

Overheating in Scotland: contributing factors in occupied homes.

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Abstract

There is growing awareness of the overheating risks in new-build properties in the UK. However, this tends to be considered a problem principally for the southern regions in the UK, only becoming a serious issue in the North of England in the medium term and in the long term for Scotland. This notion tends to be largely predicated upon climate change predictions, differences in latitude and summer air temperatures. This paper describes the results from Building Performance Evaluation (BPE) studies over a two-year period from 26 occupied new-build homes across Scotland which demonstrated incidences of overheating. Results suggest that low energy buildings are susceptible to overheating despite northerly latitudes, with 54% of houses studied overheating for more than six months annually, and 27% of homes overheating for less than 10% of the year. Evidence indicated that commonly used prediction tools do not appear to adequately anticipate overheating. This paper maps common overheating causes due to design and the role of occupants, identifying the risks due to the regulatory system, prediction and procurement processes, and the design and construction. A common finding was that design and occupancy factors appear to greater impact on overheating more than location and climatic factors.

Keywords: Overheating, Building Evaluation, Design, Occupant behaviour, Low energy buildings, Passive House, Scotland.

Introduction

In recent years in the UK, responses to climate change by government (Parliament of the United Kingdom [UK], 2008; Scottish Parliament, 2009) and the construction industry (Parliament of the UK, 2006a) have led to improvements in building standards (Her Majesties Government [HMG], 2013; Scottish Government, 2015) and zero carbon reduction targets (Parliament of the UK, 2006b, p. 168). This has resulted in a

transformation of UK housing and manufacture, leading to improved insulation levels, airtightness, performance and technologies (National House Building Council [NHBC], 2015). However, these changes have not always been accompanied by industry-wide capacity, understanding or skills, nor by occupant understanding of some of the new strategies and technologies (NHBC, 2015).

Davies & Oreszczyn (2012) raised concerns about the unintended consequences of rapid change in the construction industry, which include summer overheating. A growing body of research in recent years has led to the identification of a number of variances between design intentions and as built performance in new building types which need to be addressed (Zero Carbon Hub [ZCH], 2014; NHBC, 2012; ZCH, 2015a). These variations tend to be known collectively as constituting a 'Performance Gap' between intended or predicted, and real or monitored outcomes (ZCH, 2014). Building Performance Evaluation (BPE) is used to identify the performance gap of buildings, and the impact of this may have on energy consumption and occupants (Stevenson & Leaman, 2010).

Overheating Concern

Within the context of dwellings in the UK, one acknowledged issue is that of overheating (NHBC, 2012; ZCH, 2015a). However, this has mostly been identified as a problem in the South of the UK with overheating occurring in the North and in Scotland by the middle of the century due to an increase in external temperature due to climate change (Department for Communities and Local Government [DCLG], 2012, p. 35). Dynamic simulation of future climates in different building types by Peacock, Jenkins and Kane (2010) suggested that overheating in Edinburgh is a low risk particularly in buildings with thermal mass. These studies typically base their conclusions on the results of virtual modelling taking into account known patterns of summer temperatures,

linked to latitude and future climate change predictions. Beizaee, Lomas and Firth (2013) studied overheating risk in English homes during summer, they found that the least warm homes were in the North East, North West and Yorkshire. However, they recommended for more research to be undertaken as to what temperatures are acceptable in English regions. Despite this, there is growing practice based evidence of overheating in Scotland and comparable northern latitude countries. McLeod, Hopfe, and Kwan (2013) suggest that Passive House and other super-insulated dwellings are already at risk of overheating in the UK, Ireland and Northern Europe. Morgan, Foster, Sharpe, and Poston (2015) suggest that there is increasing evidence of overheating already occurring in Scotland.

There is growing evidence of overheating in low energy and Passive House properties in other northern latitude countries. Larsen and Jensen (2011) monitored 10 Passive House dwellings in Skibet, Denmark (latitude is 55.7° N, Glasgow's latitude is 55.9° N) for three years, commencing October 2008; all homes were found to have severely overheated during the 2009 and 2010 summers. Their overheating assessment used the Danish Standards Authority "Ventilation for building – Design criteria for the indoor environment" with the acceptable Category B temperature range of 23-26°C selected for assessment. Analysis of one home indicated that during July and August the Category B temperature was exceeded 40% and 60% of the time during 2009 and 2010 respectively; this level of overheating was not predicted by the Passive House Planning Package (PHPP) model which uses a temperature of 25°C as its overheating threshold. A study by Ruud and Lundin (2004) in Lindas, Sweden (latitude of 57.2° N, Inverness' latitude is 57.5° N) found mean temperatures across 20 terraced apartments of 25.2°C, however temperatures were variable and some exceeded 30°C.

Further north in Estonia (average latitude 59° N, around the same as the Scottish Orkney Islands), Maivel, Kurnitski & Kalamees (2014) note that while overheating has not been considered an issue in Nordic countries, new buildings are changing and they compare increased levels of overheating in newer apartments compared to older ones. The Estonian regulations have a criterion for overheating, based on excess degree hours over 27° C. This was exceeded 13.7% of the time in new apartments that were monitored.

Given that overheating is occurring in well insulated buildings in northern latitudes now and not under future climate scenarios, it follows that the causes of this needs further study, not only because it might represent additional energy consumption, but also due to the known risk that overheating represents to the comfort and health of occupants, , especially to the more vulnerable sections of society (Office of the Deputy Prime Minister [ODPM], 2006; Kovats & Hajat, 2008; NHBC, 2012).

Overheating Definition & Calculation

The assessment of overheating can be in relation to thermal comfort, health or productivity. As a result various evidence-based overheating thresholds are used by different disciplines with incomparable metrics (ZCH, 2015b, p. 2). Peacock et al. (2010) and ZCH (2015a) highlight that there is currently no precise definition of overheating of dwellings in the UK. A limitation of fixed temperature thresholds is that they do not take variation of occupancy comfort levels in relation to other factors and external temperatures into consideration (ZCH, 2015a). Use of adaptive comfort models such as CIBSE TM52 are limited as they are currently based on non-domestic evidence and testing is required as to the appropriateness for night-time comfort in bedrooms (ZCH, 2015a). A survey of housing providers by ZCH (2015, p. 36) found that fixed thermal comfort definitions for overheating assessment were derived variously from the

Standard Assessment Procedure (SAP) Appendix P, CIBSE Guide A (2006) and Passive House Institute design criteria.

SAP is the UK Government's adopted means of assessing and comparing environmental and energy performance of dwellings and is primarily used as a threshold within the building regulations in each of the four constituent countries of the UK to assess compliance with the energy efficiency requirements of that country. Although it is primarily used as a compliance tool and contains a number of default assumptions, the data derived from these assessments is often used to underpin national policy initiatives (ZCH, 2015c). Appendix P of SAP provides an overheating check which uses predicted design and performance data to calculate the predicted average internal temperature for June, July and August, with overheating risk defined as slight between 20.5 – 22°C, medium between 22-23.5°C and high when greater than 23.5°C (ZCH, 2015a; ZCH, 2015c).

As with SAP, the PHPP overheating calculation method is also a monthly calculation however PHPP uses a dynamic single zone building model where risk of overheating is based on exceedance of a fixed internal temperature threshold of 25°C. The difference between the two methods is PHPP's use of a full calendar year and historical weather files for the assessment of solar gains, whereas SAP overheating criteria is based three summer months data, is independent of location and uses floor area assumptions for internal gains (ZCH, 2015c). An internal temperature of 25°C is an important health threshold identified in the UK Government Housing Health and Safety Rating System (HHSRS) (ODPM, 2006; ZCH, 2015). This temperature threshold is also used by the Passivhaus Institute in their PHPP software (Certified European Passive House [CEPH], 2014), to indicate risk of overheating during the design phase. For certification of Passive Houses, the PHPP temperature threshold may not exceed 25°C

for more than 10% of the year. Bearing in mind climate change predictions and the fact that 10% of a year is a long time for a property to be overheating, good practice within the Passive House community acknowledges that less than 5% overheating annually is acceptable practice while ideally Architects and designers should aim for 0% exceedance of the temperature threshold annually (CEPH, 2014 p. 79, BRE 2011).

Due to the health risks associated with temperatures that exceed 25°C the Passive House overheating criterion has been selected for use in this study. Temperatures have been noted in this paper without associated reference to relative or absolute humidity measurements. Relative humidity readings were taken as part of the monitoring of all properties but are rarely used in discussion of overheating generally and have not been used in this paper to avoid confusion.

Project information

The case studies in this paper represent six separate sites across Scotland with a total of 26 occupied homes (see Table 1 and Figure 1) all of these dwellings were participating in the £8m Innovate UK (IUK) funded BPE studies and were located in rural and urban areas. The rural sites are located in Lockerbie, Dunoon and Inverness; the urban sites in Barrhead, Livingston and Glasgow. Of the 26 homes, 20 were provided for affordable rent and six were owner occupied and sold to the occupants under a shared equity scheme. The dwellings were designed and constructed as affordable Passive House dwellings (5no.) and low energy housing (21no.) these were subjects of the Phase 2 of the IUK BPE project that required data collection for a two year period. The objective of the BPE was to compare the designed performance against the actual indoor environmental conditions, energy consumption and fabric performance of new occupied domestic and non-domestic buildings across the UK. The data analysed for this paper represents one full calendar year (2013) to allow comparison across the various sites, as

the project start and end dates were not synchronised.

Table 1. Basic data for the 26 monitored homes.

Site	Code	Home type	Built Form	Occupants (A=adult, C = child)	Floor Area (m ²)	No. of Bedrooms	Storeys
Lockerbie Latitude 55.1; Longitude 3.4	DA1	House	Semi-detached	1A 1C	87.00	2	2
	DA2	House	Semi-detached	1A 1C	87.00	2	2
	DB1	House	Semi-detached	3A	102.77	3	2
	DB2	House	Semi-detached	2A	102.77	3	2
Dunoon Latitude 55.9; Longitude 4.9	TB1	House	Semi-detached	1A 1C	104.00	2	2
	TA1	House	Semi-detached	2A 3C	120.00	3	2
	TA2	House	Semi-detached	2A 2C	120.00	3	2
North Glasgow Latitude 55.9; Longitude 4.3	GA1	Flat	Flat – ground floor	1A	51.00	1	1
	GA2	Flat	Flat – mid floor	1A	51.00	1	1
	GA3	Flat	Flat – top floor	1A	53.00	1	1
	GB1	Flat	Flat – ground floor	1A	66.00	2	1
	GB2	Flat	Flat – top floor	2A 1C	66.00	2	1
	GB3	Flat	Flat – ground floor	2A 1C	73.30	2	1
Livingstone Latitude 55.9; Longitude 3.5	LA5	House	Mid-terrace	3A	104.00	3	2
	LA6	House	End-terrace	3A	104.00	3	2
Barrhead Latitude 55.8; Longitude 4.4	BA1	House	Mid-terrace	2A	93.09	2	2
	BB2	Flat	Flat – top floor	2A	75.80	2	1
	BC1	House	End-terrace	2A	75.44	2	1
Inverness Latitude 57.4; Longitude 4.2	IA1	House	End-terrace	2A 4C	110.00	3	2
	IA2	House	Mid-terrace	1A 5C	110.00	3	2
	IB1	House	Semi-detached	2A 2C	90.00	3	2
	IB2	House	Semi-detached	2A 2C	90.00	3	2
	IC1	Flat	Flat – ground floor	1A	63.00	1	1
	IC2	Flat	Flat – Top Floor	2A	63.00	1	1
	ID1	Flat	Flat – ground floor	2A	76.00	2	1
	ID2	Flat	Flat – ground floor	2A	76.00	2	1

Note: Grey shading denotes Passive Houses



Figure 1. Locations of the 26 monitored homes across Scotland.

Methodology

The internal temperature in three different rooms were monitored in each home during the calendar year of 2013, this data is represented as a percentage of each month the temperature exceeded the thermal threshold for an overall representation of the whole house for each home. This is represented to allow comparison with the single whole house volume of the Passive House standards. Monitoring of temperatures in the living room and master bedroom was common to all properties and this data provides a comparison of internal temperature for two rooms that form the main focus of this study.

It should be noted that although the UK weather on average in 2013 was average, significant weather events occurred including a late cold spring with unseasonable snowfalls. The summer was sunny and warm with heatwave conditions in July with external temperatures 1.9°C above the 1981-2010 average. October and

December were stormy with high winds and rainfall (Met-Office, 2016). Whilst 2013 could be seen as slightly anomalous in the context of the preceding and surrounding years, it is nonetheless perhaps more representative of the years to come with more extreme weather events and predicted global surface temperature increases of 0.3°C to 0.7°C between 2016-2035 and 1.5°C – 2°C between 2081-2100 (IPCC 2014).

Indoor environmental monitoring data was collected via EnOcean Wireless Sensor Technology (WiST) using combined wall-mounted sensors to provide readings representative of the occupied rooms. These were positioned around 1.6m from finished floor level in locations away from draughts, heat sources and direct sunlight. The sensors measured internal temperature (°C) (0-51°C range, accuracy $\pm 0.5^\circ\text{C}$ over full range), Relative Humidity (RH) (0-100% range, accuracy $\pm 1.5\%$ over full range) and Carbon Dioxide (CO₂) concentration (0-5000ppm range, accuracy $\pm 50\text{ppm}$ over full range with auto-calibration every eight days). Wireless solar powered window contact sensors were used to monitor window opening occurrences in the rooms subjected to environmental monitoring. Data from these apparatus was transmitted via Modbus Receiver Unit every five minutes throughout the monitoring period to a central off-site server, transmitting data over General Packet Radio Service (GPRS) networks.

Mains powered repeater units with internal antenna were positioned centrally in each dwelling to boost signals and improve reliability of data transfer. However, transmission problems were encountered at one of the rural sites due to lack of GPRS network reception. In these dwellings the data transfer was made via an Ethernet connection. A manual data cleansing process was adopted, where missing or corrupt data was amended using averages from readings immediately before and after the interruption. In dwelling DA1, large gaps in the data were detected effecting three months of data, these incomplete months were excluded from analysis.

Additional studies informing this research were occupant interviews and questionnaires, these consisted of semi-structured interviews delivered by the research team, as well as a detailed understanding of the building fabric, made through a number of non-destructive surveys in adherence to the requirements of the BPE programme.

The data is represented in two ways. The first is through the use of measured, quantitative data representing recorded temperatures from the monitored rooms. Secondly, a matrix of overheating factors was developed, based on a mixed methods approach, mapping a range of potential circumstances, design aspects and known occupancy behaviour factors which could lead to overheating in living rooms and master bedrooms in the 26 dwellings monitored.

The matrix provides an overview of the range and frequency of these factors rather than an accurate assessment of each. In each case, a point is gained where there is an increased likelihood of overheating against a nominal UK average or for example where a measure has, or has not been taken, for example, provision of external shading on a South-facing window. Unlike computer modelling processes, the monitoring process does not allow for disaggregation or individual measurement of each factor. It is recognised that this study comprises a limited sample of dwellings from which to draw definitive conclusions, particularly for Passive House, with a limited geographical spread. The aim of this study is to use the data collected to illustrate the issues in relation to overheating that are arising in new homes in Scotland; and to demonstrate that overheating of dwellings is a current problem in Scotland.

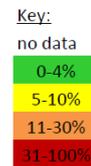
Results

Table 2 depicts the results of the temperature monitoring at five minute intervals across all dwellings in 2013. The results represent the mean temperature across the whole (monitored) house, indicating the total percentage of time for each month and total year

that the temperature in the house was over 25°C. This is in keeping with the Passive House criteria whereby: 0-5% of time annually over 25°C is considered acceptable, anything over 10% of time annually is considered for the building to have overheated. Total time over 30% is also depicted in the study to demonstrate the severity of overheating experienced in some homes, this represents the equivalent of overheating continuously for more than three months.

Table 2. Percentage of time the whole (monitored) dwelling is overheating (>25°C) by month.

	J	F	M	A	M	J	J	A	S	O	N	D	Y
DA1	62	51			69	62	80	61	31	19	6		49
DA2	22	22	13	19	10	19	53	23	11	6	3	19	18
DB1	4	11	7	13	13	19	48	17	17	13	11	22	16
DB2	5	9	3	4	26	81	85	81	45	31	2	1	31
TB1	0	0	0	0	0	4	24	5	1	0	0	0	3
TA1	0	0	0	0	0	0	12	0	0	0	0	0	1
TA2	5	6	5	6	2	1	24	2	1	3	3	4	5
GA1	0	0	0	0	1	10	82	46	27	2	1	1	14
GA2	7	23	10	56	59	74	99	99.8	93	64	28	15	52
GA3	5	12	27	12	34	34	58	42	14	49	45	11	29
GB1	0	0	1	0	0	2	31	1	0	1	0	0	3
GB2	20	36	36	46	46	60	80	54	34	13	14	9	37
GB3	1	1	1	0	4	28	73	47	18	6	0	2	15
LA5	30	37	30	36	45	72	91	82	35	33	44	38	48
LA6	23	33	11	14	19	14	67	37	21	14	12	14	23
BA1	2	10	15	17	12	25	61	36	14	15	14	14	20
BB1	1	3	2	3	5	4	35	7	2	1	2	1	6
BC1	32	28	34	33	42	52	75	62	54	38	35	35	43
IA1	20	21	23	31	48	73	93	57	61	46	45	40	46
IA2	7	12	8	14	8	9	48	20	13	11	8	1	13
IB1	46	22	24	31	35	57	67	48	31	27	29	36	38
IB2	1	9	2	3	2	5	23	8	2	1	3	3	5
IC1	1	1	1	0	0	2	28	5	3	6	6	9	5
IC2	7	5	6	9	3	0	11	1	1	1	4	5	4
ID1	0	4	1	7	5	15	47	17	7	8	10	9	11
ID2	6	6	4	10	4	10	61	22	5	1	2	1	11



Two findings are evident from this table. The first is the high levels of overheating recorded generally, and the second is that this overheating – in certain properties - appears to be spread widely throughout the year. In a domestic context, this calls into question the general assumption that overheating is only a summer issue caused by external temperature.

With each of the five homes demonstrating the highest levels of overheating (DA1, GA2, LA5, BC1 and IA1 - over 40%) from different regions in Scotland, there is

no overall trend relating overheating incidence to location, except perhaps in the case of Dunoon, which is discussed below.

Of the five Passive House projects, one registered the second highest levels of overheating (DA1, 49%), while another registered the second lowest level (TB1, 3%). All of the Lockerbie projects had levels of overheating above the 10% threshold acceptable for Passive House compliance in reality, whereas the incidence of overheating predicted in their PHPP calculation was 0.2%. Overall however, it cannot be said that the Passive Houses fare particularly well or badly in comparison to the other homes.

The general rise of overheating in the summer months may be expected but the significant peak of overheating recorded in the month of July is noticeable and in some cases it appears anomalous. Table 3 displays the combined mean internal monthly and annual temperatures of the living rooms and master bedrooms for each dwelling. July exhibits the highest mean temperatures with 60% of rooms overheating, with mean temperatures as high as 29.5°C (GA2 – Bedroom) and 28.3°C (GB2 Living Room). Of all of the rooms, 56% of living rooms and 68% of bedrooms were revealed to be overheating when compared with Passive House criteria. These temperatures may be a result of the July 2013 heatwave, with an average UK external temperature of 17°C, 1.9°C above the average (Met-Office, 2016), as only 25% of rooms exhibited overheating out with this period. However, temperature patterns in adjacent months indicate that in the majority of homes, high mean temperatures were still achieved, but the mean was below the 25°C threshold.

Table 3. Combined mean internal monthly and annual temperature (°C) in the living rooms and master bedrooms of all dwellings.

		J	F	M	A	M	J	J	A	S	O	N	D	Y
DA1	LR	22.9	21.6			24.4	24.4	25.9	24.5	23.5	22.7	20.6		23.4
DA1	Bed1	26.9	25.7			26.6	26.3	27.6	25.7	24.6	23.7	22.3		25.5
DA2	LR	23.8	23.2	22.9	23.3	22.1	23.4	25.5	23.7	22.7	20.2	21.5	20.9	22.9
DA2	Bed1	24.1	24.3	23.7	23.9	23.1	24.3	26.5	24.8	23.8	21.3	22.4	21.8	23.8
DB1	LR	21.6	22.9	22.4	23.1	23.0	23.4	24.4	23.9	23.7	23.7	22.7	23.3	23.3
DB1	Bed1	22.3	23.2	23.1	23.3	23.8	24.7	25.6	24.3	24.0	23.6	23.1	23.3	23.8
DB2	LR	22.8	23.1	22.6	22.7	24.2	25.1	26.2	25.3	24.7	24.4	22.2	22.0	24.2
DB2	Bed1	22.4	22.7	21.9	22.3	24.0	25.8	27.0	25.6	24.8	24.2	21.5	20.7	24.2
TB1	LR	18.5	18.4	17.5	18.8	19.6	21.6	22.7	22.2	20.2	18.8	17.3	17.7	19.9
TB1	Bed1	19.3	19.3	18.6	19.7	20.8	22.6	24.0	23.3	21.1	19.5	17.7	18.0	20.8
TA1	LR	21.9	22.0	22.5	22.5	21.7	22.4	23.5	22.4	21.9	20.6	21.8	21.8	22.0
TA1	Bed1	19.8	20.1	20.3	20.9	21.0	22.0	23.5	21.2	21.0	19.6	19.8	19.4	20.9
TA2	LR	23.7	23.8	23.4	23.2	22.4	21.6	22.8	22.0	21.8	22.8	23.4	23.3	22.7
TA2	Bed1	21.5	21.4	20.6	21.4	22.0	22.1	24.2	22.5	21.6	21.6	21.5	21.4	22.0
GA1	LR	22.2	21.9	21.3	21.9	22.6	23.7	26.0	24.5	24.2	23.3	22.7	22.5	23.5
GA1	Bed1	22.2	22.4	21.9	22.4	23.2	24.4	26.5	25.0	24.3	23.4	22.8	22.4	23.8
GA2	LR	22.6	23.5	22.9	24.3	24.5	24.9	27.8	26.6	25.7	24.6	23.8	21.5	24.9
GA2	Bed1	23.7	24.4	23.8	25.4	25.3	26.5	29.5	28.0	26.6	25.6	24.7	22.9	26.1
GA3	LR	23.3	23.1	24.1	23.4	25.4	24.5	25.9	24.8	22.9	25.3	25.0	20.8	24.5
GA3	Bed1	23.4	23.7	24.4	24.0	25.5	25.1	26.5	25.5	23.6	25.7	26.0	21.8	25.0
GB1	LR	17.0	17.4	17.5	18.6	20.2	21.4	23.8	22.4	20.8	20.4	18.3	19.4	20.2
GB1	Bed1	17.4	17.1	18.0	18.4	19.2	20.9	23.2	21.4	20.0	19.5	17.6	17.5	19.6
GB2	LR	25.1	26.0	26.3	25.4	25.3	25.9	28.3	25.8	25.2	23.9	23.8	23.5	25.5
GB2	Bed1	22.3	23.2	23.2	23.7	23.6	24.2	26.8	24.7	23.9	22.7	23.0	22.6	23.8
GB3	LR	21.6	21.6	21.9	21.6	22.6	24.3	25.4	24.9	23.8	23.2	21.8	21.9	23.2
GB3	Bed1	20.0	21.2	21.1	21.1	22.2	24.2	25.9	24.6	24.0	22.8	20.7	19.7	22.8
LA5	LR	24.8	25.1	24.7	24.8	25.1	25.4	27.0	25.9	24.9	25.1	25.4	25.2	25.4
LA5	Bed1	24.0	24.2	23.9	24.4	24.6	25.9	27.3	25.6	23.7	23.2	23.8	23.2	24.7
LA6	LR	23.7	24.8	24.1	23.9	23.5	23.5	25.7	24.9	24.6	23.5	24.6	24.3	24.3
LA6	Bed1	22.9	24.3	23.5	23.7	24.3	24.3	26.2	24.8	23.7	22.9	23.7	24.2	24.1
BA1	LR	18.9	22.4	23.1	23.5	22.7	23.2	24.6	23.9	22.1	22.7	23.3	23.3	22.6
BA1	Bed1	17.8	19.9	20.1	21.3	21.6	23.5	25.3	23.6	21.2	21.4	19.9	19.9	21.6
BB1	LR	21.0	21.4	21.2	21.9	22.4	22.3	24.2	22.8	21.4	21.3	21.0	20.9	22.0
BB1	Bed1	18.2	18.4	17.4	19.5	21.0	21.8	23.8	22.3	20.4	19.9	18.5	19.0	20.5
BC1	LR	23.2	23.0	23.5	23.8	24.3	25.0	25.7	25.3	25.3	24.3	23.6	23.8	24.4
BC1	Bed1	22.1	22.3	22.5	22.6	23.4	24.4	25.3	24.7	24.2	22.9	22.7	22.8	23.6
IA1	LR	23.8	24.3	24.1	24.2	25.1	27.1	27.9	25.8	26.0	26.1	24.6	24.7	25.6
IA1	Bed1	24.8	24.7	24.7	24.7	25.0	25.1	25.6	25.0	25.1	24.9	24.9	24.8	25.0
IA2	LR	23.0	23.4	23.1	23.5	23.1	23.2	24.3	23.6	23.4	23.0	23.2	22.8	23.3
IA2	Bed1	22.9	23.7	22.4	23.5	22.8	23.8	25.3	24.2	23.6	23.8	22.9	21.3	23.7
IB1	LR	23.1	22.3	22.2	22.4	22.4	23.7	24.4	23.5	22.7	22.7	22.4	22.6	23.0
IB1	Bed1	24.9	24.4	24.6	23.8	23.9	25.1	25.5	24.3	23.4	23.5	23.5	23.6	24.3
IB2	LR	20.8	21.7	21.1	21.7	21.7	22.0	22.9	22.4	22.0	21.8	21.7	21.5	21.9
IB2	Bed1	21.7	22.8	22.1	22.4	22.4	22.8	23.9	22.7	22.7	22.3	22.5	22.5	22.6
IC1	LR	20.5	21.3	18.6	20.9	18.5	22.6	24.3	22.9	21.3	21.2	19.7	19.4	21.4
IC1	Bed1	20.2	20.8	18.1	20.1	17.4	22.2	23.7	22.5	20.8	20.2	17.4	17.3	20.6
IC2	LR	21.8	19.2	21.5	22.6	20.8	21.0	22.6	21.4	20.8	20.5	20.7	19.8	21.0
IC2	Bed1	19.2	17.4	19.1	20.6	19.6	20.8	22.8	21.3	20.0	19.3	18.7	19.2	19.9
ID1	LR	22.6	22.8	21.9	23.3	22.8	23.8	25.7	24.1	22.7	23.9	24.1	23.8	23.6
ID1	Bed1	20.8	21.2	19.7	21.9	22.3	22.3	23.5	22.5	21.5	22.7	22.8	21.8	22.2
ID2	LR	22.5	22.1	21.5	22.9	22.0	22.8	25.0	23.4	22.1	20.9	20.8	21.1	22.4
ID2	Bed1	21.9	21.9	21.6	22.6	22.6	23.3	25.7	24.5	22.9	22.0	21.1	21.2	22.9

Key:

	No data
	Mean temperature >20 <25°C
	Mean temperature >25°C

Throughout the whole year, by monthly mean temperature, 25% of rooms were found to be overheating for between three and nine months. The total annual data indicated that

seven rooms were found to have mean annual temperatures which exceeded 25°C. In both monthly and annual mean data, bedrooms represented 50% of the overheating. IA1 was the only house which was overheating in both living room and bedroom. These findings are of particular concern as high temperatures in bedrooms do not allow the body to recover from daytime thermal stress (Kovats & Hajat, 2008). Many of the occupants stated that they opened windows in bedrooms overnight when it was hot, but some, particularly in ground floor flats did not do so due to issues with noise and security.

Table 4 is the matrix, which maps a number of relevant factors relating to overheating in living rooms and bedrooms in all 26 homes while Table 5 describes each factor in more detail. The first three columns in Table 4 indicate basic incidence of overheating with black diamonds as shown more graphically in the preceding tables to allow comparison with the factors shown by red dots. Overheating was predicted in only two of the 26 properties, using the requisite SAP calculation and PHPP assessment for the Passive Houses. The SAP overheating prediction for dwellings ID1 and ID2, indicated a household incidence of 11% per annum. 64% of the homes monitored experienced a greater percentage of overheating than those where it had been predicted by SAP.

Table 5. Matrix factors and parameters.

Factor	Parameter
Overheating	
Overheating over 10% year	Point if over 10% of whole year overheating
May-Sept overheating	Point if overheating took place for any month in this period
Oct-April overheating	Point if overheating took place for any month in this period
Predicted in SAP?	Point if overheating predicted in SAP design calculations?
Predicted in Other?	Point if predicted in another tool, e.g. PHPP, dynamic modelling etc.
High-risk occupants	Point if occupants include children, elderly, infirm, other vulnerable. This does not change overheating, but alters the severity of risk
Identified by occupants	Point where occupants themselves have identified overheating as an issue in the room studied or house as a whole. Does not alter overheating but indicates awareness / concern.
Location	
Latitude	Point if property is in southern half of UK (none)
Altitude	Point if property is below 50m altitude
Urban	Point if urban location. References potential effect of Urban Heat Island
Av. July temperature	Point if greater than UK 2013 average of 17°C for July
Av. July sunshine hours	Point if greater than UK 2013 average of 249 hours for July
Microclimate shading	Point if no effective microclimate shading. For example: by trees or nearby buildings / high ground which would reduce direct solar gain
Form and Orientation	
Upper storey	Point if room is on an upper floor. References potential for stack effect heat gain
Room height	Point if ceiling heights are no more than 2.4m
Windows / Room area ratio	Point if window area / room area ratio is greater than 0.3 (30%)
Orientation	Point if windows face East, South or West
External shading	Point if no fixed / adjustable shading and facing, East, South or West
Construction	
Heat Loss Parameter (HLP) (W/m ² K)	Point if HLP less than 2.1W/m ² K. (UK new build average) Heat Loss Parameter = Overall heat loss (fabric + vent) / total floor area. Refers to house overall.
Thermally coupled wall/roof	Point if thermally coupled fabric (eg solid stone wall). Vented cavity or insulation 'de-coupling' reduces risk of overheating via fabric conduction.
Airtightness	Overall house value, point if tested to below 3.0 m ³ /h/m ² @50Pa
Low Thermal Mass	Point where useful thermal mass exposed internally deemed to be 'low' under SAP assessment. (potential high / medium / low)
Window U-value	Point if windows av. U-value below 1.4 W/ m ² K (UK Building Standards Minimum standard) relates to potential for increased heat retention
Ventilation	
Windows openable	Point if windows cannot be accessed / opened (unusual in domestic, more common in non-domestic)
High/Low purge	Point if no designed high / low openings, including accessible rooflights to allow natural purge ventilation
Cross ventilation	Point where no capacity for cross ventilation possible
Continuous MEV	Point if no continuous extract, ie intermittent only with trickle vents
Summer bypass etc.	Point if MVHR is fitted without summer bypass.
Heating	
Thermostatic control	Point if no thermostatic control installed or demonstrably not understood by occupants?
Programmatic control	Point if no programmatic control installed or demonstrably not understood by occupants?
Occupancy	
Occupancy level	Point if occupancy level is above UK average of 2.3, used for living rooms only
Trickle vents closed	Point if installed trickle vents inoperative or unused / left closed.
Windows kept closed	Point where windows habitually kept closed. May be closed in practice due to security, noise or pollution.
Thermostat set high	Point where thermostats knowingly set high (more than 25°C or Thermostatic Radiator Valves (TRVs) on 4 or 5)
Internal Gains	
Cooking	Point if high level of cooking and associated heat gains. Derived from sub-metering of cooker circuit recording more than 30 kWh/month
Hot water storage	Point if hot water storage vessel (if present) poorly or not insulated
Insulation of DHW pipes	Point if hot water pipework (DHW) generally uninsulated
District heating / solar thermal	Point if district heating or solar thermal pipework present and uninsulated
Electrical equipment	Point if medium or high level of incidental gains from electrical equipment, derived from sub-metering of circuits recording more than 250kWh/month.

Note: SAP=Standard Assessment Procedure; MEV=mechanical extract ventilation; DHW=domestic hot water.

Of the eight properties with more than 30% overheating, half of the occupants concerned did not consider their home to have overheated, or at least did not consider it a problem. However, most of these occupants had moved from old draughty properties that were typically difficult to heat. Conversely, in the three homes registering the

lowest percentages of overheating (TA1 – 1%, TB1 – 3% and GB1 – 3%) overheating was identified as an issue in the occupant feedback. TB1 in Dunoon had one of the lowest frequencies of overheating, but the occupant considered her house to have overheated at temperatures of over 22°C and took measures to mitigate against this.

Occupants vary considerably in their attitude to overheating. In IA1, the house is recorded as overheating for a total of 46% of the year, but the occupants did not mention overheating in their feedback. Next door, in identical dwelling IA2, the occupants registered concern about overheating while their home overheated for a comparatively small 13% of the year. Similarly, IB1 in Inverness overheated for 38% of the year with no mention of overheating, while identical and adjacent IB2 overheated for only 5% of the time but the occupants noted overheating in their feedback.

All monitored homes are north of the nominal mid-point of the UK suggesting a lower risk of overheating relative to the UK overall. Those located in Dunoon and North Glasgow were below 50m altitude, the Glasgow homes additionally being within an urban area, both factors which could increase risk of overheating. Only the homes in Dunoon were judged to have microclimate shading, due to high land mass to their immediate West. The three Dunoon homes also have no South facing windows as they form an East-West facing terrace of dwellings, it is worth noting that these homes consistently evidenced lower internal temperatures.

A number of commonly considered factors are indicated in Table 4 within the ‘Design Form and Orientation’ grouping but no clear trends emerge from this data relating to room size, ceiling height and relationships with window size. Perhaps surprisingly given the significance of solar gain on internal temperature, only 18 of the 52 rooms monitored have a greater than 30% ratio of window to room size, and the incidence of these does not tally well with the overall incidence of overheating.

However, of the houses monitored only one (BA1) at Barrhead had any form of external shading, a technique known to deal effectively with solar gain and reduce overheating 'at source'. At this dwelling there is an installed framework onto which a deciduous climbing plant is trained but the climber is not yet well established so its effects are yet to be felt and currently no benefit can be seen. The BPE process highlighted that a number of these dwellings had fixed solar shading initially proposed but was subsequently removed due to value engineering.

The Heat Loss Parameter (HLP) available from all SAP calculations was used as a representative single figure for the overall level of heat loss from each dwelling. HLP is defined as the specific heat loss (W/K) (including both fabric and ventilation losses) divided by the building's internal floor area (m^2) giving a resultant figure in W/m^2K . The UK average for new build is $2.1W/m^2K$ (Cooper & Palmer, 2011) so all of the projects as relatively low energy new builds were some way below this threshold. It is noteworthy that the two highest HLPs ('worst insulated') belong to BC1 and IA1 which also exhibit some of the highest levels of overheating.

Thermal mass is often discussed in relation to reducing overheating so it is worth noting that almost all but three of the properties were built with little thermal mass exposed to the internal spaces. The generally high levels of overheating could support the argument that thermal mass is valuable in reducing overheating if purged correctly, but it should be noted that one of the properties, IA1 in Inverness, deemed to have higher levels of available thermal mass also exhibited one of the highest levels (46%) of overheating over the year.

Cross ventilation was possible in 65% of the homes, although a similar majority do not allow for effective stack ventilation, for example a rooflight and ground floor window that can be left open to cool the house overnight. In still and warm weather this

ventilation method can be more effective than cross ventilation, but in both cases successful ventilation of warm air can be compromised if internal doors are kept closed and do not have sufficient undercuts.

Although the majority of the homes have some form of thermostatic control, about half have no form of programmatic control. In addition, a common finding as part of the occupancy feedback during the research was that occupants did not fully understand their heating and ventilation controls. In some cases, this lack of understanding was exacerbated by the complexity of the systems, the use of unfamiliar renewable technologies and controls, and a number of mistakes made in the installations themselves.

In 42% of the properties, either trickle vents, or windows, or both, were kept closed at all times, thereby preventing the possibility of effective ventilation. In most cases, this behaviour was associated with those who did not mention overheating in their feedback but that is not the case in six properties (DB1, DB2, GB1, IA2, ID1 and ID2) which raises questions about the level of occupants' understanding of the control mechanisms available to them. A clear correlation can be seen between four households (GA3, IA2, IB1 and IC1) where the thermostatic control was set to a consistently high level, and who did not mention overheating in their feedback. This suggests that in certain households, what is being defined in this paper as overheating could simply be the desired comfort range of some occupants.

Table 4 indicates a high incidence of hot water storage and uninsulated hot water pipework, including 'additional' pipework associated with district heating or a solar thermal system that increase the internal temperature.

Figure 2 maps the incidence of overheating in the properties, against the sum of all overheating factors noted in Table 4. As can be seen clearly, there is no discernible

correlation between the incidence of potential factors causing overheating, and the monitored levels of overheating which suggests that there is no obvious priorities or evident first lines of enquiry.

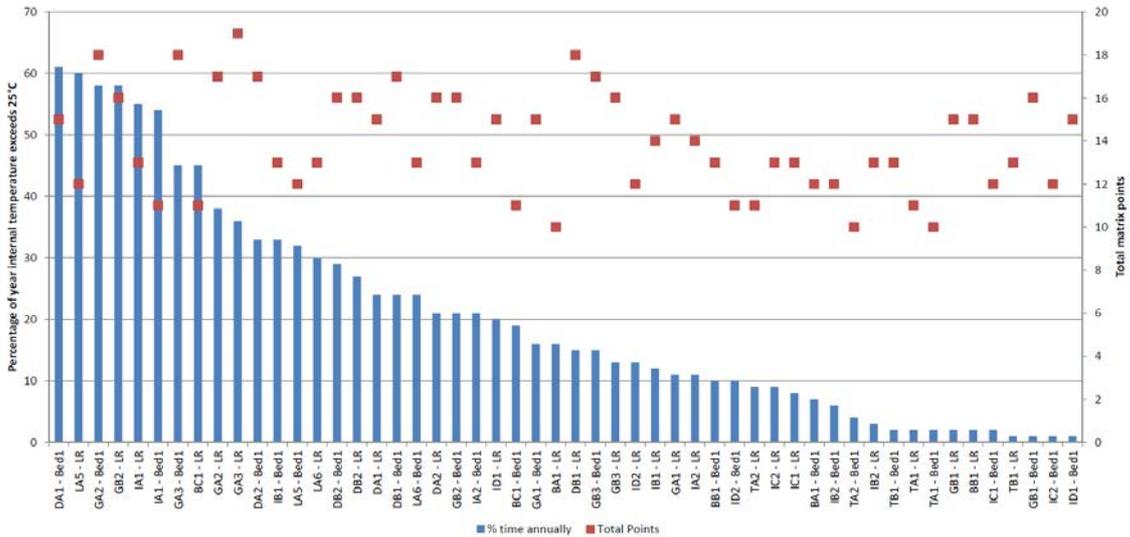


Figure 2. Percentage Overheating versus Matrix total points: by room.

Discussion

This study analysed temperature data from a sample of 26 new homes built to comply with 2007 and 2010 building (Scotland) regulations, the results indicate that overheating is currently occurring in Scotland. There is no denying that overheating is likely to be a greater problem in the South of the UK both now and in the future, but the evidence presented in this paper counters the notion that overheating is a medium- or long-term problem for the northern parts of the UK and Scotland in particular. The likely consequences of this are that policy makers, clients and those involved in the construction industry in Scotland may put off making the changes to dwelling design that increasing evidence suggests is needed now.

Assuming that all new buildings will be built to similar or improved thermal standards, it is reasonable to suggest that a significant proportion of new properties constructed in the near future without ‘future-proofing’ against overheating could be

similarly affected. These buildings will still be occupied in the 2050s and 2080s when climate change modelling suggests that overheating will be as serious in the North of the UK as it is currently becoming in the South of the UK (Peacock et al., 2010). However, to state this with certainty requires a wider study of house types, construction, occupant types, behaviour and geographical location within Scotland, similar to the English study by Beizaee et al. (2013).

The extent of overheating and high mean internal temperatures, represented in Tables 2 and 3 respectively, provides evidence that within the 26 occupied homes, overheating presents a significant issue affecting all of the homes for at least one month per annum, with 54% of the houses being affected for more than six months and into the heating season. This runs counter to conventional wisdom in which overheating is associated with (external) summer temperatures, increasing with climate change. Over one year only 15% of houses managed to attain 'acceptable' conditions for less than 4% of the year and 27% of houses were found to be below the annual 10% Passive House overheating threshold, which itself represents the equivalent of more than one continuous month. It should be remembered that the results in Table 2 are averaged over the whole year and include an additional one or two rooms worth of data. In addition, there is no data correlating overheating with occupied hours, nonetheless, these figures give cause for concern.

Comparing properties situated in the same locations and identical in form and construction, it would seem that occupant behaviour appears to be the biggest variable in determining likelihood of overheating. This can be seen when comparing identical or very similar house pairs such as DA1 and DA2, IA1 and IA2 and IB1 and IB2. However, the occupant profiles in two sets of the dwelling pairs (DA1 and DA2 and IB1 and IB2) are marginally different, thus requiring further investigation.

Another observation of interest is that a number of occupants surveyed do not perceive the measured temperatures to be ‘overheating’ as such, but desirable conditions of comfort. Thus while a number of properties exhibited significant periods in which temperatures exceeded 25°C, overheating was not mentioned in occupant feedback. This may be due in part to the occupants having inhabited draughty inefficient homes previously. Conversely, a number of occupants of other households were concerned about overheating, whereas their homes exhibited far lower temperatures in general. Thus occupant perception of overheating, as well as resultant behaviour can be seen as a major factor.

Table 4 takes a broad overview of the factors pertaining to overheating in the 26 properties monitored. Few clear trends can be established but from the perspective of design, the following are of note: none of the properties have any form of effective external shading; only 19% have any thermal mass exposed to the internal spaces; and 38% of rooms have potential for stack ventilation. In addition, it appears that hot water pipework is not being effectively insulated and many occupants do not clearly understand heating controls i.e. of those studied, 46% did not understand or use programmatic control and 15% did not understand or adjust thermostatic controls.

Focused studies, particularly those based on modelling are valuable in that they enable the community of interest to understand the relative contribution of different factors within a controlled set of variables. previous studies have concentrated on locational and future climate change scenarios (Beizaee et al., 2013; Peacock et al., 2010; Taylor et al., 2014), others have looked at constructional options and thermal mass (Adekunle & Nikolopoulou , 2016) while others have examined occupant control aspects in detail (Nicol & Humphreys, 2002). Whilst research based on monitoring of occupied homes may not allow us to identify the relative contribution of each factor, it

has demonstrated that much design prediction modelling fails to take account of the myriad of design factors and in particular variations in occupant behaviour. By mapping potential causes, both the range and complexity of possible causes can be identified.

The risks of overheating extend not just to those associated with thermal comfort and health of building occupants, but to the risks of increased electricity consumption from an uptake in air conditioning use (Peacock et al., 2010) to provide comfort cooling. Such an uptake would have a detrimental effect on the UK's attempts to reduce carbon emissions and put greater strain on the National Grid.

Architects and designers can do little about the wider developments of climate change, nor can they change the geography of their projects, but they can affect most of the other factors which tend to increase overheating risk, including the options for occupants. It should also be ensured that these measures are delivered in finished buildings. With an aim to provide buildings which are designed and built to inherently protect against overheating and provide opportunities for occupants to manage residual overheating risk is not difficult, nor costly to do, but requires an awareness of the risks from all of those involved in the built environment.

Conclusions

This paper intended to address overheating in energy efficient housing in Scotland using data collected through BPE studies and a matrix to identify design and occupant factors. Internal air temperature data collected over a one year period demonstrated that overheating, as defined by the Passive House standard, is occurring to concerning levels in dwellings in Scotland; in some cases this is not limited to the summer months. The matrix developed demonstrates that although there were no clear correlations for overheating there are a number of significant contributing factors in both the design and occupancy that requires to be considered for future developments. In short, design and

occupancy factors appear to override geography and climate change.

The fact that overheating appears not to be entirely a function of external temperature suggests that other factors are contributing to this phenomenon. Further research needs to be undertaken to demonstrate the interrelationship between contributing factors and overheating risk, which can be used to inform change in policy and construction practices. However, beyond both location and design factors, it appears that the individual behaviour of occupants, derived from varying individual perceptions of what constitutes comfortable conditions, can radically alter the performance of buildings in respect of overheating. Thus identical buildings were seen to perform very differently with different occupant patterns and behaviour. Further BPE research into overheating is required and needs to consider specific granular user data, including: use and understanding of systems and controls, window opening, internal door opening, trickle vent use, occupancy patterns and occupant perceptions.

Awareness by policy makers and the regulatory system, supported by more accurate prediction tools, could create the context within which Architects and designers could easily adjust common strategies, details and specifications with the importance of these communicated to builders and occupants. Crucially, occupants would be able to take simple measures to maintain comfortable conditions and mitigate the effects of climate change for as long as possible.

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References

- Adekunle, T. O., & Nikolopoulou, M. (2016). Thermal comfort, summertime temperatures and overheating in prefabricated timber housing. *Building and Environment*, 103, 21–35. <http://doi.org/10.1016/j.buildenv.2016.04.001>
- Beizaee, A., Lomas, K. J., & Firth, S. K. (2013). National survey of summertime temperatures and overheating risk in English homes. *Building and Environment*, 65, 1–17. <http://doi.org/10.1016/j.buildenv.2013.03.011>
- Building Research Establishment [BRE] (2011) *Passivhaus Primer: Designer's Guide: A guide for the design team and local authorities*. Retrieved from: http://www.passivhaus.org.uk/filelibrary/Primers/KN4430_Passivhaus_Designers_Guide_WEB.pdf
- Certified European Passive House - Developing Group [CEPH]. (2014) *Certified European Passive House Designer Course. Volume A: The Passive House Standard*. University of Strathclyde.
- Cooper, I., & Palmer, J. (2011). Great Britain's housing energy fact file, 1–118. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48195/3224-great-britains-housing-energy-fact-file-2011.pdf
- M. Davies and T. Oreszczyn, "The unintended consequences of decarbonising the built environment: A UK case study," *Energy Build.*, vol. 46, pp. 80–85, 2012.
- Department for Communities and Local Government [DCLG]. (2012). *Investigation into Overheating in Homes: Literature review*, (July). Retrieved from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/7604/2185850.pdf
- Her Majesties Government [HMG]. (2013). *The Building Regulations, Conservation of fuel and power Approved Document Part L1A (2013 version)*, 48. Retrieved from UK Government planning

- portal: http://www.planningportal.gov.uk/uploads/br/BR_PDF_AD_L1A_2013.pdf
- Kovats, S., Hajat, S. (2008) Heat stress and public health: A critical review. *Annual Review of Public Health*, 29 (9)1–9.15. <http://doi.org/10.1146/annurev.publhealth.29.020907.090843>
- Larsen, T. S., & Jensen, R. L. (2011). Comparison of measured and calculated values for the indoor environment in one of the first Danish Passive Houses, Aalborg University, Denmark, 14–16. Retrieved from http://www.ibpsa.org/proceedings/BS2011/P_1475.pdf
- Maivel, M., Kurnitski J. & Kalamees T. (2015). Field survey of overheating problems in Estonian apartment buildings. *Architectural Science Review*, 8628, 0–10. <http://doi.org/10.1080/00038628.2014.970610>
- McLeod, R. S., Hopfe, C. J., & Kwan, A. (2013). An investigation into future performance and overheating risks in Passivhaus dwellings. *Building and Environment*, 70, 189–209. <http://doi.org/10.1016/j.buildenv.2013.08.024>
- Morgan, C., Foster, J., Sharpe, T., & Poston, A. (2015). Overheating in Scotland: Lessons From 26 Monitored Low Energy Homes. CISBAT 2015 International Conference “Future Buildings and Districts - Sustainability from Nano to Urban Scale”. 167–172. Retrieved from <http://radar.gsa.ac.uk/3719/>
- National House Building Council [NHBC]. (2012). Overheating in new homes: A review of the evidence. Retrieved from NHBC Foundation: <http://www.nhbcfoundation.org/Publications/Research-Review/Overheating-in-new-homes-NF46>
- National House Building Council [NHBC]. (2015). Homes through the decades. Retrieved from NHBC Foundation: <http://www.nhbc.co.uk/NewsandComment/Documents/filedownload,59849,en.pdf>
- Nicol, J. F., & Humphreys, M. a. (2002). Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and Buildings*, 34(6), 563–572. [http://doi.org/10.1016/S0378-7788\(02\)00006-3](http://doi.org/10.1016/S0378-7788(02)00006-3)
- Office of the Deputy Prime Minister [ODPM]. (2004). Housing Health and Safety Rating System. Retrieved from UK Government: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/15810/142631.pdf

- Ruud S, Lundin L. (2004) Bostadhus utan traditionellt uppvärmningssystem– resultat från två års matningar. SP Report 2004:31. SP Technical Research Institute of Sweden. (Original in Swedish)
- Parliament of the United Kingdom [UK]. (2006a) Stern Review on The Economics of Climate Change. 2006. Retrieved from: http://webarchive.nationalarchives.gov.uk/+http://www.hm-treasury.gov.uk/sternreview_index.htm
- Parliament of the United Kingdom [UK]. (2006b) Pre-Budget Report; Investing in Britain's potential: Building our long-term future. Retrieved from: http://webarchive.nationalarchives.gov.uk/20071204131415/http://www.hm-treasury.gov.uk/media/2/2/pbr06_chapter7.pdf
- Parliament of the United Kingdom [UK]. (2008) Climate Change Act 2008. Retrieved from UK Government: <http://www.legislation.gov.uk/ukpga/2008/27/contents>
- Passive House Institute (<http://www.passiv.de/en/index.php>)
- Peacock, a. D., Jenkins, D. P., & Kane, D. (2010). Investigating the potential of overheating in UK dwellings as a consequence of extant climate change. *Energy Policy*, 38(7), 3277–3288. <http://doi.org/10.1016/j.enpol.2010.01.021>
- Scottish Parliament. (2009). Climate Change (Scotland) Act 2009, 2009(asp 12), 68. Retrieved from: <http://www.scotland.gov.uk/Topics/Environment/climatechange/scotlands-action/climatechangeact>
- Scottish Government. (2015). Scottish Building Regulations: Technical handbook, Domestic. Retrieved from Scottish Government: <http://www.gov.scot/Resource/0047/00478112.pdf>
- Stevenson, F., & Leaman, A. (2010). Evaluating housing performance in relation to human behaviour: new challenges. *Building Research & Information*, 38(5), 437–441. <http://doi.org/10.1080/09613218.2010.497282>
- Taylor, J., Davies, M., Mavrogianni, a., Chalabi, Z., Biddulph, P., Oikonomou, E., ... Jones, B. (2014). The relative importance of input weather data for indoor overheating risk assessment in dwellings. *Building and Environment*, 76, 81–91. <http://doi.org/10.1016/j.buildenv.2014.03.010>
- Zero Carbon Hub [ZCH]. (2014). Closing the Gap Between Performance, (July). Retrieved from:

http://www.zerocarbonhub.org/sites/default/files/resources/reports/Closing_the_Gap_Between_Design_and_As-Built_Performance_Interim_Report.pdf

Zero Carbon Hub [ZCH]. (2015a). Overheating in Homes - The Big Picture. Retrieved from: <http://www.zerocarbonhub.org/sites/default/files/resources/reports/ZCH-OverheatingInHomes-TheBigPicture-01.1.pdf>

Zero Carbon Hub [ZCH]. (2015b). Defining overheating – Evidence Review. Retrieved from:

<http://doi.org/http://www.zerocarbonhub.org/sites/default/files/resources/reports/ZCH-OverheatingEvidenceReview-Definitions.pdf>

Zero Carbon Hub [ZCH]. (2015c) Assessing Overheating Risk – Evidence Review. Retrieved

from: <http://www.zerocarbonhub.org/sites/default/files/resources/reports/ZCH-OverheatingEvidenceReview-Methodologies.pdf>