance criteria. An important finding from this sensitivity analysis was that designs optimized in relation to achieving a low specific heating load (SHL) showed a better correlation with factors resulting in reduced overheating risks than designs optimized in favour of a low specific heat demand (SHD). This finding suggests that better whole life thermal comfort may be achieved in Passivhaus dwellings which are designed on the basis of minimising the SHL than the conventional approach based on minimising the SHD.

7.2.4 LIMITATIONS ASSOCIATED WITH ADAPTING EXISTING UK CONSTRUCTION METHODS TO COPE WITH THE HYGROTHERMAL IMPLICATIONS OF PASSIVHAUS AND ENERPHIT DWELLINGS (RESEARCH QUESTION 11)

Chapter 5 addresses the hygrothermal implications of implementing low energy and zero carbon standards in relation to the UK climate and existing construction methods.

11. Are there additional issues specific to UK construction methods and the UK's maritime climate that may affect the long term hygrothermal performance of Passivhaus and EnerPHit dwellings?

    An analysis of existing UK guidance and practice in relation to the evaluation of moisture risks in building fabrics suggests (Section 5.1.3) that potentially serious risks are likely to occur unless significant changes are implemented. The use of the steady state (Glaser) analysis method has been shown to provide misleading results (Section 5.2.1) when assessing the long term performance of super-insulated wall, roof and floor constructions. The potential use of internal insulation and fully filled cavity wall constructions (Section 5.3), in relation to meeting advanced energy performance standards, significantly changes both the vapour pressure gradient and the location of the dew point within a construction profile. Furthermore large areas of the UK are exposed to severe wind driven rain (Section 5.1.4) which poses additional risks from capillary saturation that cannot be accounted for in a steady state analysis. In EnerPHit refurbishment and Passivhaus new build projects it is strongly recommended that one and two-dimensional transient hygrothermal risk assessment are carried out (in accordance with EN 15026 -2007) using appropriate boundary assumptions and climatic data. This is particularly important in contexts where internal insulation, fully- filled cavity walls, or construction detailing which has not been tested in a similar UK climate, is proposed.

7.3 FUTURE CHALLENGES

As a result of the research carried out in this thesis a number of recommendations can be made for further research which would contribute to strengthening the findings:

- Parametric and sensitivity analysis studies investigating the future performance of a broader range of Passivhaus building typologies (e.g. apartments, mixed use, care homes, schools etc.) in a wide range of micro-regional climatic zones.

- A detailed inter-model evaluation of outputs predicted by SAP (2009) in comparison to PHPP V8 (2013) in order to establish the magnitude of uncertainty associated with the predictions of both models, and to establish a means of valid inter-model comparison.

- A detailed assessment of the uncertainty associated with the use of summed hourly, versus mean daily, slope irradiation models used in the determination of the peak load irradiation data in PHPP.

- Further investigation of the appropriate peak load time constant (t_{peak}) or CIBSE response factor (f_r) methods in relation to both the sizing and uncertainty associated with the selection of appropriate (W1 and W2) heating and cooling load data in different Passivhaus and ultra-low energy building typologies.

- More precise (sub hourly) data is needed regarding the spatial distribution, timing and absolute levels of internal gains representative of a range of Passivhaus building typologies in the UK, in order to improve modelling accuracy. This would be best obtained from post occupancy monitoring or the development of a 'real time' project monitoring database.

- Further investigation of occupant behavioural interactions with shading devices in Passivhaus dwellings, through post occupancy evaluation. This research is needed to better understand user satisfaction and compounding interactions with ancillary criteria (such as visual comfort and wellbeing). The findings of this work would help refine modelling and design assumptions in relation to the acceptability and usage of external shading devices.

- Comparative research involving coupled transient heat and moisture responses in a single building model, in order to assess the likely impacts of fluctuating moisture loads on key performance outputs (for example using the WUFI-Passive model).

- Field studies and CFD modelling are needed to investigate the implications of off-gassing of Volatile Organic Compounds (VOC's) and other airborne pollutants within confined airtight building envelopes (e.g. social Passivhaus dwellings) particularly under restricted natural ventilation protocols (i.e. urban contexts).

- Large scale epidemiological studies are needed to determine whether the use of filtration systems in conjunction with MVHR ventilations systems in airtight dwellings are capable of contributing to reduced incidences of respiratory disorders and also to reduced morbidity levels during heat wave events (e.g. through reduced PM 10 concentrations).

- Field studies are needed to evaluate whether the occupants of Passivhaus dwellings perceive thermal comfort in accordance with the expectations typical of occupants of naturally ventilated dwellings or whether their expectations fall in to a narrower bandwidth and are more closely aligned to the inhabitants of actively conditioned dwellings.

- Further epidemiological research is needed to establish the internal environmental thresholds (i.e. operative temperature, radiant surface temperatures, humidity etc.) that are statistically correlated with excess mortality and morbidity during heat wave events in the UK. This will assist those modelling overheating risks in establishing appropriate risk exposure classes.

- Further validation testing of the overheating algorithm in PHPP should be carried out to determine its accuracy and establish whether an improved procedure can be implemented. This could be carried out through comparative testing (against dynamic simulation predictions) and also empirical validation (based on post completion monitoring of Passivhaus projects).

- Further parametric and sensitivity investigations into the overheating risk mitigation potential of a range of passive and semi-passive (low energy) cooling technologies (e.g. TABs, EAHEs, PCMs etc.) suitable for incorporation into UK Passivhaus dwellings are needed, to determine whether the future use of conventional refrigerant cooling techniques can be enhanced or avoided.

- Collation of a data library containing documented statistical distributions for input data ranges of common building materials and systems, in order to improve the accuracy of uncertainty propagation in the modelling and analysis process. This would represent a further improvement on the Lambda (90/90) method.

- Further post occupancy evaluation studies and in-situ monitoring of completed UK Passivhaus projects in order to establish better correlations between modelling predictions and real world performance. This would help to determine whether the use of micro-regional or site specific climate data could substantially improve the accuracy of modelling predictions. Post occupancy monitoring will also provide a better understanding of how different Passivhaus building typologies are operated (i.e. establishing typical heating, cooling and ventilation schedules etc.).

The list of further research to be done in this area is virtually unlimited as performance standards and building simulation techniques continue to evolve over time. From that perspective the work undertaken in this thesis can be seen as the beginning and not the end of an important phase in the evolution of the Passivhaus concept.

7.4 CLOSING REMARKS

This thesis has argued that the transfer of the Passivhaus standard (or any other ultra-low energy standard) from one country or region to another, should be accompanied by an extensive programme of context specific research and application testing. Although the fundamental laws of building physics do not change from one geographic region to another, the application of design performance standards must be regarded as a context specific process - which is refined by the continual evolution of knowledge.

The findings of this research have shown that the implementation of the Passivhaus standard, in its current format, in the UK is not without risks. However, when properly implemented the Passivhaus standard is able to provide high levels of quality assurance in the delivery of long term energy and carbon savings (relative to the FEES alternative). Faced with the potential of a poorly regulated alternative such benefits appear substantial and merit the challenges involved in addressing its successful implementation. Although the Passivhaus standard cannot purport to fulfil the definition of a true zero carbon dwelling, it does provide an essential pre-requisite: a template for the delivery of ultra-low energy buildings.

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CURRICULUM VITAE

Rob McLeod was born in Wailuku, Maui, USA and was educated in New Zealand, Canada and the UK. He graduated with an MSc (distinction) in Architecture and Advanced Environmental Energy Studies from the University of East London and the Centre for Alternative Technology in 2007. He was one of the first Certified European Passivhaus Designers (CEPH) and accredited Passivhaus Trainers in the UK.

Rob was previously Technical Manager of the BRE Ltd (Wales and SW region) from 2007- 2010. During this time he was Principle Passivhaus Consultant on the UK's first zero carbon (CSH Level 5 and 6) social Passivhaus dwellings, as well as a number of award winning low energy schemes. He currently works as an Associate of the BRE Ltd (Garston) where he has been an advisor to the Passivhaus UK team and Lead Trainer of the Certified European Passive House (CEPH) Designer training course, since 2010. He is also a Director of Regeneration Partnership Ltd, an RIBA chartered practice specialising in Passivhaus and sustainable design.

Rob is the co-author of a technical reference book about Passivhaus design that is due to be published in 2014, and has played an instrumental role in the testing and development of the Design-PH and LightUp analytics software.

APPENDICES

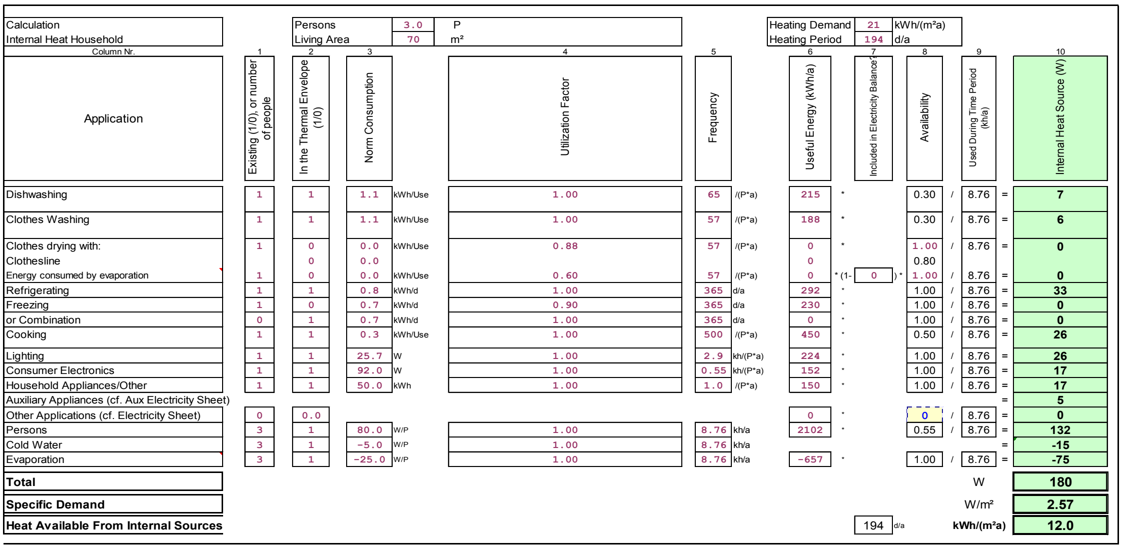
APPENDIX A – ADDITIONAL INFORMATION

APPENDIX B – JOURNAL PUBLICATIONS

APPENDIX C – BRE PASSIVHAUS PRIMERS

A1 - INTERNAL HEAT GAIN WORKSHEET

The PHPP uses a default assumption of 2.1 W/m^2 with respect to standard residential internal gains (Feist et al, 2012). This figure is then rounded upwards to 2.6 W/m^2 (as a safety margin) in PHPP for the purpose of assessing summer overheating risk. The derivation of these figures is based on assessments carried out in German PH dwellings using a default occupant density of 35m^2 per person and actual appliance schedules (Feist, 1994). The figures used in PHPP account for both the internal heat gains (including occupants) as well as the internal heat losses (such as cold water entering cisterns) (Feist et al, 2012). A detailed breakdown of this calculation can be found in Schneiders (2009, p75). For the purpose of this thesis the standard internal gain figures were adjusted using the PHPP 'Internal Gains' worksheet (see below) in order to reflect the higher UK occupant densities used. In order to do this the occupant gains were first subtracted from the worksheet and the remaining appliance and auxillary gains were then scaled as a function of the ratio between the German/UK TFA.



Calculation
Internal Heat Household

Persons 3.0 P
Living Area 70 m²

Heating Demand 21 kWh/(m²a)
Heating Period 194 d/a

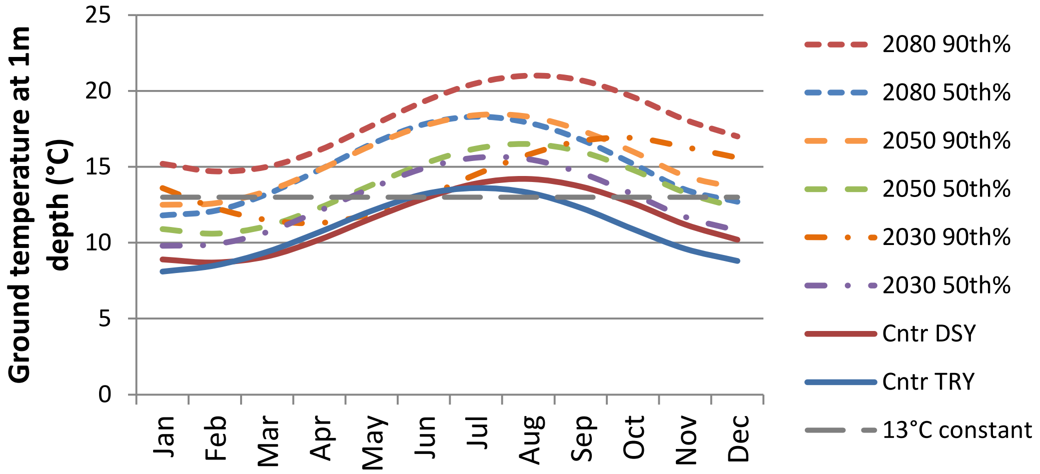
Application	Existing (1/0), or number of people	In the Thermal Envelope (1/0)	Norm Consumption		Utilization Factor	Frequency		Useful Energy (kWh/a)		Included in Electricity Balance?		Availability		Used During Time Period (kh/a)		Internal Heat Source (W)
Column Nr.	1	2	3		4	5		6		7		8		9		10
Dishwashing	1	1	1.1	kWh/Use	1.00	65	/(P*a)	215	*			0.30	/	8.76	=	7
Clothes Washing	1	1	1.1	kWh/Use	1.00	57	/(P*a)	188	*			0.30	/	8.76	=	6
Clothes drying with:	1	0	0.0	kWh/Use	0.88	57	/(P*a)	0	*			1.00	/	8.76	=	0
Clothesline		0	0.0					0				0.80				
Energy consumed by evaporation	1	0	0.0	kWh/Use	0.60	57	/(P*a)	0	* (1-	0	) *	1.00	/	8.76	=	0
Refrigerating	1	1	0.8	kWh/d	1.00	365	d/a	292	*			1.00	/	8.76	=	33
Freezing	1	0	0.7	kWh/d	0.90	365	d/a	230	*			1.00	/	8.76	=	0
or Combination	0	1	0.7	kWh/d	1.00	365	d/a	0	*			1.00	/	8.76	=	0
Cooking	1	1	0.3	kWh/Use	1.00	500	/(P*a)	450	*			0.50	/	8.76	=	26
Lighting	1	1	25.7	W	1.00	2.9	kh/(P*a)	224	*			1.00	/	8.76	=	26
Consumer Electronics	1	1	92.0	W	1.00	0.55	kh/(P*a)	152	*			1.00	/	8.76	=	17
Household Appliances/Other	1	1	50.0	kWh	1.00	1.0	/(P*a)	150	*			1.00	/	8.76	=	17
Auxiliary Appliances (cf. Aux Electricity Sheet)															=	5
Other Applications (cf. Electricity Sheet)	0	0.0						0	*			0	/	8.76	=	0
Persons	3	1	80.0	W/P	1.00	8.76	kh/a	2102	*			0.55	/	8.76	=	132
Cold Water	3	1	-5.0	W/P	1.00	8.76	kh/a								=	-15
Evaporation	3	1	-25.0	W/P	1.00	8.76	kh/a	-657	*			1.00	/	8.76	=	-75
Total														W		**180**
Specific Demand														W/m²		**2.57**
Heat Available From Internal Sources										194	d/a			**kWh/(m²a)**		**12.0**

Using this method the mean internal gains based on 3 occupants (but excluding the solar and occupant gains) are: 180 W (total) – 132W (occupant gains) = 48W (net). Adjusting this to the 70m2 TFA the net specific internal gains are 0.69 W/m^2. Using occupant gains from CIBSE Guide A (2006) based on three occupants (assuming two adults and a mature child) the total internal sensible heat gains are: 48W + (3*70W)= 258W. Adjusting this to the 70m2 TFA the total specific internal gains are 3.69 W/m2 (when the dwelling is fully occupied). Notably this estimation of equivalent UK internal gains is approximately 42% higher than the PHPP summer overheating algorithm currently assumes. The above figures are thought to be more representative of typical internal gains in UK passive house dwellings than the German default assumptions.

A2 – GROUND TEMPERATURE USED In The IES MODELS

The boundary conditions for conductive elements of the IES building model are dictated by conditions in the spaces either side of the element. According to the Apache View User Guide (IES 2013, page 16), "In the UK a ground temperature of about 13°C may be assumed for the ground temperature at a depth of 1m. This can be modelled using a Temperature from profile Adjacent Condition with the Temperature Profile set to the system weekly profile '13', a profile which has a value of 13.0 year-round."

In a small dwelling the ground floor area can make up a large percentage of the total external heat exchange surface area (particularly where the dwelling has shared party wall boundaries). Ideally the ground boundary temperature would be modelled explicitly however whilst APpro permits modulating profiles to be written the complexity of sub-surface temperature equations such as Lab's method (Labs, 1979) are beyond the current capabilities of APpro. Furthermore the implementation of explicit equations typically requires knowledge of the site's mean annual ground temperature, the phase constant, and the thermal diffusivity of the soil. The assumption that a constant ground floor base temperature of 13°C would not influence the modelled predictions (IES, 2013) was investigated, by graphing the monthly 1m soil depth temperature profiles from the respective EPW climate files (below).



From this analysis of the 1m soil depth temperatures (from the corresponding EPW climate files for the London Islington reference location (5350185)) it can be seen that the peak temperature in the 2080 90th percentile 1m ground depth temperature dataset is predicted to reach 21°C. Both the shift in the phase constant and the amplitude of the ground temperatures are likely to have a progressive influence on the predicted heating and cooling loads as climate change scenarios become more pronounced over time. For this reason the EPW 1m monthly ground temperatures were implemented as absolute temperature profiles in the IES models used in Chapter 4.

APPENDIX B – JOURNAL PUBLICATIONS

B1 - AN INVESTIGATION INTO RECENT PROPOSALS FOR A REVISED DEFINITION OF ZERO CARBON HOMES IN THE UK

McLeod R., Hopfe, C., and Rezgui, Y., 2012. An investigation into recent proposals for a revised definition of Zero Carbon homes in the UK. *Energy Policy*, 46 (2012) 25–35 http://dx.doi.org/10.1016/j.enpol.2012.02.066

B2 - A PROPOSED METHOD FOR GENERATING HIGH RESOLUTION CURRENT AND FUTURE CLIMATE DATA FOR PASSIVHAUS DESIGN

McLeod R., Hopfe, C., and Rezgui, Y., 2012. A proposed method for generating high resolution current and future climate data for Passivhaus design. *Energy and Buildings*, 55 (2012) 481–493 http://dx.doi.org/10.1016/j.enbuild.2012.08.045

B3 - AN INVESTIGATION INTO FUTURE PERFORMANCE AND OVERHEATING RISKS IN PASSIVHAUS DWELLINGS

McLeod, R., Hopfe, C., and Kwan, A., 2013. An investigation into future performance and overheating risks in Passivhaus dwellings. *Building & Environment* 70 (2013) 189-209. http://dx.doi.org/10.1016/j.buildenv.2013.08.024

B4 - HYGROTHERMAL IMPLICATIONS OF LOW AND ZERO ENERGY STANDARDS FOR BUILDING ENVELOPE PERFORMANCE IN THE UK

McLeod, R., and Hopfe, C., 2013. Hygrothermal implications of low and zero energy standards for building envelope performance in the UK. *Journal of Building Performance Simulation*, 6, (2013) Issue 5, 1-18, Special Issue: Heat and moisture - issues and applications. DOI: 10.1080/19401493.2012.7628094

APPENDIX C - BUILDING RESEARCH ESTABLISHMENT PRIMERS

C1 - PASSIVHAUS PRIMER: DESIGNERS GUIDE: A GUIDE FOR THE DESIGN TEAM AND LOCAL AUTHORITIES

McLeod, R., Mead, K., and Standen, M., 2012. *Passivhaus Primer: Designers guide: A guide for the design team and local authorities.* Available at: www.passivhaus.org.uk

C2 - PASSIVHAUS PRIMER: CONTRACTORS GUIDE: SO YOU HAVE BEEN ASKED TO BUILD A PASSIVHAUS?

McLeod, R., Tilford, A., and Mead, K., 2012. *Passivhaus Primer: Contractors guide: So you have been asked to build a passivhaus?* Available at: www.passivhaus.org.uk

C3 - PASSIVHAUS PRIMER: AIRTIGHTNESS GUIDE: PROCEDURES FOR CARRYING OUT AIR PRESSURE TESTING IN ACCORDANCE WITH THE PASSIVHAUS STANDARD

McLeod, R., Jaggs, M., and Cheeseman, B., 2014. *Passivhaus Primer: Airtightness guide: Procedures for carrying out air pressure testing in accordance with the Passivhaus Standard.* Available at: www.passivhaus.org.uk