Passivhaus Trust
The UK Passive House Organisation

The performance of Passivhaus in new construction:

Post occupancy evaluation of certified Passivhaus dwellings in the UK: Early Results

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Acknowledgements

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Introduction

Domestic energy consumption accounts for 27% of total UK final energy use and carbon emissions. The Climate Change Act 2008 established long term targets for the UK to reduce Green House Gas (GHG) emissions by 80% by 2050 with an interim target of 34% by 2020 (1). Reducing energy in housing, is a major opportunity to reduce greenhouse gas emissions and it would not be possible to meet overall UK emissions reductions targets without addressing energy use in the home (2). The Climate Change Committee (CCC) have identified energy efficiency in buildings and low carbon forms of heating as a priority to delivering the overall carbon budget of the UK(3). Therefore the building sector and the construction industry are key to energy and carbon reduction strategies (4).

The performance gap in buildings is described as the difference between the thermal performance predicted from building modelling and the actual measured energy in-use once the building is built and occupied (5-8). It would be realistic to expect some variations in measured building performance, as people will not use buildings in a uniform way: households are diverse, occupation patterns are different, and internal comfort temperatures vary (6, 8). Therefore, some dwellings will use more energy than predicted and others less. However, emerging research suggests that mean measured energy is significantly higher than mean predicted energy and this suggests there is an inherent problem between design expectations and the energy performance of buildings in-use. The Zero Carbon Hub have undertaken a review of research into the performance gap and have concluded that there is clear evidence of a performance gap in new dwellings, which is a risk to home owners, developers, and government. (ZCH, 2014). Field testing has shown that heat loss can be up to 50%-60% more than design predictions (4, 9) and total energy use between 150% and 250% more.(8, 10).

One of the challenges to understanding the performance gap is the lack of post construction monitoring and this lack of post occupancy performance data means that the building industry does not know to what standards it is building now and, as these standards increase, there is a greater risk that the performance gap will also increase. (5, 9).

However, homes constructed the Passivhaus Standard do not appear to suffer from the same performance gap as measured energy performance is much closer to, or better than, predicted thermal performance. (11-14)

Overheating is also a performance gap issue if the building models used are not able to predict the overheating risk once the building is occupied. There is some evidence to suggest that homes which are highly insulated and air tight are at risk of overheating (15), while other studies find this is not the case.(11). Most of the evidence to date from Passivhaus homes in the UK is from small scale case studies, and what is missing is an overview of all the evidence available. This will allow an overview of the performance of homes built to the standard and a systematic evaluation of energy use and overheating risks.

The Passivhaus Standard

Passivhaus is the world's leading and fastest growing standard for low energy building and to date over 45,000 homes have been certified to this standard (16). Passivhaus is an energy and comfort standard which sets maximum performance criteria for space heating and cooling demand, heat load, air permeability, overheating and final energy. Passivhaus can be achieved by using a range of construction methods and technologies (17). Table 1 opposite gives a summary of the main elements of the Passivhaus standards.

Energy	Limiting Standard
Space heating demand	≤15 kWh $m^{-2}a^{-1}$
Heat load	≤10 W $m^{-2}a^{-1}$
Primary energy demand	≤120 kWh $m^{-2}a^{-1}$
Overheating	≤10% occupied hours over 25ºC (internal temperature)
Building Fabric	**Limiting Standard**
Floor/Walls/Roof	≤0.15 $Wm^{-2}K^{-1}$
Windows and doors	≤0.8 $Wm^{-2}K$
Air permeability	≤0.6ach_{n50}
Thermal bridges	Zero

There have been some post occupancy studies of Passivhaus homes and these early studies suggest that Passivhaus homes do not suffer from the same performance gap as homes built to other standards and the gap between design and predicted energy performance is small. This small difference between design and predicted fabric performance is best illustrated by the Leeds Beckett Co- heating database which shows the results of 33 dwellings which have been subjected to an electric co- heating test. The last six dwellings on the right show the heat loss co-efficient from 6 certified Passivhaus' and demonstrate that in this sample the Passivhaus dwellings consistently meet, or are closer to, their performance predictions.

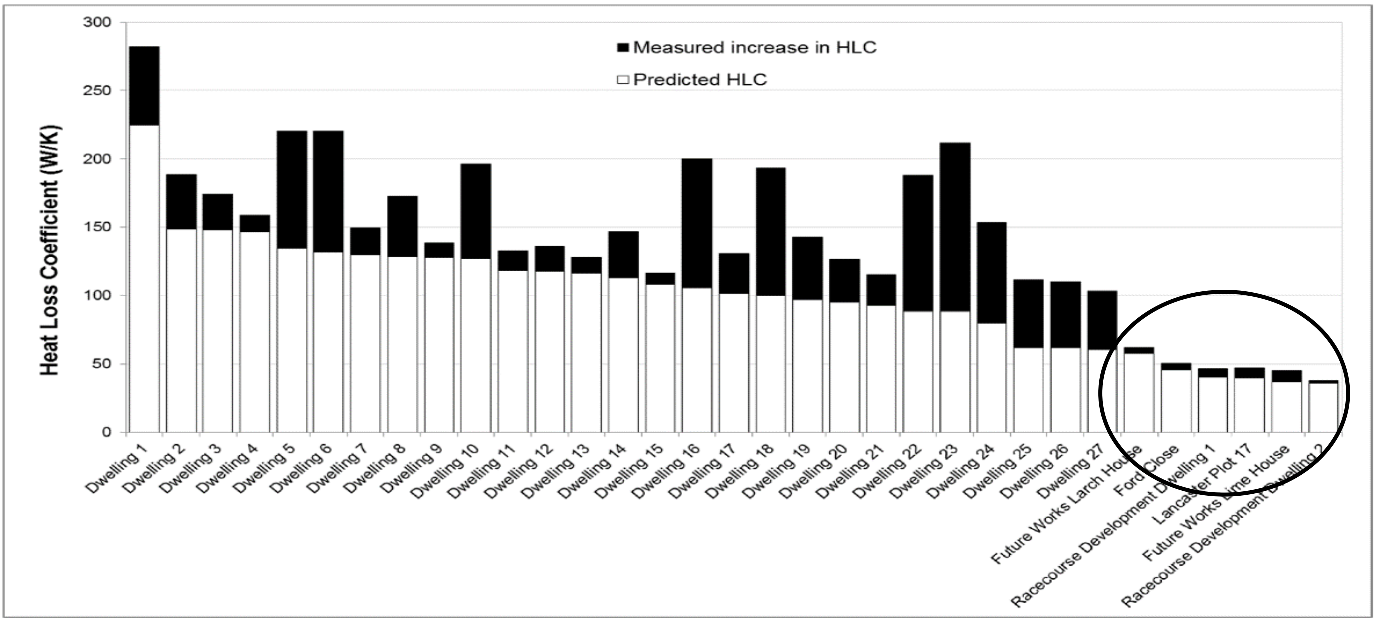


Table 2 Leeds Beckett Co-Heating Data Base (14)

All the studies of Passivhaus dwellings recognise that the sample sizes were small and therefore made it difficult to draw wider conclusions.

Overheating in buildings

Overheating in buildings is not well defined or fully understood (18, 19). Overheating occurs when the heat built up within a building cannot be easily dissipated or removed (20). Overheating can also be affected by humidity, air movement, activity in the building and attitudes of occupants. Thermal comfort is an individual experience; what one person would find warm another may find too hot or too cool. For example a study of a Passivhaus care home found that whilst staff found the internal temperatures too high, for residents who were frail and less active, temperatures were more acceptable. (21)

The ZCH defined overheating as *the phenomenon of excessive or prolonged high temperatures in the home, resulting from internal or external heat gains, which may have adverse effects on the comfort, health or productivity of the occupants*. (20)p 11

There is currently a debate as to whether homes built to higher energy efficiency standards overheat because of high levels of insulation and low levels of air permeability. Moreover, as external temperatures increase with climate change as predicted the potential risk of summer overheating also increases. Evidence is currently divided on whether there is (15) (22) or is not (23) a greater overheating risk in highly insulated buildings.

If high levels of insulation and air tightness were the only risk factors for overheating, then in theory, homes built to the Passivhaus standard should be at highest risk. However, the Passivhaus standard requires a calculation of heat gains and likely overheating risk that is more detailed using PHPP, compared to the approach taken for most other low energy homes, which typically would only be assessed in SAP (22). This should lead to a lower overheating risk for certified Passivhaus homes.

The NHBC reviewed post occupancy data from 736 Passivhaus homes built in Germany and found that while initially 56% of occupants reported overheating, once strategies such as drawing blinds, night time ventilation and using the summer bypass on the MVHR were utilised, overheating could be reduced (24). Modelling has also been undertaken to test the standard against future predicted climates and found that strategies such as fixing solar shading and reducing glazing ratios were critical for reducing overheating (25).

Whilst some overheating in Passivhaus homes has been reported, this has been attributed to design decisions and user behaviour rather than an inherent problem with the building standard and that, once strategies are undertaken, overheating risk is reduced. However, this means that managing overheating becomes an active task rather than passive and that a greater understanding of how overheating is caused and what strategies can be adopted to overcome this is needed by both designers and occupants.

CEPHEUS research project

The European research project CEPHEUS (Cost Efficient Passive Houses as European Standards) was an EU funded project set up to test the technical feasibility and viability of the Passivhaus standard in Germany, Sweden, Austria, Switzerland, and France. Between 1998 and 2001, 221 housing units on 14 different sites were constructed.
The average measured space heating demand across all sites for year one was found to be approximately 20 kWh/m^2/year compared to the design standard of 15 kWh/m^2/year. At the time 20 kWh/m^2/year was an 83% reduction in heating energy demand compared to the building codes and therefore a considerable achievement. (11, 17)

The CEPHEUS project has a large sample size. The results also showed large differences between space heating consumption, both among and between the projects. Indoor summer temperatures were monitored on two sites of 38 homes and mean indoor temperatures between May and August were 21.9^{o}c and 23.6^{o}C and overall no overheating risk was identified.

Aims and objectives

It is expected that, by 2017, over 1,000 buildings will be built and certified to the Passivhaus standard in the UK. Whilst there has been some post occupancy reporting of individual schemes there has been no national systematic evaluation of the energy and comfort performance of these homes to see if the Passivhaus standard delivers in the UK. As part of the UK Passive House Trust research program, post occupancy data from space heating demand, internal and external temperatures, and solar radiation, will be collected from homes constructed and certified to the Passivhaus Standard.

The aim of the study is to collect data from a statistically significant sample of homes (over 100 dwellings) and test for the existence of a performance gap for winter heating demand and summer overheating. The hypothesis tested is that *homes built to the certified Passivhaus standard in the UK will not suffer a performance gap for space heating demand and summer overheating.*
The objectives are:

- To collect post occupancy hourly data for internal and external temperatures and annual space heating demand from 100 + homes certified to the Passivhaus standard.

- To normalise the data using a methodology from the EU CEPHEUS project which will allow for comparison across both the national projects and with CEPHEUS. Normalising makes an adjustment to space heating demand which considers measured internal and external temperatures, and solar radiation, which will vary from the assumptions in the building modelling software Passive House Planning Package (PHPP). For example, a home with a winter internal temperature set above 20ºC will use more energy for space heat than predicted.

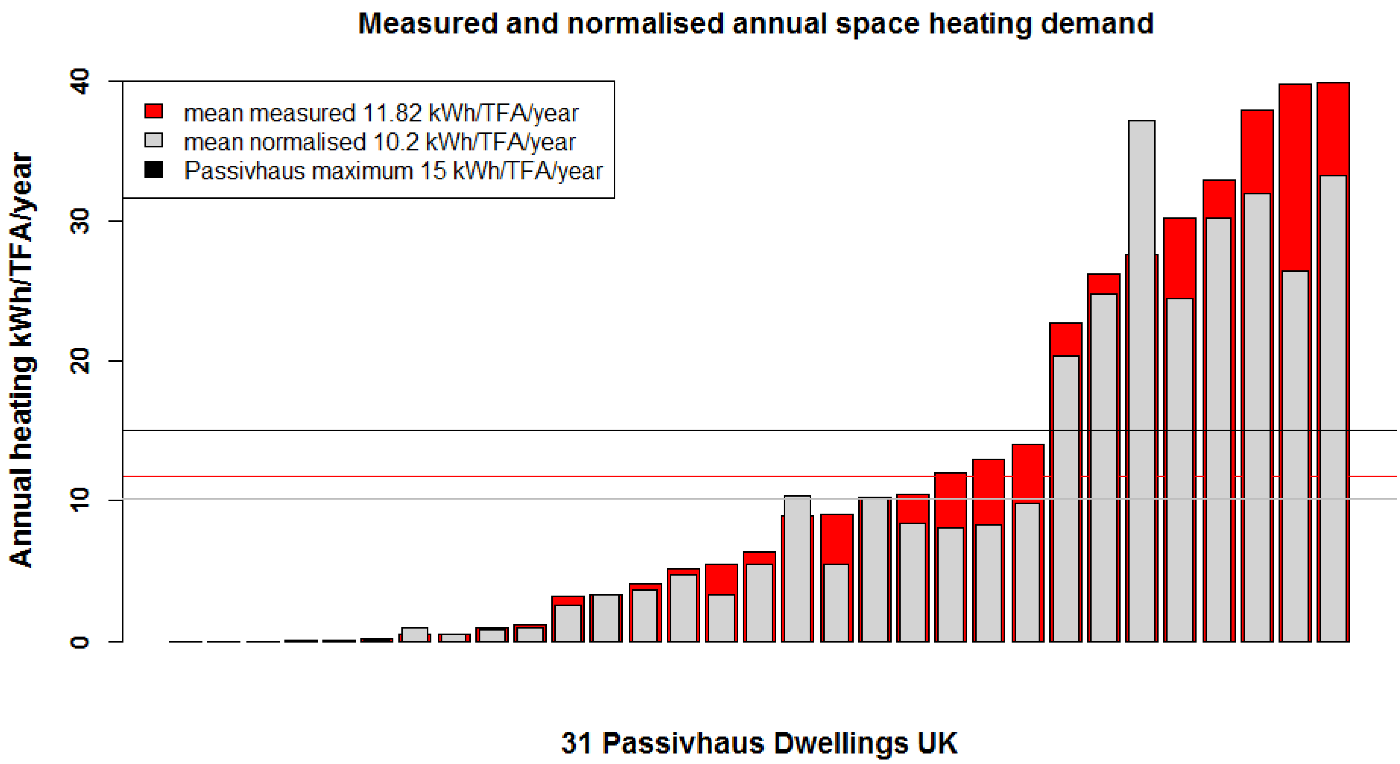
- To analyse the data for evidence of a performance gap for heating demand and summer overheating.

Results

To date measured data has been collected from 31 dwellings. Over the next 2 years, this dataset will be expanded using the same methodology.

Space Heating demand

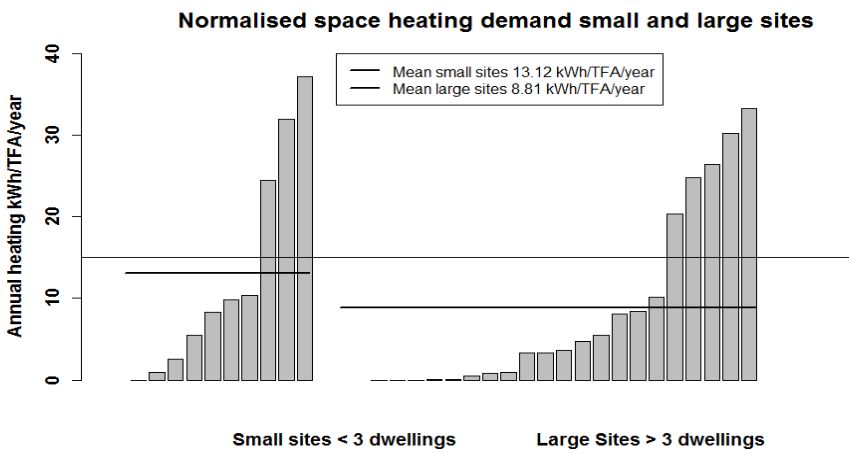
The average measured annual space heating demand for all 31 homes was 11.8 kWh/m²/year. When this was adjusted to consider site conditions (external temperature and solar radiation) and measured internal temperatures, the average space heating demand (normalised) reduced to 10.2 kWh/m²/year. This is shown in graph 1 below. The maximum allowable space heating demand for a certified Passivhaus is 15 kWh/m²/year. Therefore the 31 homes were, on average, performing better than the design expectation. Within these 31 homes, some were using more energy than expected for space heating and others less. Several dwellings had no or very low measured heating demand (discussed later).



Graph 1 normalised and measured heating demand for each site

Graph 2 shows the normalised space heating demand split between small and large sites. A small site was defined as 2 or less homes on the development and a large site all other developments (3 or more homes on the site). The average heating demand for both site types is given.

The results show that average space heating demand was less on the larger sites, 8.8 kWh/m²/year compared to 13.1 kWh/m²/year. Larger sites tended to be social housing projects, smaller sites tended to be individual homes, where the owner had specified a Passivhaus to be constructed.

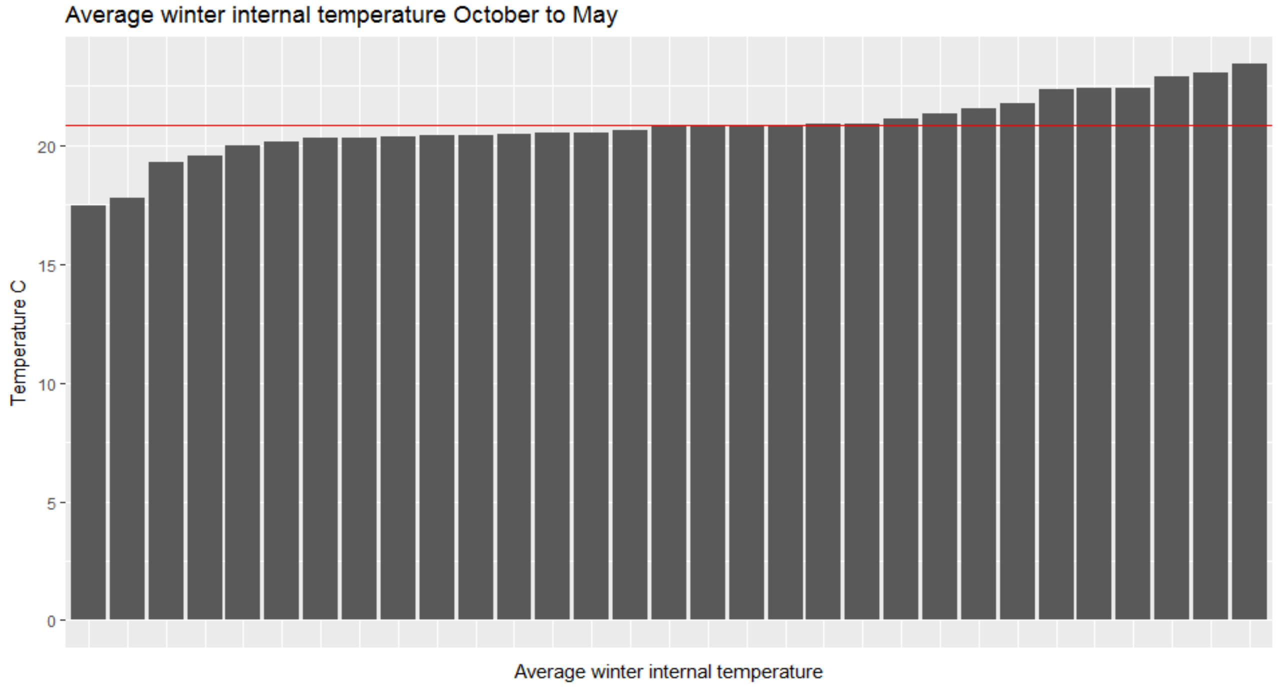


Graph 2 Annual normalised heating demand by site type with average heating demand for each site

Winter internal temperatures

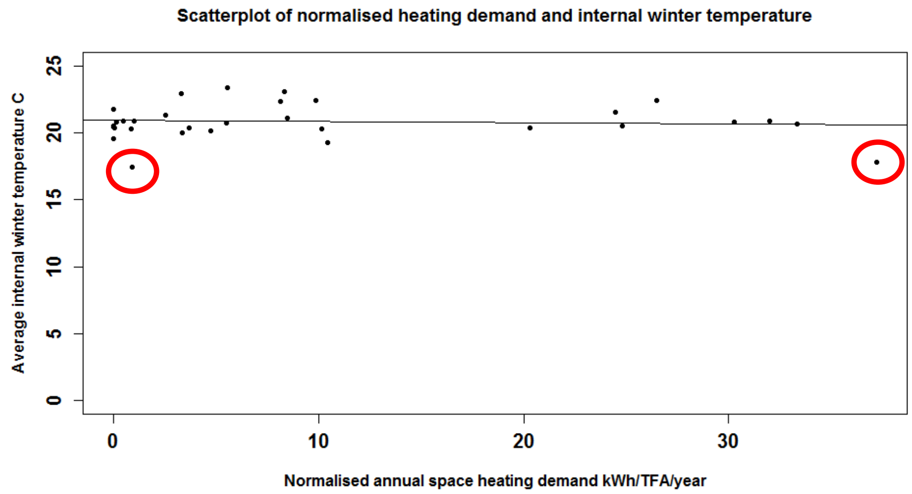
It could be that low space heating demand was a result of internal winter temperatures being lower than the model assumed.

The average internal winter temperature was 20.83°C and is shown in graph 3. This is above the assumed internal temperature of 20°C which is used at the building modelling stage in PHPP. Within the range of results, the lowest average temperature is 17.46°C and the highest 23.41°C. Only 4 of the 31 dwellings have an average internal temperature of less than 20°C. Therefore, there is no evidence of systematic underheating in winter and most homes have comfortable internal winter temperatures.



Graph 3 Average winter temperature (October to March) for 31 sites

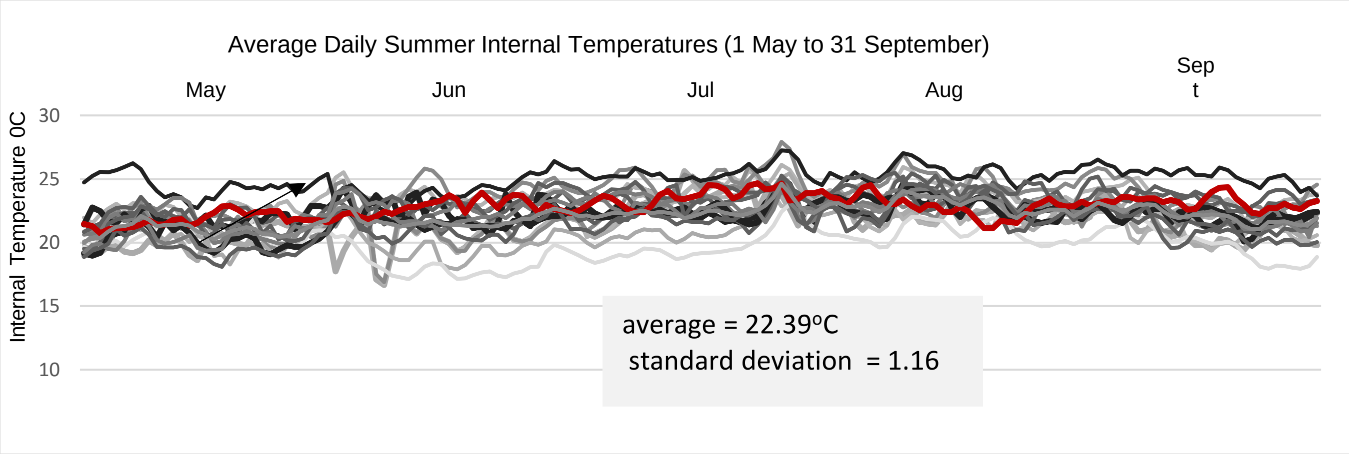
The relationship between internal winter temperatures and low space heating demand was further explored as 11 of the 31 homes used less than 5 kWh/m²/year for space heating. Graph 4 below shows a scatter plot of normalised space heating demand and average winter internal temperature to see if homes with low internal temperatures also have low space heating demand. The graph shows there is no relationship between internal temperature and space heating demand. Therefore, low space heating demand is not a result. of underheating. The two dwellings with the lowest internal winter temperature had both one of the lowest and the highest space heating demands as shown by the red circles.



Graph 4 normalised annual heating demand and average internal winter temperature

Overheating

To date, data has only been analysed from 19 of the 31 dwellings. Graph 5 below shows the average daily internal temperatures for summer (May to September) The results show that the average summer internal temperature across all dwellings is 22.39°C. There are periods when internal temperature in the dwellings rises above 25°C and for one home the average summer temperature is 25°C, while other homes remain much cooler.



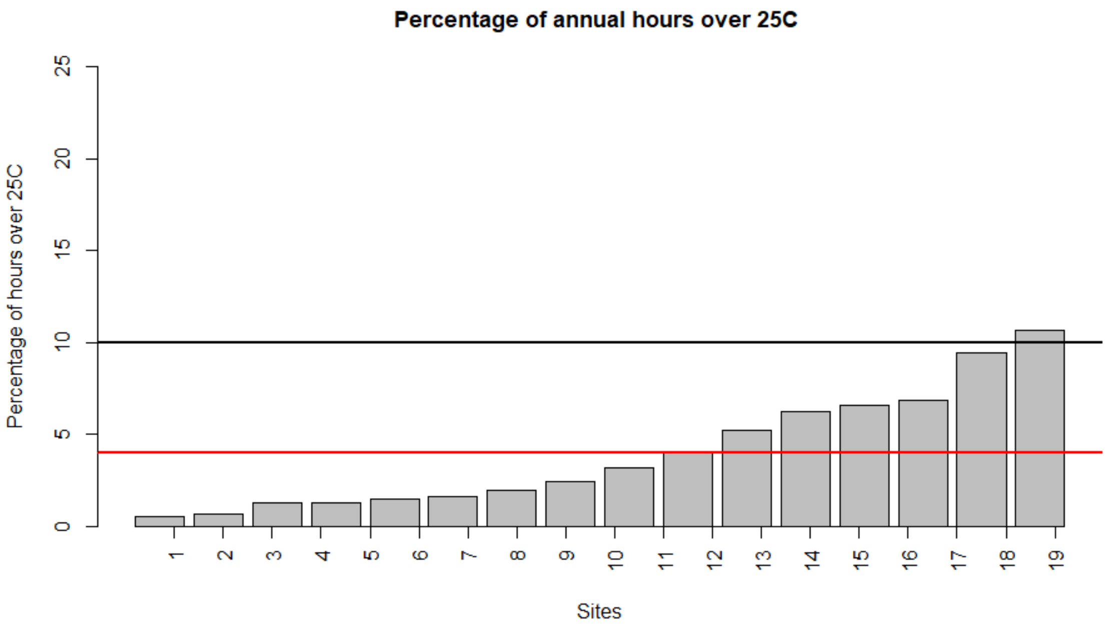
Graph 5 Daily internal summer internal temperatures all sites

Therefore, on average the homes are not overheating, but within this, there are some exceptions.

Overheating standards

The Passivhaus standard includes a limit on the predicted numbers of hours internal temperatures can rise above 25°C. This is limited to no more than 10% of occupied hours. The PHPP assessment methodology assumes that domestic dwellings are occupied continuously i.e. 8760 hours per year.

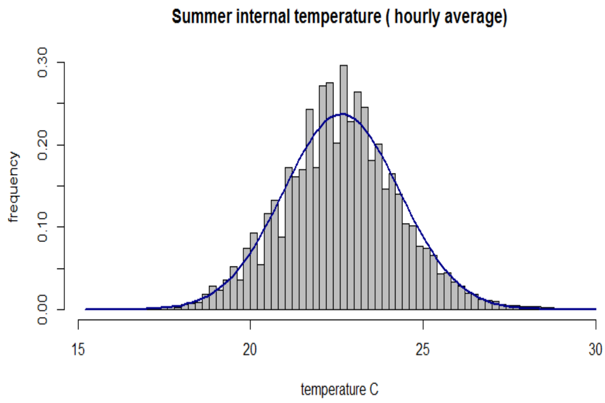
The graph below shows the percentage of hours, for one year, that the measured internal temperature exceeds 25°C. The black line shows the 10% upper limit and the red line the average number of hours for all the 19 sites. The average is 3.97% of total number of hours.



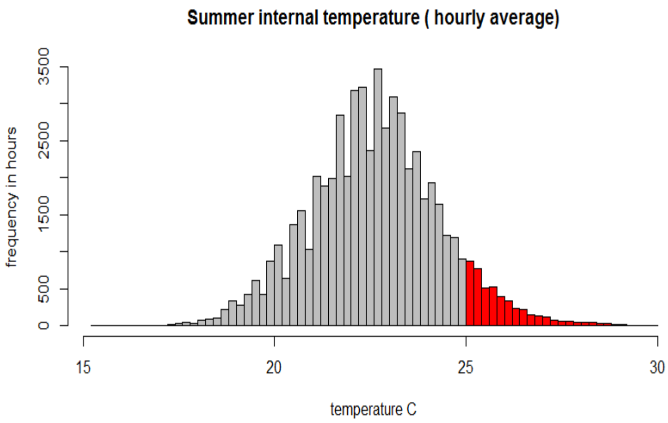
Graph 6 Percentage of annual hours over 25°C

This average number of hours is within the overheating threshold of the Passivhaus standard and within the good practice guidance of 5%. There are a range of temperatures, and one home recorded temperatures over 25°C for 10.67% hours which is slightly above the standard.

The graphs 7 and 8 below show the distribution of average hourly internal temperatures over the summer months with a normal distribution curve overlaid of the first graph. Graph 8 shows the frequency of hours above 25°C in red.



Graph 7 Distribution of hourly internal summer temperatures with normal distribution



Graph 8 Distribution of hourly internal summer temperatures over 25°C

Discussion

Heating

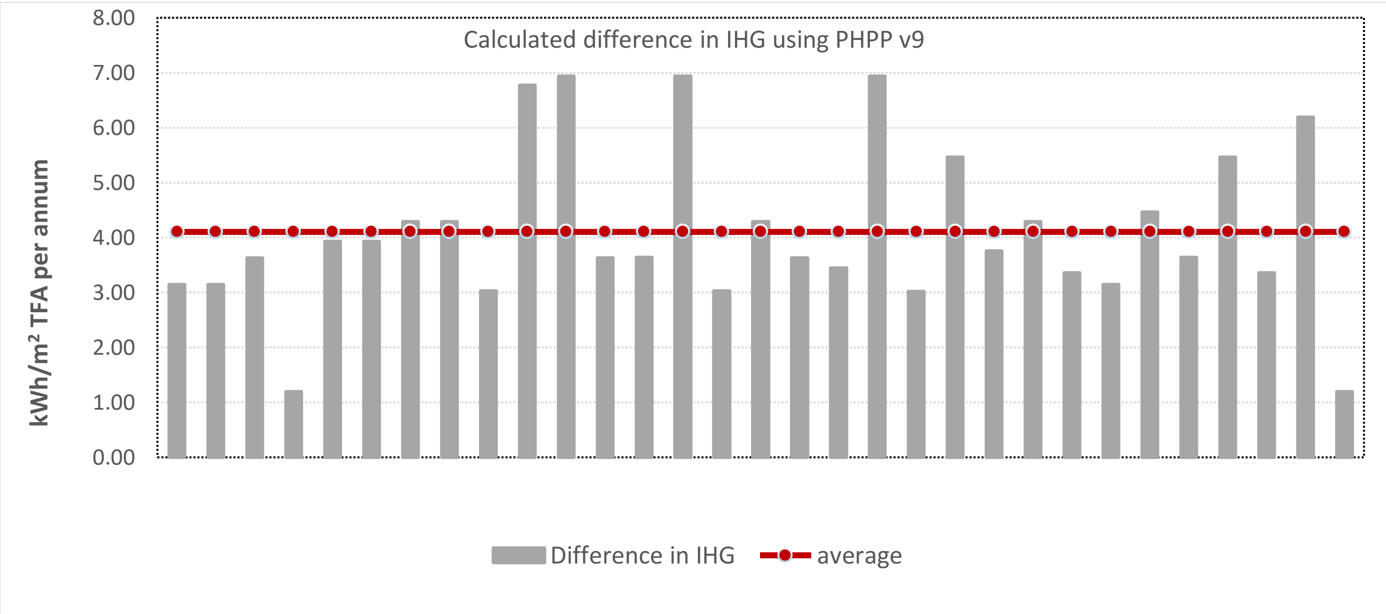
The results showed that the dwellings were using on average 10.2 kWh/m^2/year (normalised) for space heating per year. Within the sample, 13 of the 31 dwellings were using less than 5 kWh/m^2/year and eight of the homes were using < 1 kWh/m^2/year (normalised) for space heating per year. Some homes had lower internal temperatures than the design assumptions. However, the average internal temperature was 20.8 °C which is above the assumption in PHPP of 20^{o}C. Homes with lower internal temperatures where not always the homes with low space heating demand.

Therefore, the homes are, on average, performing better than the design prediction of 15 kWh/m^2/year and the performance gap seen in other dwellings, where more energy is being used for space heating, is not being seen in these certified Passivhaus dwellings. Two key assumptions may be implicated in the lower than predicted space heating demand, discussed below.

Impact of assumed internal gains

Grant and Clarke (2014) reported that PHPP used low fixed internal heat gains (IHG) in its calculations based on internal treated floor area. This may lead to an underestimation of internal gains in smaller houses. PHPP assumes a fixed occupancy rate of 35m^2 per person, whereas social housing may have two or three occupants in a dwelling of 65m^2 and four or five in 85m^2. Therefore internal heat gains may be underestimated in PHPP for smaller dwellings and overestimated in larger dwellings (26). Within the sample, 19 of the 31 measured dwellings were social housing units, which tend to have higher rates of occupancy and lower under occupancy rates compared to average households (27). This may lead to higher internal gains from metabolism, cooking, dishwashing, laundry, lights, and consumer electronics. Simply put, more people could mean potentially more internal gains and therefore less space heating demand.

The internal gains calculation has been revised in PHPP v9, and smaller homes will now have higher fixed internal gains assumed in predicted heating demand calculations. Since all the dwellings in the database were modelled in an earlier version of PHPP, Graph 10 shows the difference that would have occurred if the newer calculations from PHPPv9 were used (assuming standard occupancy and electrical loads) for each of the 31 dwellings. This suggests that, on average, remodelling in PHPP 9 would add an additional 4 kWhm^{-2}a^{-1} to the internal gains calculation.



Graph 10 The difference between internal gains calculation in PHPPv9 and PHPPv8 for all dwellings in the data base

Impact of electrical loads

PHPP will assume standard occupancy rates and, at design stage, assumptions will be made relating to electrical loads. PHPP tends to assume a low electrical load which is in line with the low energy philosophy of Passivhaus. Once occupied, not only could occupancy rates be greater but electrical loads may be higher than assumed at the modelling stage.

The impact of occupancy rates and electrical loads on internal gains calculations and space heating demand was calculated using a row of four x 3 bed town houses modelled in PHPPv9. The treated floor area (TFA) for each dwelling is 89m^2 and the homes were designed for a housing association. Occupation levels and electrical loads for 6 scenarios were considered and these are shown in the table below. Electrical consumption data was used from three sources:

1. Assumptions made in PHPP "electricity" sheet.
2. Average electrical consumption load measured from one site in the database[1].
3. Household Electrical Survey 2012 (28).

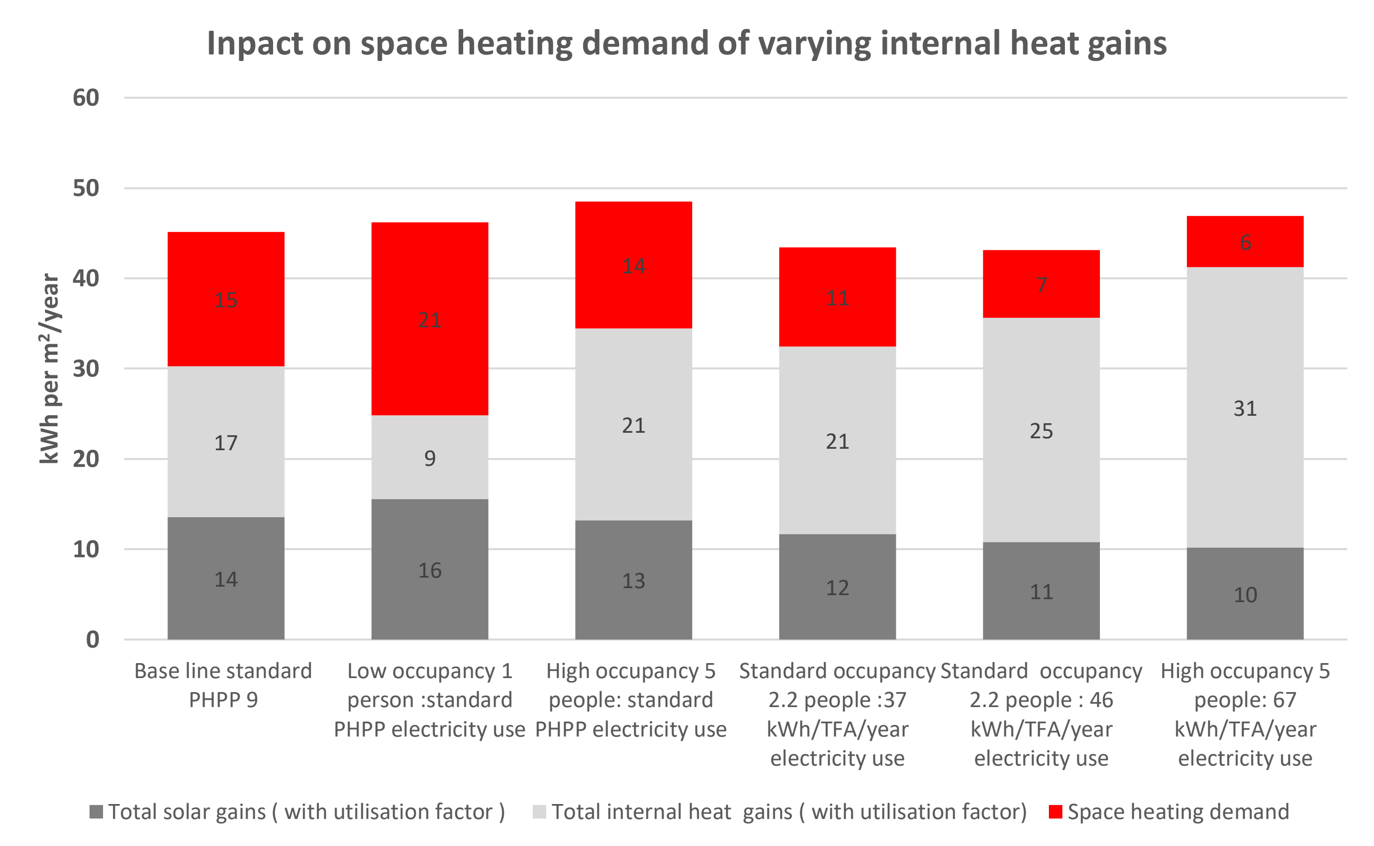
The table gives the outputs from the 'Heating' sheet for IHG (with the utilisation factor applied) and space heating demand, and from the 'Electricity' sheets for electrical load.

6 scenarios modelled in PHPPv9	Occupancy per dwelling	Electrical load kWh/m^2/year	Total gains solar and IHG kWh/m^2/year	Heating demand kWh/m^2/year
Baseline PHPP – standard assumptions	2.2	24	31	15
Low occupancy rate- standard PHPP and electrical use assumptions	1	17	25	21
High occupancy rate- standard PHPP electrical use assumptions	5	45	34	14
Standard occupancy average electrical use in Electrical Household Survey 2012 (3244 kWh per year)	2.2	37	33	11
Standard occupancy average electrical use measured from site (4053 kWh per year)	2.2	46.	36	7
High occupancy average electrical use per m2 from Household Survey	5	67	41	6

The last option – high occupancy rate and high electrical load gives a 67 kWh/m^2 electrical consumption load which is like the average found in the Household Electrical Survey of 65kWhm^2 for a household with children and this is much higher than the electricity use assumption of 24 kWh/m^2 made in a standard PHPP assessment.

Graph 11 below shows the same data, and the impact on internal gains, solar gains, and space heating demand is clearly shown.

[1] Data courtesy of Warm low energy practice.



Graph 11: 6 scenarios in a row of 4 dwellings modelled in PHPPv9)

The last two scenarios, which use the higher electrical loads coupled with standard and higher occupancy levels, show the impact on modelled space heating demand. The graph shows that higher than predicted electrical loads coupled with higher occupancy levels will lead to much lower space heating demand predictions, which may account for the low space heating demand measured in some of the houses in the database.

Overheating

To meet the Passivhaus standard, dwellings should not show an overheating risk (internal temperature is over 25˚C). This limit for a certified passivhaus is no more than 10% of occupied hours and domestic dwellings are assumed to be occupied 100% of the year for certification purposes. When compared to this standard, on average the dwellings are not showing an overheating risk. Based on the sample, the average percentage of hours where the measured internal temperature is over 25˚C is 3.95%. The range is between 0.5 % of and 10.7% of hours. Therefore, on average the database of dwellings are performing within the design parameters for PHPP and not showing an overheating risk, but within that there are exceptions.

The performance gap

The aim of the research is to test the hypothesis that *homes built to the certified Passivhaus standard in the UK will not suffer a performance gap for space heating demand and summer overheating.*
The performance gap would occur when homes used more energy for space heating or the hours when internal temperatures rose above 25°C were more than 10% of total hours.

The early results show that taking the average of all the 31 dwellings with space heating measurements and 19 homes with internal temperature measurements, there is no evidence of a performance gap in certified Passivhaus homes in the UK. However, the number of homes in the database is still small. This will be further tested as more homes are added to the database and there can then be greater confidence in the results.

References

1. DECC. 2013 UK Greenhouse gas emisisons, final figures. In: DECC, editor. London UK: National Statistics; 2015.
2. Palmer J, Cooper I. United Kingdon housing energy fact file 2013. In: DECC, editor. Londong UK2014.
3. CCC. The fifth carbon budget : The next steps to a low-carbon ecconomy In: Change CoC, editor. London UK2015.
4. Gorse C, Glew D, Miles-Shenton D, Farmer D, Gorse C, editors. Addressing the thermal performance gap: Possible performance control tools for the construction manager. Proceedings 31st Annual ARCOM Conference; 2015: Association of Researchers in Construction Management.
5. Wingfield J, Bell M, Miles-Shenton D, South T, Lowe R. Lessons from Stamford Brook : Understanding the gap between designed and real performance Partners in Innovation projects CI 39/3/663. Leeds UK: Leeds Metropolitan University; 2008.
6. Bell M, Wingfield J, Miles-Shenton D, Seavers J. Low carbon housing: lessons from Elm Tree Mews. Joseph Rowntree Foundation, York ISBN. 2010:978-1.
7. Gupta R, Dantsiou D. Understanding the Gap between 'as Designed'and 'as Built'Performance of a New Low Carbon Housing Development in UK. Sustainability in Energy and Buildings: Springer; 2013. p. 567-80.
8. de Wilde P. The gap between predicted and measured energy performance of buildings: A framework for investigation. Automation in Construction. 2014;41:40-9.
9. Gorse CA, David G, Miles-Shenton D, Farmer D, Fletcher M, editors. Building Performance: Fabric, Impact and Implications2013: Sustainable Building 2013 Hong Kong Regional Conference: Urban Density & Sustainability, Hong Kong SAR. Leeds: Leeds Metropolitan University.
10. CarbonBuzz. Website at www.carbonbuzz.org 2016 [
11. Schnieders J. CEPHEUS–measurement results from more than 100 dwelling units in passive houses. European Council for an Energy Efficient Economy: Summer Study. 2003;2003.
12. Ridley I, Clarke A, Bere J, Altamirano H, Lewis S, Durdev M, et al. The monitored performance of the first new London dwelling certified to the Passive House standard. Energy and Buildings. 2013;63:67-78.
13. Ridley I, Bere J, Clarke A, Schwartz Y, Farr A. The side by side in use monitored performance of two passive and low carbon Welsh houses. Energy and Buildings. 2014;82:13-26.
14. Johnston D, Siddall M. The Building Fabric Thermal Performance of Passivhaus Dwellings—Does It Do What It Says on the Tin? Sustainability. 2016;8(1):97.
15. Sameni S, Gaterell M, Montazami A, Ahmed A. Overheating investigation in UK social housing flats built to the Passivhaus standard. Building and Environment. 2015.
16. iPHA. http://www.passivehouse-international.org/ Darmstadt Germany2015 [
17. Fiest W, Peper S, Gorg M. CEPHEUS Cost efficient passive houses as european standards Final Report Germany: Passivhaus Institute; 2001.
18. CIBSE. The limits of thermal comfort in european buildings London: CIBSE; 2013.
19. ZCH. Defining overheating: Evidence review. London UK: Zero Carbon Hub; 2015.
20. Hub ZC. Overheating in homes: The big picture full report. London: Zero Carbon Hub; 2015.
21. Guerra Santin O, Tweed AC, editors. Summer post occupancy evaluation of a Passivhaus care home in the UK. Conference: PLEA Sustainable Architecture for a Renewable Future; 2013.
22. Anglia UoE. Wimbish Passivhaus Development Performance Evaluation Executive Summary. 2014.
23. Schnieders J, Hermelink A. CEPHEUS results: measurements and occupants' satisfaction provide evidence for Passive Houses being an option for sustainable building. Energy Policy. 2006;34(2):151-71.
24. <Lessons from Germany's Passivhaus experience.pdf>.
25. McLeod R, Hopfe CJ, Kwan A. An investigation into future performance and overheating risks in Passivhaus dwellings. Build Environ. 2013;70:189-209.
26. Grant N, Clarke A. Internal heat gain assumptions in PHPP. 2014 International Passivhaus Conference; Aachen Germany: Passive House Institute; 2014.
27. DCLG. English Housing Survey: Households: Annual report of England's households 2012-13. London UK2014.
28. Zimmermann J-P, Evans M, Griggs J, King N, Harding L, Roberts P, et al. Household electricity survey: A study of domestic electrical product usage. Intertek Testing & Certification Ltd. 2012.
29. Siddall M, Grant N. Designing for summer comfort in the UK. London UK 2016.