Department for
Energy Security
& Net Zero

Comparison of the Home Energy Model to Camden Passivhaus measured data

Focus on space heating consumption in this Passivhaus home

December 2023

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Introduction

This paper summarises the work undertaken and results from a comparison of Home Energy Model simulations with measured data from the Camden Passivhaus, a house in London designed by bere:architects and certified to the Passivhaus standard.

The work has been undertaken as part of the existing data validation exercise of the Home Energy Model, so that model outputs can be compared with the measured data from existing homes.

The Camden Passivhaus case study

The Passive House concept adopts proven approaches to reducing domestic energy use, with an emphasis on reducing space heating demand. It is often referred to by its German name of "Passivhaus", as the concept originated in Germany. In the Camden Passivhaus, high levels of insulation were used, the building fabric was very airtight, heat recovery ventilation was used, and solar gain was maximised. It is noteworthy because it was the first house in London to obtain Passivhaus certification, and its performance has been studied in detail.

The Camden Passivhaus Building Performance Evaluation was funded by the Technology Strategy Board (now Innovate UK) as part of the wider Building Performance Evaluation (BPE) Programme[1]. This was a programme of systematic research into energy use in buildings and the 'performance gap' in the UK.

DESNZ was interested to undertake comparisons against studies of the energy performance of real homes as part of the validation of the Home Energy Model. DESNZ requested that the Camden Passivhaus was used for this purpose given prior evaluation of this home. This BPE Programme was not designed to validate building simulation models, and it was understood that there were some limitations to the extent that the Home Energy Model could be validated with the dataset associated with the Camden Passivhaus. The intention is to continue the validation process and identify further case studies better designed to validate the Home Energy Model.

The BPE case study evaluated the energy performance of the Camden Passivhaus, along with a study of occupant satisfaction and their interactions with the building. The findings were published in two phases, *Phase 1: Post construction and early occupation*[2], and *Phase 2: In-*

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[1] UKRI, *Low-carbon homes: best strategies and pitfalls* https://www.ukri.org/publications/low-carbon-homes-best-strategies-and-pitfalls/

[2] Palmer, Jason (2012) *Building Performance Evaluation Final report Camden Passive House. Domestic Buildings Phase 1: Post construction and early occupation. BPE ref no: 4638-31202.* Technology Strategy Board. Available at https://bere.co.uk/research/camden-passive-house-bsria-phase-1-short-case-study-for-technology-strategy-board/

use performance and post occupancy evaluation[3]. The information reported in this study has been used to create Home Energy Model simulations that represent the energy performance of the building over a 12-month period, from February 2012 to January 2013.

Post-occupation monitored data used for this evaluation included the following:

- total electricity consumption,
- total gas consumption
- sub-metered energy consumption for eight separate energy uses: (i) total space heating, (ii) hot water, (iii) lighting, (iv) ventilation, (v) cooking, (vi) appliances, (vii) cylinder distribution and heat losses and boiler efficiency losses, (viii) pumps and other consumption, and
- internal temperature data (sensors in open-plan kitchen and in both bedrooms).

The table below lists the location of the submetering monitors. Further details can be found in the BPE Phase 1 report, Appendix 3: Monitoring Guide.

Sub-metered use	**Location**
Total space heating	Heat flow meters in the utility room, duct heater and towel radiator
Hot water	Heat meter on hot water consumption
Lighting	Submeter on lighting circuits
Ventilation	Submeter on HRV under the stairs
Cooking	Hob and oven
Appliances	Sockets
Cylinder distribution and heat losses and boiler efficiency losses	Total gas meter usage compared to heat flow meter readings
Pumps and other consumption	In utility room with gas boiler and cylinder. Other consumption may include a water irrigation system outside the house.

The house also had a solar thermal panel. The output from this was not modelled, because at the time of modelling, the Home Energy Model solar thermal module was not able to output its hot water energy output to the results file. The solar thermal panel was not operating as intended for most of the case study period, so the data would also have been of limited value. Instead the solar thermal hot water heat contribution has been added to the total domestic hot water consumption. In the Home Energy Model, the combined gas and solar thermal hot water

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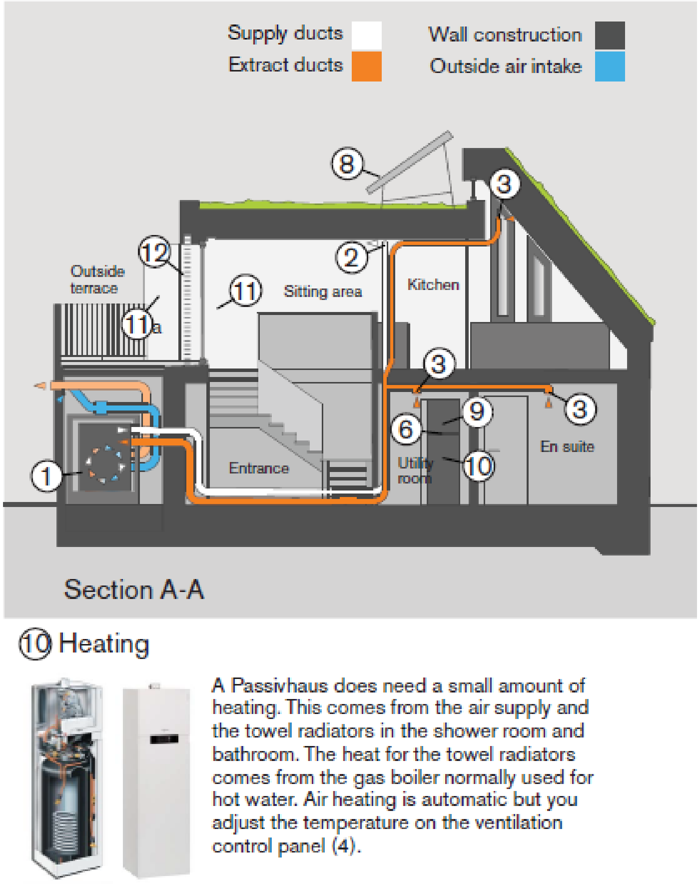
[3] Technology Strategy Board (2014). *Building Performance Evaluation. Final report: The Camden Passive House. Phase 2: In-use performance and post occupancy evaluation. BPE ref no: 450049.* Available at https://bere.co.uk/research/camden-passive-house-final-report/

consumption has therefore been modelled as gas powered hot water consumption. Comparisons were then made between the Home Energy Model hot water consumption and the combined measured gas and solar hot water consumption.

Post-occupancy data was available for a 24-month period from October 2011 to September 2013. The 12-month period from February 2012 to January 2013 was selected for analysis in this report. The dates were selected to avoid times when the heating system was reported to be not working as intended. For the charts in this report which display monthly data, the months are displayed from January to December, to help visualise the data as a year starting from January.

Figure 1: Camden Passivhaus – cross-section from the User Guide



A Passivhaus does need a small amount of heating. This comes from the air supply and the towel radiators in the shower room and bathroom. The heat for the towel radiators comes from the gas boiler normally used for hot water. Air heating is automatic but you adjust the temperature on the ventilation control panel (4).

The diagram in Figure 1 is from the Camden Passivhaus User Guide, as provided to the occupants[4]. The MVHR unit is outside the building in the cycle store. Ventilation air is supplied to the living room, and extract ventilation is taken from the kitchen and bathrooms. The ventilation control panel and thermostat are in the living room. The numbered items in the diagram are:

1. Heat recovery ventilation unit
2. Fresh air vents
3. Extract air vents
4. Heat recovery ventilation control panel (in living room, not shown on diagram)

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[4] Camden Passivhaus - User Guide, available at https://bere.co.uk/research/camden-passivhaus-user-guide/

5. Thermostat panel (in living room, not shown on diagram)
6. Solar tank and boiler control panel
7. Towel radiator control (on ground floor, not shown on diagram)
8. Solar thermal panel
9. Hot water tank
10. Boiler
11. External blinds control
12. Windows (with tilt-opening to allow secure night-time ventilation)

Heat is supplied from the gas boiler through a heating circuit with these heat emitters:

1. A convector heater which heats the ventilation supply air
2. Towel radiators in the bathrooms

Figure 2: Camden Passivhaus – view from front of the house

Figure 3: Camden Passivhaus – view of living room

The house has been designed with large south-facing windows, intended to maximise solar gain. Additional solar gains can also come from the south-facing clerestory roof window. External blinds have been installed to control solar gain in summer to prevent overheating. Internal blinds have also been installed, for use throughout the year to control unwanted glare and provide privacy. There is an open stairwell, which facilitates airflow between the living room and the ground floor. Images are from bere:architects[5].

Approach to modelling with the Home Energy Model

This section describes the approach to modelling with the Home Energy Model. It summarises:

- the information used in the various configurations of the Home Energy Model to represent the Camden Passivhaus as a building energy model.
- the approach to calibrating the Home Energy Model analysis in order to better represent the actual conditions for the house during the monitoring period. In the uncalibrated model, there are assumptions on variables related to weather, heating patterns and occupancy patterns which are established for Part L compliance assessment. In the calibrated models, these variables were modified to represent known actual conditions. The weather, occupancy, and space heating regime were independently calibrated for, and then the three separate calibrations were combined into a fully calibrated model.

The Camden Passivhaus building performance evaluation study was not undertaken with the intention to validate the Home Energy Model. Hence, reasonable estimates are included for the Home Energy Model inputs as necessary. A discussion of uncertainties around these estimates is given later in this paper.

The version of the Home Energy Model used for modelling was the development version 0.19, as released on 26 May 2023. While the HEM issued for consultation is a newer release, the changes have a very small impact on the results for space heating, which is the focus of this comparison.

Information used for the Home Energy Model simulations

Dimensional data from architectural drawings was used to describe opaque objects such as walls, roofs, floors and doors, and transparent objects such as windows.

Details of the performance of the building components were documented in the BPE case study reports. In most cases, the performance of the components was measured on-site.

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[5] Bere:architects (2011). *Latest Camden Passivhaus pictures.* Available at https://bere.co.uk/press/latest-camden-passivhaus-pictures/

Relatively few U-value measurements were documented, although design U-values were documented. The overall performance of the whole-house building fabric was measured onsite by a UCL team with a co-heating test[6], following the procedure defined by Leeds Metropolitan University (now Leeds Beckett University)[7]. This allows a confirmation of the overall combined effect of the U-values from all components, together with thermal bridging and the infiltration rate.

Some further details of the performance values used are provided below.

Future Homes Standard assessment wrapper

For use with the Future Homes Standard, various data items are pre-entered based on a typical UK home. These include hot water usage events, appliance usage events, lighting events, metabolic output events representing someone in the property, and other items that represent typical energy usage. This is termed as a “wrapper”, because it adds this information to the Home Energy Model. It is abbreviated to “FHS assessment wrapper” when mentioned elsewhere in this document. The Home Energy Model can use the actual values for all data items if the user knows the values applicable to the modelled home. For this calibration work, some of the FHS assessment wrapper values were retained if the equivalent data was not available in the measured data.

Building dimensions

High resolution architectural drawings were not available for this validation study. Due to the low resolution of the available drawings and some missing dimension data, relevant dimensions were calculated by counting pixels on a drawing length (for example a wall) and creating a scale ruler based on the number of pixels on a length which had a clearly illustrated dimension.

The total floor area calculated by this method was 118 m^2. The floor area definition used is the same as in the SAP 10 Specification, under ‘1 Dwelling Dimensions’. It is similar to Gross Internal Floor area, but the SAP 10 Specification gives further details about what should and should not be included.

This floor area is the same as the area documented in the Low Energy Database for the Camden Passivhaus (Low Energy Database, 2010)[8], providing confirmation that the floor area was correctly calculated:

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[6] Stamp, Samuel, (2013). *Co-heating test of Camden Passivhaus*. UCL Energy Institute. Available at https://bere.co.uk/research/camden-passivhaus-co-heating-test/

[7] Johnston, D., Miles-Shenton, D., Farmer, D. and Wingfield, J., 2013. *Whole house heat loss test method (Coheating).* Leeds Metropolitan University. Available at https://www.leedsbeckett.ac.uk/-/media/files/research/leeds-sustainability-institute/coheating-method-for-whole-house-heat-loss/lsi_cebe_coheating_test_method_june2013.pdf

[8] https://www.lowenergybuildings.org.uk/viewproject.php?id=207

> *"Camden Passivhaus in Ranulf Road, designed by bere:architects and completed in April 2010, is London's first Passivhaus. The project is a 118m^2 single family house split over two floors."*

Note this is a higher value than the PHPP Treated Floor Area calculation, which has a different definition, and is based on German building regulations. The BPE Phase 1 report says:

> *"It is a two-storey detached house of 101m^2 Treated Floor Area."*

The difference in the two types of floor area is due to the large area under the sloping roof, and the presence of an open stairwell. The Treated Floor Area calculation discounts floor areas in such situations.

The difference in dimensions also has an impact on the numerical values of energy use intensity (such as kWh/a·m^2) when comparing the Home Energy Model and PHPP figures. In the case of the Camden Passivhaus, there would be an apparent 18% difference. Caution therefore is needed to ensure that any comparisons between the Home Energy Model and other models are based on like-for-like data.

Thermal mass

Thermal mass is the default value assumed by the Home Energy Model, plus the thermal mass of the internal walls. The modelling of thermal mass follows the conventions defined in *Energy Performance of Buildings - Energy Needs for Heating and Cooling, Internal Temperatures and Sensible and Latent Heat Loads - Part 1: Calculation Procedures*, BS EN ISO 52016-1:2017.

- The Home Energy Model assumes a default value for the thermal capacity of furniture and air of 10,000 J/(m².K) (BS EN ISO 52016-1:2017, Table B.17)
- The areal heat capacity was calculated for the full depth of the construction elements. This was calculated from the thickness, density and specific heat capacity of each layer of the element.
- A "mass distribution class" was assigned to the construction element, according to whether the thermal mass was externally facing, inside the element itself, or internally facing. (These classes are defined in BS EN ISO 52016-1:2017)
- The thermal mass of internal walls and floors were included to better represent the actual thermal mass of the dwellings.

Thermal bridging

Thermal bridges were taken from *Appendix 2: Thermal Bridge Calculations*, Page 57 of the Phase 1 BPE report (Palmer, 2012). These thermal bridges follow the conventions in the Passive House Planning Package (PHPP) which uses external dimensions of the building. Window to wall installation thermal bridges were additionally based on the PHPP default value of 0.04 W/m^2·K. The window thermal bridges may be an over-estimate, since well installed windows installed according to Passivhaus principles should have a lower psi-value than this[9].

The Home Energy Model uses internal dimensions for building components. Where there are external corners in the walls, the external surface area of the walls is greater than the internal surface area of the walls. However, the heat loss area of the model is based on the internal surface area. This then creates a geometric thermal bridge at the corner, and a thermal bridge needs to be added to the Home Energy Model. When instead external dimensions are used, as in PHPP, the heat loss area of the model is the external surface area of the wall. However, this often over-estimates heat loss at the corner, and this in some cases results in a negative external thermal bridge value to compensate for the over-estimation. Further explanation of this can be found online at https://www.greenspec.co.uk/building-design/thermal-bridge-free-construction/.

Negative external thermal bridges listed in the BPE report are therefore not included, since the negative values were a result of using external dimensions and would not have occurred when using internal dimensions. Psi-values from the PHPP listing are used when they have a positive value but are ignored when they have a negative value. The Home Energy Model always uses internal dimensions, so in this model, the PHPP external dimension psi-values have been matched to the equivalent locations when using internal dimensions. The use of external dimensions may also cause some of the geometric thermal bridges in the Home Energy Model to have over-estimated values.

The table below lists the thermal bridge values used for the Home Energy Model

Thermal bridge description	length	psi-value
flat-roof window	7.05	0.043
back-beam sloping roof	7.05	0.021
intermed floor courtyard wall	4.71	0.044
16)gf corner vertical	3.15	0.06
18)gf corner vertical	2.84	0.032
20)gf corner vertical	2.84	0.056
21)id 18 gf corner vertical	2.84	0.032
25)lf corner vertical	2.84	0.075
28)lf corner vertical	2.84	0.055

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[9] This is explained in *PHPP Illustrated, A Designer's Companion to the Planning House Planning Package,* 7.2 'Window Thermal Bridging' (Lewis, 2022), RIBA Publishing

11.1 gf internal 120mm-slab	6.12	0.37
11.2 gf internal 80mm-slab	7.33	0.035
11.3 gf internal 120mm-slab	4.59	0.035
11.4 gf internal 80mm-slab	5.46	0.056
Window edge thermal bridges	31.64	0.04

The total contribution of these thermal bridges to the whole house static heat transfer co-efficient is 5.81 W/K. This is about 10% of the total heat transfer coefficient. The amount of error in the heat loss coefficient due to use of external dimension psi-values and default window psi-values is unknown. However, it is unlikely to differ by an order of magnitude. If, for example, it is assumed that Home Energy Model thermal bridges were over-estimated by two times, it would cause an error in the static heat transfer co-efficient of around 5%. This implies a potential additional uncertainty in space heating predictions of also around 5%.

Floor and basement wall U-values

The U-values for the floor and basement walls were measured by the University College London (UCL) team and documented in the BPE report[10]. The floor had a measured U-value of 0.099 W / m^2·K, and the basement walls had a measured U-value of 0.097 W / m^2·K.

The external perimeter and the U-value were together used to derive the other parameters needed for the ISO ground floor thermal transmittance calculations.

For the ground floor and basement walls, the thermal resistance and periodic heat transfer calculations were derived from the floor and basement wall U-values, and other variables including the external heat loss perimeter. These were calculated using the equations for a “Heated Basement” as in *ISO 13370:2017 Thermal performance of buildings - Heat transfer via the ground*.

U-value selection

There were several tables of U-values in the various reports about the Camden Passivhaus. The values were not consistent with each other, and none of the tables were complete individually. Measured values were not available in most cases. Therefore, the following rules were used to select U-values from the various sources.

1. Use measured U-values if available.
2. Use the Passive House Planning Package (PHPP) U-value for windows because it calculates U-value according to ISO 10077-1, *Thermal performance of windows, doors and shutters - Calculation of thermal transmittance - Part 1*, including the effects of

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[10] Palmer, Jason (2012) BPE report Phase 1, p30, Heat Flux Study.

dimensions of the glazing and frame. This is likely to be more accurate than the manufacturer’s default U-value.

3. Use the highest U-value listed from all the reports, to select the worst-case U-value.

	U-value used for the Home Energy Model (W/m^2·K)	**Source for U-value**	**Reason for selecting this U-value**
South windows	0.744	BPE report Phase 1. Appendix 2: Thermal Bridge Calculations. (Palmer, 2012)	Final calculated values as used in the PHPP listing, which adjusts for frame and glazing area.
West windows	0.85		
Exterior Wall - Ambient	0.116	BPE Dissemination. Table 2: Design targets. (Bunn 2012)	Highest value stated in reports
Exterior Wall - Ground	0.097	BPE report Phase 1, p30, Heat Flux Study. (Palmer, 2012)	Measured value
Roof/Ceiling - Ambient	0.11	Low Energy Database - Building construction (2010)	Highest value stated in reports
Sloping roof	0.116	BPE Dissemination. Table 2: Design targets. (Bunn 2012)	
Floor Slab	0.099	BPE report Phase 1, p30, Heat Flux Study. (Palmer, 2012)	Measured value
Doors	0.81	Low Energy Building Database - Building construction (2010)	Highest value stated in reports
Roof Terrace	0.139	BPE Dissemination. Table 2: Design targets. (Bunn 2012)	

Glazing g-value

The BPE report documented the window g-value as 0.5. This value was used for the uncalibrated, heating calibrated, and weather calibrated models.

For the occupancy calibrated and fully calibrated simulations, the additional effect of occupant blind usage on the effective g-value was estimated.

Window opening for cooling

The occupants rarely opened the windows, so the default area of window opening for cooling was reduced. The Phase 1 report, p41-2, stated that no windows were left open overnight. Instead, the occupants used a fan, and they did not mind the heat.

> *“During the night the occupant uses a fan. The architects suggested opening the window instead, but the occupant prefers not to because they do not feel safe with the bedroom on the ground floor, even though the windows are secured when tilted. The occupant once tried to leave small windows in the living room open but this resulted in overcooling according to the BUS. As a result the occupant does not use night purge ventilation as often as expected as she enjoys the warmer temperatures.”*

A minimal amount of window opening was assumed for hot weather if the temperature reached 26°C.

In the Home Energy Model, this was entered as an area of window opening of 0.1 m^2 when the temperature reached 26°C. In effect, this means the windows are hardly ever opened in the model.

Shading

All window reveals and overhangs were included. Where there were fences connected to windows, these were treated as additional side fins.

External shading obstructions were estimated from drawings and photographs of the site. Both distance and heights were estimates since there are no site measurements. The obstructions have 100% opacity in the Home Energy Model, so do not take into account any solar gain passing through trees when they lose their leaves. The following values were used:

Direction	Distance / m	Height / m
S	8	3.1 (fence)
SW	0	0
W	1	10 (fence and trees)
NW	1	10 (fence and trees)
N	8.2	5.1 (opposite house)
NE	8.2	5.1 (opposite house)
E	1	5
SE	1	5

Air permeability

Air permeability was taken from the air-tightness test as reported in the Phase 1 report, which was 0.44 ach at 50 Pa.

Static heat transfer coefficient

A cross-check was made of the dimensions and input values related to the building's thermal performance. This was done by comparing the Home Energy Model predicted static heat transfer co-efficient for the whole house to the measured co-heating test value. This is called "static" since it does not include the dynamic effects of solar gain. It is a measure of the heat transfer from inside the building to the outside, including the whole thermal envelope, through the building fabric and through infiltration. The calculated value is derived from:

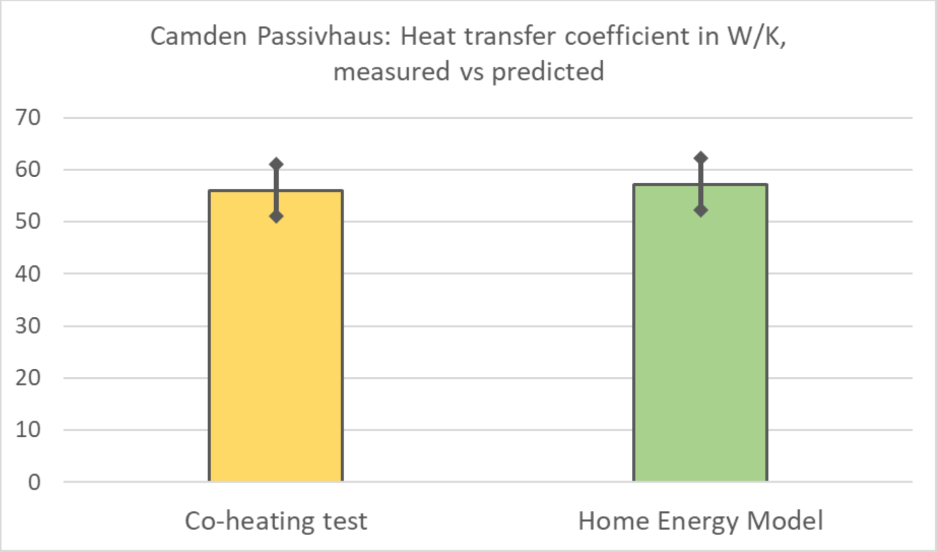
- Dimensions
- U-values
- Thermal bridges
- Air infiltration rate from the air-tightness test

For both a co-heating test and the Home Energy Model, the heat transfer coefficient only includes ventilation from unintended infiltration. The MVHR ventilation is therefore excluded.

The measured and predicted values are a close match, indicating that the dimensions, U-values, thermal bridges and air infiltration rate were close to actual values. The same dimensions and U-values were used for all calibrations. There was no attempt to calibrate the U-values or thermal bridges to the measured co-heating test value. In principle, it is possible that there are errors in these parameters but they cancel each other out resulting in a good fit with the measured heat transfer coefficient.

Therefore, the uncertainty around fabric heat transfer is low for all of the modelled scenarios. The uncertainty is about the same as the measurement error range for the co-heating test, which is +/- 10%.

Figure 4: Camden Passivhaus – heat transfer co-efficient, measured and calculated



Camden Passivhaus co-heating test	Home Energy Model static heat transfer co-efficient
56 W/K +/- 5 W/K	57 W/K

Hot water cylinder

A minimum stored hot water temperature of 60°C was assumed, based on the temperature requirement for legionnaires' disease prevention. The actual cylinder temperature was not available.

It is a factory insulated cylinder. A thickness of 120 mm estimated from Viessman brochure 'Heating with gas' p59.

The BPE final report stated the volume was 200 litres, while the UCL Energy and Buildings paper stated it was 250 litres (Ridley et al, 2013). The volume of the cylinder was then estimated at 220 litres, and this was used in the model. Loss rate for this insulation thickness was taken from the SAP 10 specification, which was 0.0094 kWh per litre per day. The total loss rate was estimated to be 2.068 kWh/day.

Subsequently, a Viessmann datasheet was found for a typical Viessman hot water cylinder, the Vitocell 300-W, which stated the insulation thickness was 68 mm and a standing heat loss was 0.4°C per hour. This would result in a heat loss rate of 2.45 kWh/day. The modelled loss rate may therefore be an under-estimate of the cylinder heat losses of about 0.4 kWh/day.

There is no primary pipework since the boiler and cylinder are an integrated unit.

Zone control for heating systems

Zone control for heating systems was based on two zones, for living and non-living areas. The heating setpoint for the living area was set to the average observed temperature while the heating system was in operation. The heating setpoint for the non-living area was set to average observed temperatures in this zone during the winter. (See section on heating calibration for more explanation).

Ventilation and MVHR

A required air change rate of 0.43 ach was calculated based on Part F ventilation requirements based on the house floor area and number of bedrooms.

The MVHR unit was a Paul Thermos 200 MVHR, as described in the BPE Phase 1 report. This unit is not available in the PCDB (Product Characteristics Database). The manufacturer's efficiency values were not used, since the measured values were available in the BPE reports and are likely to be more accurate.

The measured value for MVHR Specific Fan Power was 1.15 watts per litre per second. The measured value for MVHR Heat Recovery Efficiency was 0.82.

MVHR ductwork lengths were estimated from drawings, since lengths were not stated.

MVHR ductwork diameter and insulation values were not available. Values were instead taken from the Building for 2050 calibration study for the Home Energy Model, which were assumed to be similar to the Camden Passivhaus. The houses in Building for 2050 used similar MVHR systems to the Camden Passivhaus. Also, from photographs, the ductwork and insulation in the Camden Passivhaus look similar to the ductwork and insulation used in Building for 2050.

Hot water pipework

The length of hot water distribution pipework was estimated at 6 m, based on the distance of the boiler to the bathroom. For the insulation, a reasonable assumption was made based on a similar case study for Building for 2050. The insulation thermal conductivity was assumed to be 0.021 W / m·K, and the insulation thickness 17 mm.

Baths and Showers

The Camden Passivhaus does not have a bath. The input configuration was modified to ensure the FHS assessment wrapper did not generate bath hot water events, and would generate shower hot water events only.

Solar thermal

An attempt was made to model solar thermal hot water. However, the version of the Home Energy Model available when commencing the modelling did not output its hot water usage, so modelling of solar thermal was not continued. Furthermore, the solar thermal system was not operating correctly during the measurement period which would make meaningful comparison to models challenging. Instead, any output from solar thermal contributing to hot water output was added to the total hot water output for the house. The model then models the hot water output as gas heated output only.

Heat emitters

The Camden Passivhaus uses air convector heaters which were heated by wet heating distribution from the gas boiler. This type of heat emitter has not previously been defined for use with the Home Energy Model, and there a constant, c, which needed to be determined for use in the Home Energy Model. Also, no tests were available to obtain the value of c.

The relevant ASHRAE equation is for ‘Corrections for Nonstandard Conditions’ (ASHRAE, 2020).

$$q = c(t_s - t_a)^n$$

where

q = heating capacity, W

c = constant determined by test

t_s = average temperature of heating medium,

t_a = room air temperature

n = exponent that varies with heat emitter type, e.g. 1.2 for cast-iron radiators, 1.42 for convectors

The ASHRAE equation was re-arranged to calculate c as follows:

$$c = \frac{q}{(t_s - t_a)^n}$$

The inputs for the above were taken from the information available in the table below:

Parameter	**Value**
q, Design Heat Loss (derived from the whole house heat transfer co-efficient and a temperature difference to outside of 24.2°C, following the BRE DAPHSE conventions.)	1.3552 kW
Flow temperature (as recommended by Viessman)	60°C
Return temperature (The return temperature is assumed to be 6/7 of the design flow temperature, in °C.)	51.4°C
t_s (the mean emitter temperature under design conditions, which is the average of the flow and return temperatures under design conditions.)	55.7°C
t_a (ground floor air temperature, assuming the heated air supply outlets were on the ground floor)	20.5°C
n (standard value for convector heater)	1.42
c (the calculated value)	0.0086

Therefore, the value for *c* was 0.0086, and the value of *n* was 1.42, for a convector heater.

Calibration

The FHS assessment wrapper calculations adopt a standard occupancy and usage pattern derived from household surveys (e.g. plug loads, DHW usage). In practice, occupancy and usage patterns vary substantially between dwellings of similar size and type. Furthermore, for the purposes of current Part L 2021 compliance assessment, UK average weather data is used which can significantly differ to local conditions.

The purpose of this analysis was to validate space heating predictions from the Home Energy Model, along with the modules that support these predictions. Hence, the Home Energy Model modelling was calibrated to be more reflective of the actual case study conditions during the monitoring period, with the actual boundary conditions found onsite. Five runs were undertaken for each plot with different levels of calibration as detailed below.

Run 1: Uncalibrated model

This adopted the standard assumptions and the UK average weather data as would be used for Part L compliance assessment. For the Home Energy Model, this is the Leeds CIBSE Test Reference Year weather file.

Run 2: Weather calibration

Weather data onsite at the Camden Passivhaus was measured at 5-minute intervals, and included dry bulb temperature, wind speed and global solar radiation (Ridley, 2013). However, the only published monitored weather data from the BPE case study were the monthly averages.

A search was made to identify a weather station close to Camden which recorded hourly weather data, since the Home Energy Model requires hourly weather data. The Met Office provided the data used for this validation. There was no single weather station which had all the data required. Three different weather stations were used to reconstruct the required data as follows:

- Dry bulb temperatures and wind speeds – Northolt weather station
- Global horizontal radiation – Heathrow weather station (no split of direct/diffuse)
- Ratio of direct horizontal radiation to diffuse radiation – Cardington weather station
    - Used for splitting Heathrow global horizontal radiation
- Calibrated weather values were cross-checked with measured onsite monthly average values
- February and March hourly temperatures further adjusted to match Camden Passivhaus onsite measured monthly values

The table below contains the calibrated weather values used, averaged for each month. Where available, these averages have been compared to the monthly average values taken onsite.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Camden onsite external temperature (°C)	4.3	4.5	9.8	8.1	13.1	14.5	16.4	18	14.2	10.3	7.5	5.6
Calibrated external temperature (°C)	4.2	4.6	9.8	8.2	13.3	14.7	16.6	17.9	14.1	10.6	7.1	5.4
Camden onsite global horizontal radiation (W/m2)	n/a	68	183	152	194	180	n/a	n/a	n/a	n/a	n/a	n/a
Calibrated global horizontal radiation (W/m2)	26	68	183	150	187	180	194	184	148	70	40	24
Camden onsite wind speeds were not available												
Calibrated wind speeds (m/s)	4.0	3.6	3.1	4.3	4.1	4.9	3.6	3.6	6.4	3.9	3.4	4.2

Run 3: Space heating regime calibration

Figure 5 and Figure 6 show the measured temperatures in the living room and the bedroom (on the ground floor) respectively, taken from the UCL paper (Ridley, 2013). The measured temperatures show that the living area was on average one degree warmer than the bedroom area.

Measured temperatures were on average:

- 21.5°C living area
- 20.5°C bedroom area

However, this includes the times when heating is switched off, so it could result in underestimated space heating demand if these average temperatures are used as basis for the heating setpoint. The graphs were taken from ‘The monitored performance of the first new London dwelling certified to the Passive House standard’, *Energy and Buildings* (Ridley et al, 2013).

Figure 5: Average hourly profile of Living Room winter temperature (top floor)

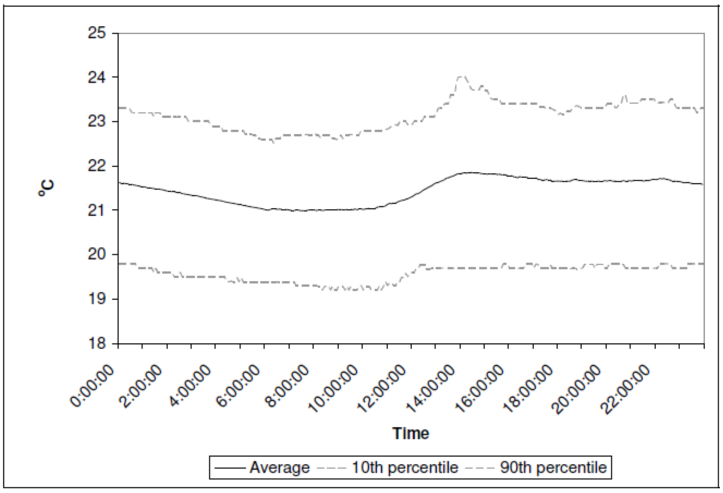


Figure 6: Average hourly profile of Master Bedroom winter temperature (ground floor)

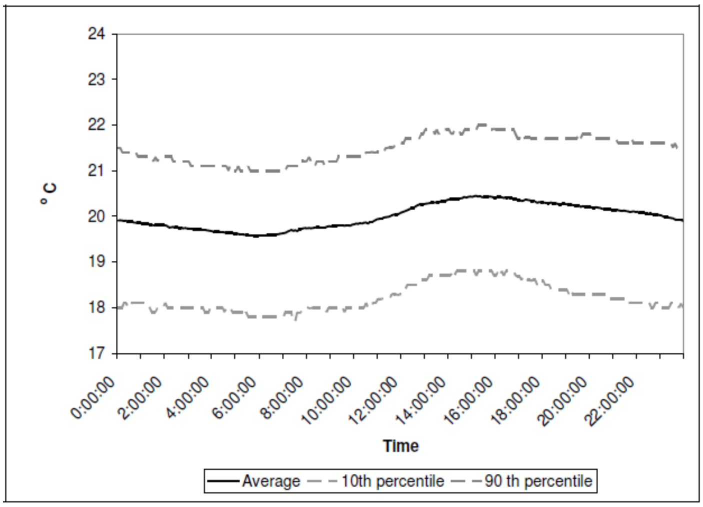
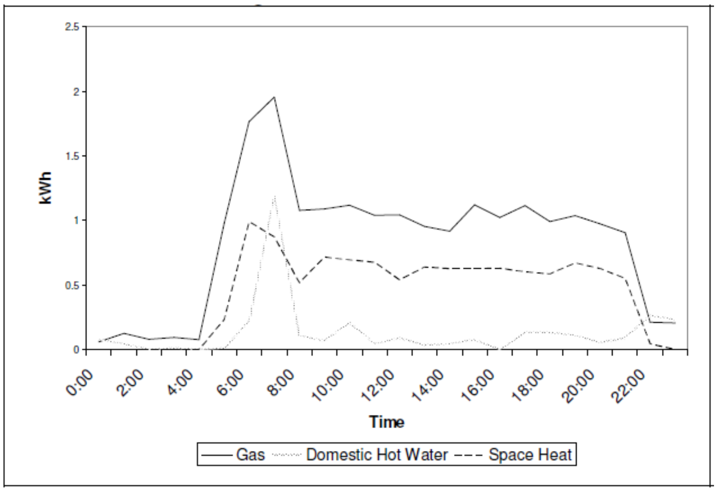


Figure 7: Hourly profiles of Gas, Domestic hot water and Space Heating Consumption



The heating was set to start at 6am and run continuously until 9pm. This can be seen in Figure 7 above, which is another graph from the UCL paper. These timings were used in the Home Energy Model.

> *"There is a clear peak in DHW consumption between 6 am and 8am associated with morning showering. Space heating is controlled by a timed programmer and takes place between 6am and 9pm in the evening. The peak in gas consumption at 5 am in the morning is associated with heating the hot water cylinder ready for morning demand."* (Ridley *et al*, 2013, p12)

The heating setpoint is not stated. An initial heating calibration of the model took 21.5°C as the heating setpoint for the living room, and 20.5°C in the bedroom, based on Figures 5 and 6. When these temperatures were used for the heating calibration, and then combined into the fully calibrated model, it resulted in an under-prediction of the space heating demand.

Further investigation was then undertaken to find further details on possible heating setpoints used. Figure 8 shows the hours when the heating system was operating, and the temperature of the living room in these hours. The average temperature in Figure 8 appears higher than in Figure 5, showing average living room temperatures in the winter (for the operating hours 6am to 9pm). However, Figure 8 may be more representative of the heating setpoint used.

A visual estimate was made of the average temperature in Figure 8. It appears to be midway between 22°C and 23°C, with slightly more hours above 23°C than below 22°C. The calibration heating point was then increased, based on:

- Average of 22°C and 23°C, plus 0.1°C = 22.6°C[11]

The BPE Phase 1 report stated the location of the thermostat was in the dining area:

> *"Room temperature control is by the ventilation control unit, which is located in the dining area and includes a room temperature sensor and user thermostat."*

The main supply of heat to the house was through heating the ventilation supply air to the living room. There was a supplementary source of heat from towel radiators in the ground floor shower room.

The ground floor was designed to be mainly heated by the supply air coming from the living room. However, the bedroom temperature was on average 1°C lower than the living room, despite receiving a supply of warm air from the living room. A possible explanation for this temperature difference is due to the buoyancy of warm air. The living room is on the top floor, and the house has an open stairwell, resulting in warm air easily rising to the top of the house. The supply air may also have lost some thermal energy as it reached the ground floor. There could have been a difference in solar gain, with relatively more solar gain in the living room. The ground floor has basement walls, which may contribute to cooler temperatures. These factors could then result in thermal stratification in the house, with warmer temperatures in the upper part of the house (the living/kitchen area). There are also towel radiators in the ground

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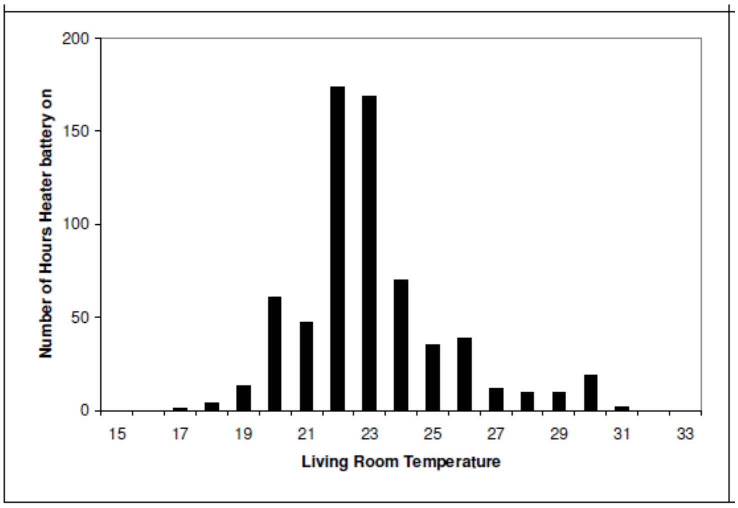
[11] Another interpretation of the graph is that the heating setpoint is at or close to the mode (the most frequently occurring temperature). This would imply that the heating setpoint is between 22°C and 23°C, which is similar to that chosen here.

floor bathrooms. These were intended only for occasional boost use, so may have only provided a small contribution to heating the ground floor.

There is no similar graph for the bedroom area, so the average bedroom temperature of 20.5°C was used at the setpoint for the bedroom. In the fully calibrated model, a good match with predicted and measured bedroom temperatures was found when using 20.5°C as the non-living area heating setpoint. The setpoint temperature for the bedroom therefore has been kept at 20.5°C.

Figure 8: Distribution of hours the heating system operated as a function of living room temperature



Heating setpoint calibration:

- 22.6°C living area
- 20.5°C bedroom area

Note that Figure 8 could be interpreted as having a wide variation of heating setpoints in actual use, and the heating system was operating in temperatures ranging from 19°C to 30°C. It is unclear whether the heating setpoints were varied over time. The lower temperatures may occur while the home is warming up. The higher temperatures may be due to the heating system not turning off as soon as a higher temperature is reached. There is also the possibility of temperature sensor measurement error.

The UCL paper (Ridley *et al*, 2013) also mentions:

> *"The heating system is observed to be sometimes on even during periods of high indoor temperature. The thermostat would appear to be set at a high value. The heating operates for 200 hours when the living room temperature is already above 24°C."*

There are some temperatures when it appears that the heating was on, and the temperature sensor recorded 27 to 30°C. A use of very high setpoints is a potential explanation, but it is unlikely people would use such high heating set-points. A plausible explanation could include solar gains to the temperature sensor, and the thermostat was located elsewhere not in the sun.

Run 4: Occupancy calibration

Space heating demand and internal temperatures are influenced by internal gains and solar gains, which in turn are influenced by occupant behaviour. Gains were calibrated to match occupant energy consumption and occupant interaction with blinds and window opening during the monitoring period.

Occupants directly influence the energy use in a building by:

- Metabolic gains
- Cooking energy usage and associated internal heat gains
- White goods and appliance energy usage and associated internal heat gains
- Use of domestic hot water and associated internal heat gains
- Lighting energy use which varies according to their preferences
- Use of blinds which may reduce solar gain

In addition to their direct impact on total energy use, the impact of these energy uses is to change the overall internal heat gains, which then alters the space heating demand.

For the purpose of this validation exercise, to assess the space heating demand predictions in the Home Energy Model, the model has been calibrated to adopt the actual internal heat gains from these factors listed above. It would not be possible to validate the space heating predictions otherwise, since random variations in occupant behaviour would cause random internal heat gains, and thereby make space heating usage unpredictable.

Details of the approach to calibration are detailed below.

Shading

Occupants used blinds much of the time, thereby significantly reducing solar gain. A shading factor was applied to allow for blind usage. Currently, the Home Energy Model does not have an input field for a shading factor. Instead, the g-value of the windows was adjusted, with a separate calculation of the shaded g-value done in a spreadsheet. The formula used was:

$$\textit{Shaded g-value} = \textit{shading factor} \times \textit{glazing g-value}$$

The shading factor represents the reduction in solar gains as a result of occupant blind usage.

Windows that were known not to have blinds did not have adjusted g-values, assuming that shading was not possible for these windows. These windows were the kitchen west-facing windows and the roof clerestory window. They had relatively small areas, so would have had a relatively minor influence on solar gain.

The shaded g-value was used only in the occupancy and fully calibrated models.

The BPE report noted that there was extensive use of blinds in the wintertime to maintain privacy. This will therefore reduce solar gains and increase space heating demand. Few details were given, apart from indications in the following quotes:

> *“replaced by a hedge of Cotoneaster. Until this provides a full screen, the ground floor blinds will remain closed day and night for privacy.”*[12]
>
> *“The occupants of the Passive House say south-facing blinds to the living spaces (that are all street-facing) are kept closed during the day in order to maintain privacy – they are kept closed during the winter months more than expected at the design stage.”*[13]
>
> *“Conversations and interviews with the occupants revealed that they put a high priority on privacy. Most of their windows face the street and they have a tendency to keep the blinds fully closed during the daytime, resulting in increased lighting consumption.”*[14]

The following variables were not recorded in the Building Performance Evaluation:

- Percentage of window shading due to the use of internal blinds
- Percentage of window shading due to the use of external blinds
- Percentage of window solar gain that was reduced by the blinds while they were in use (since some solar gain can still pass through closed blinds)

The living room windows were partially shaded by a one-metre high railing. Also, the glazed front door was heavily shaded by a fence positioned in front of it. Currently, in the Home Energy Model, it is not possible to represent shading objects placed in front of an individual window.

The descriptive information on blind usage suggests that blinds were in use most of time. To determine the in-use shading factor, different shading factors were applied to the fully calibrated model, so that space heating demand predictions and temperature predictions in the Home Energy Model matched with the measured data. Two options were trialled:

- 50% shading factor (excluding windows without installed blinds)
- 80% shading factor (excluding windows without installed blinds)

The 80% shading factor resulted in the better match of space heating demand and internal temperatures to the measured data than the run using a 50% shading factor. With the 80% shading factor, the winter living room temperature was about 1°C higher than measured, and the space heating prediction was close to measured. At this point, it was considered sufficiently well-matched. Further fine-tuning could be done later if needed. Therefore, a shading factor of 80% was applied to both the occupancy calibration and the full calibration cases.

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[12] Page 8 of the BPE Phase 2 report

[13] Page 52 of the BPE Phase 2 report

[14] Page 52 of the BPE Phase 2 report

Metabolic gains

Metabolic gains were adjusted to the FHS profile for 2 occupants. The uncalibrated run was modified to have 2 occupants, and the predicted metabolic gains for 2 people were extracted and entered into the occupancy calibration input file.

Cooking energy usage

The actual sub-metered cooking energy use was entered into the Home Energy Model simulation. The Home Energy Model engine then calculates the internal heat gains from the actual cooking usage with the cooking usage algorithm. The adjustment was done on a monthly basis.

Lighting energy usage

The lighting efficacy used in FHS assessment wrapper is 100 lm/W. This represents LED lightbulbs, which may have higher efficacy than available in 2012 with the case study. However, the lighting installed in the Camden Passivhaus was the most efficient available at the time, including LED and fluorescent lighting. Therefore, the impact of variations in lighting efficacy on the lighting energy predictions from the FHS assessment wrapper is expected to be minor.

The "Low Energy Database" entry for the Camden Passivhaus has the following comment about use of lighting: *"Low energy LED and fluorescent lighting throughout the building."*

More artificial lighting was used in the house than expected, since the occupants often kept the blinds closed during the day for privacy reasons. This resulted in higher lighting energy use than would be expected, even when using low-energy lightbulbs. This difference can be seen in Figure 9. The uncalibrated Home Energy Model estimated 138 kWh annual lighting electricity consumption, but the measured annual lighting consumption was 500 kWh, over three times more. From the BPE Final Report:

> *"Throughout the Phase 2 study, energy consumption for lighting was higher than PHPP design predictions. The design team noted that in spite of large glazed areas and good natural lighting potential, artificial lighting was often used during the hours of daylight.*
>
> *Conversations and interviews with the occupants revealed that they put a high priority on privacy. Most of their windows face the street and they have a tendency to keep the blinds fully closed during the daytime, resulting in increased lighting consumption."*

Appliance energy usage and internal heat gains

The actual sub-metered appliance energy use was entered into the Home Energy Model input file. Appliances include all white goods except for cooking appliances. The Home Energy Model engine then adds the associated appliance gains to the internal heat gains. The adjustment was done on a monthly basis.

While setting up the configuration of the input file for the Camden Passivhaus, it was noticed that the gains factor for appliance energy use was set at 100%. This appeared incorrect, since appliances such as dishwashers, washing machines and dryers have waste heat which is either lost in wastewater or vented waste air. Other appliance types in the house are more likely to convert 100% of their energy to internal gains. An educated estimate of 75% gains factor was chosen and applied to the Camden Passivhaus model. (The current version of the Home Energy Model FHS assessment wrapper now uses an appliance gains factor of 70%.)

Use of domestic hot water

The energy use for domestic hot water was adjusted so that it was close to the estimated energy used in heating the water. The Home Energy Model input does not have a simple adjustment factor for hot water energy consumption, since hot water consumption is based on a series of hot water usage events. Therefore, to achieve the required calibration, the temperature of the hot water for each hot water event was decreased or increased, in proportion to the percentage difference in hot water energy use for each month; this percentage difference is the difference between the predicted DHW energy usage in the Part L assumptions and the actual DHW energy usage. The cold-water feed temperature was assumed to be 13°C, which is the average over the year. The average cold-water temperature was used to simplify the calculation needed to calibrate the DHW energy usage. Note that this adjustment technique may not result in an exact match of hot water energy usage, although it will be much closer than without the adjustment. The accuracy of losses and gains from pipework may be reduced slightly.

The Home Energy Model engine then calculates the internal heat gains from hot water usage in its pipework and cylinder heat loss algorithms.

Run 5: Full calibration

All of the adjustments included in Runs 2 to 4 were combined. This is the main set of the Home Energy Model results which is able to get closest to the Camden Passivhaus measured data.

The following aspects of the Home Energy Model listed below can be directly validated against measured data in this validation exercise, after the models have been fully calibrated:

- Internal temperature predictions
- Space heating energy usage
- MVHR ventilation energy usage

Most other aspects of the Home Energy Model cannot be validated in this calibration study in terms of accuracy. This is due to uncertainties in the input data available for the calibration, as it is only possible to use what was published in the BPE reports. However, for these other aspects, it can be judged whether the data values are plausible, and are not out of the range of likely values.

Comments on the calibration

The case study plots can help validate both the space heating and ventilation demand predictions in the Home Energy Model. The domestic hot water, lighting and appliances (including cooking) energy demands were modified in the Home Energy Model to align with the actual energy use. There is insufficient case study data to separately validate these latter energy uses.

The energy usage for lighting, appliances, cooking and DHW in the Home Energy Model is based on a one-to-one mapping of their energy usage from the FHS assessment wrapper standardised profile. The calibrated model therefore cannot indicate how lighting and appliance parameters might influence energy usage, such as light efficacy, required illumination levels or appliance energy efficiency. There is however some potential for indirect validation of the gains factor for conversion of lighting and appliance energy usage to internal heat gains.

The Home Energy Model does have some input parameters for lighting efficacy, lighting levels and hot water events. There were no measurements of these in the case study, so it is not possible to validate the Home Energy Model for its energy use predictions based on these parameters.

Appliance energy use is an input parameter to the Home Energy Model which is identical to the output parameter on appliance energy usage. This is used only for input of internal heat gains to the calibrated mode, and for the calculation of total energy usage.

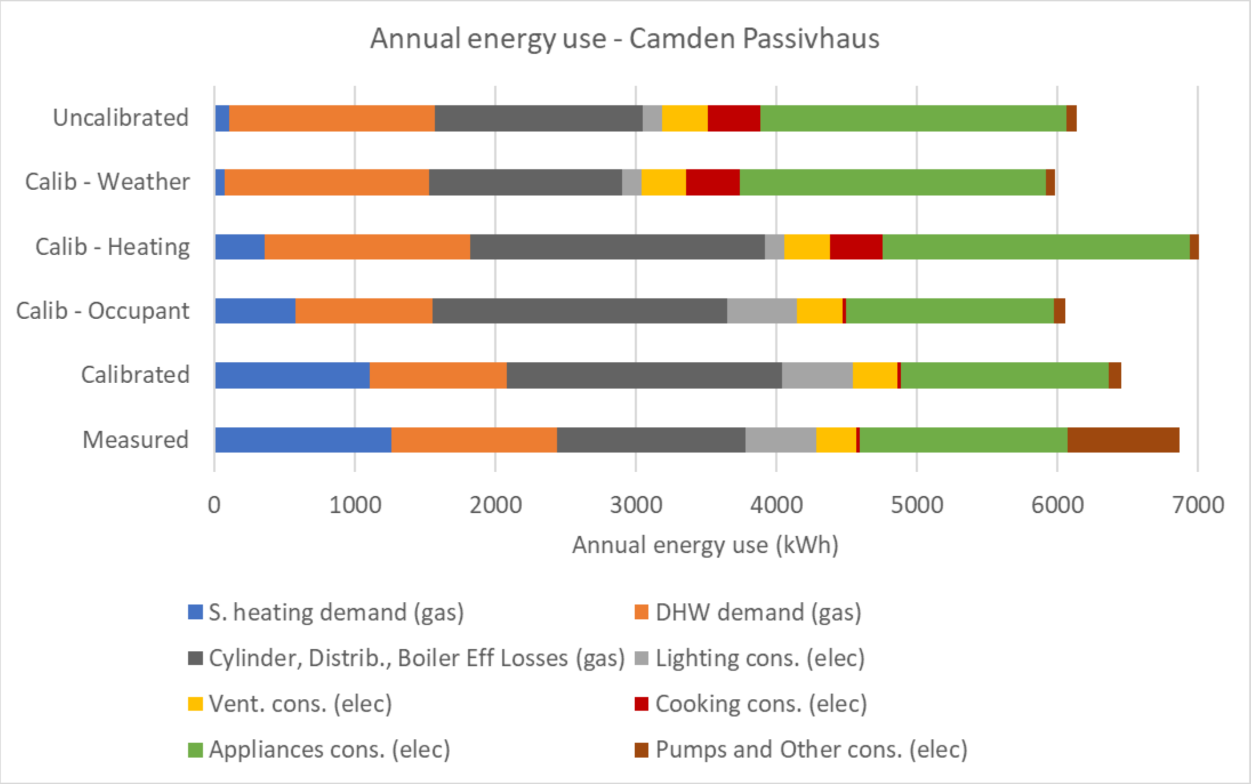
Results

Annual energy use

Figure 9 compares the annual energy consumption for the Camden Passivhaus. It shows all five of the Home Energy Model results (labelled Uncalibrated, Calib – Weather, Calib – Heating, Calib – Occupancy, Calibrated) and the measured data. The results are separated into the energy end uses. The values in the graphs show how each of the calibrated predictions of energy consumption match to the Camden Passivhaus measured results.

This figure shows the progressive impacts of the Home Energy Model calibrations. As discussed previously, the intention is that the Home Energy Model fully calibrated case matches actual energy consumption for domestic hot water, lighting and appliance (noting that the approach does not achieve an exact match for domestic hot water, as discussed in the Occupancy Calibration section).

Figure 9: Annual energy consumption Camden Passivhaus



The Cylinder, Distribution and Boiler Efficiency losses increased in the heating calibration case, and then reduced slightly in the full calibration case. These three types of losses were not separately sub-metered, so it is not known which is the main contributor to the difference between measured and predicted. There were also some uncertainties around the input data needed to calculate all three types of losses. This uncertainty could therefore lead to the difference shown on the graph.

The Pumps and Other had a much higher measured value then the predicted. It is not a like-for-like comparison however, since the solar thermal system was not modelled. The measured value also appears unusually high, which may be related to problems in the operation of the solar thermal and heating systems, as mentioned in the BPE report. Some uses external to the house may have been included, such as a garden irrigation system, also mentioned in the BPE report.

Figure 10 compares the results for Part L regulated energy use only. The difference between the fully calibrated results and the measured consumption is -8%.

Figure 10: Annual regulated energy consumption - Camden Passivhaus

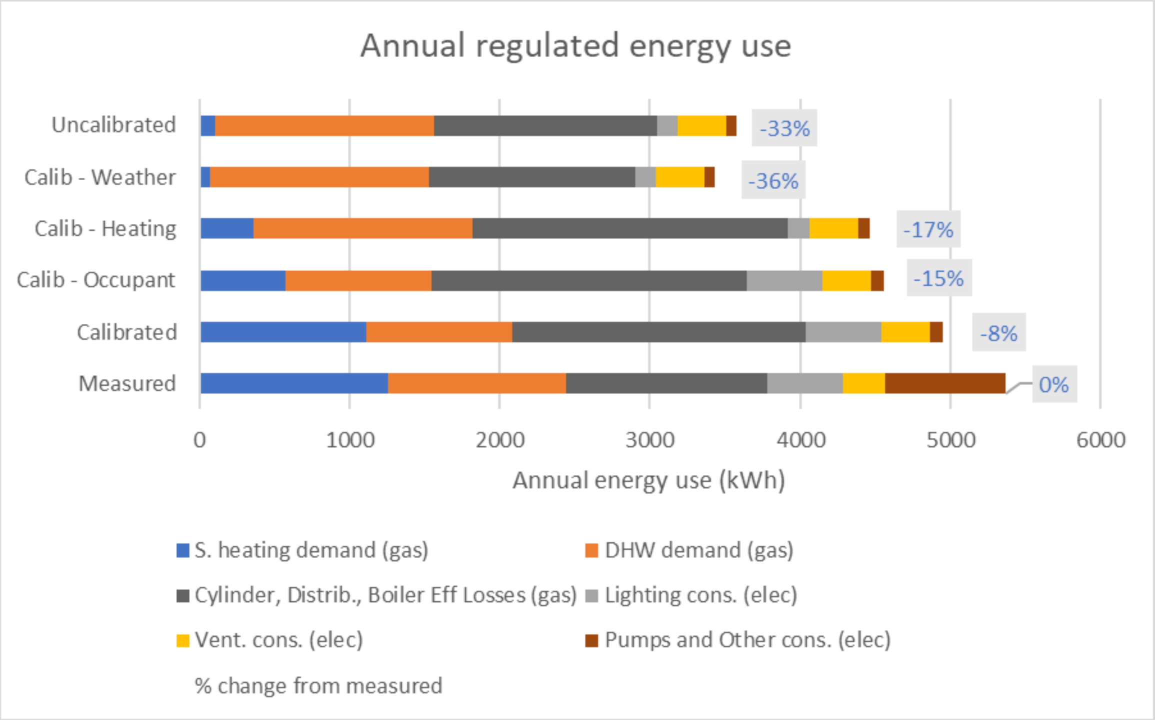


Figure 11 compares the results for annual space heating demand. As noted earlier, the fully calibrated Home Energy Model can be directly validated against measured data for space heating consumption. The difference between the fully calibrated results and the measured consumption is -7%.

With weather calibration, space heating demand reduced, due to the slightly warmer weather in London compared to the Leeds CIBSE weather. With heating calibration, space heating demand increased. This was due to raising the heating setpoints and extending the heating hours. The table below shows the difference in heating profiles between the uncalibrated and the heating and fully calibrated runs.

	Uncalibrated, Weather Calibrated and Occupancy Calibrated	**Heating Calibrated and Fully Calibrated**
Weekday heating period	07:30 - 09:30 and then 16:30 - 22:00	06:00 - 21:00
Weekend heating period	08:30 - 22:00	06:00 - 21:00
Living/Kitchen setpoint (°C)	21.0	22.6
Ground floor setpoint (°C)	18.0	20.5

With occupancy calibration, space heating demand also increased. This was due to the combined effects of additional shading from blinds reducing solar gains, and reductions in the internal gains by using sub-metered data. The fully calibrated model combined all the calibrations, which increased the space heating demand close to the measured value. When looking at the monthly space heating consumption in Figure 13, the alignment on a monthly basis is less close. On a monthly basis, uncertainties and error ranges in the modelling have cancelled themselves out to show a good alignment at an annual level. It is possible that there were variations in how occupants use space heating during the year which were not captured in the modelling.

Figure 11: Annual space heating demand - Camden Passivhaus

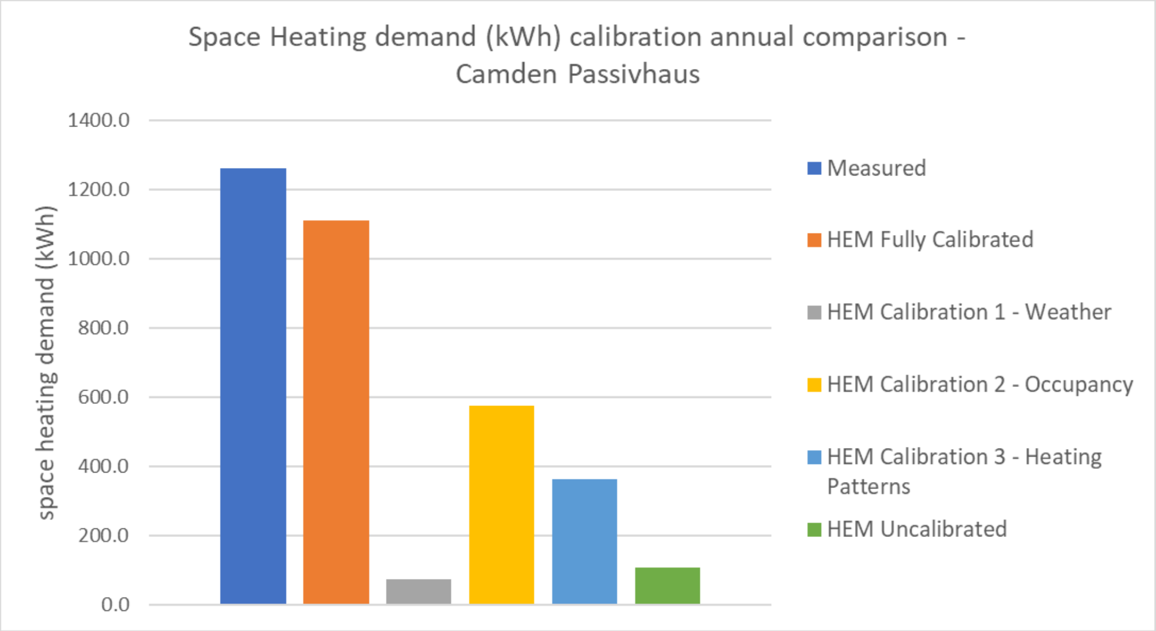
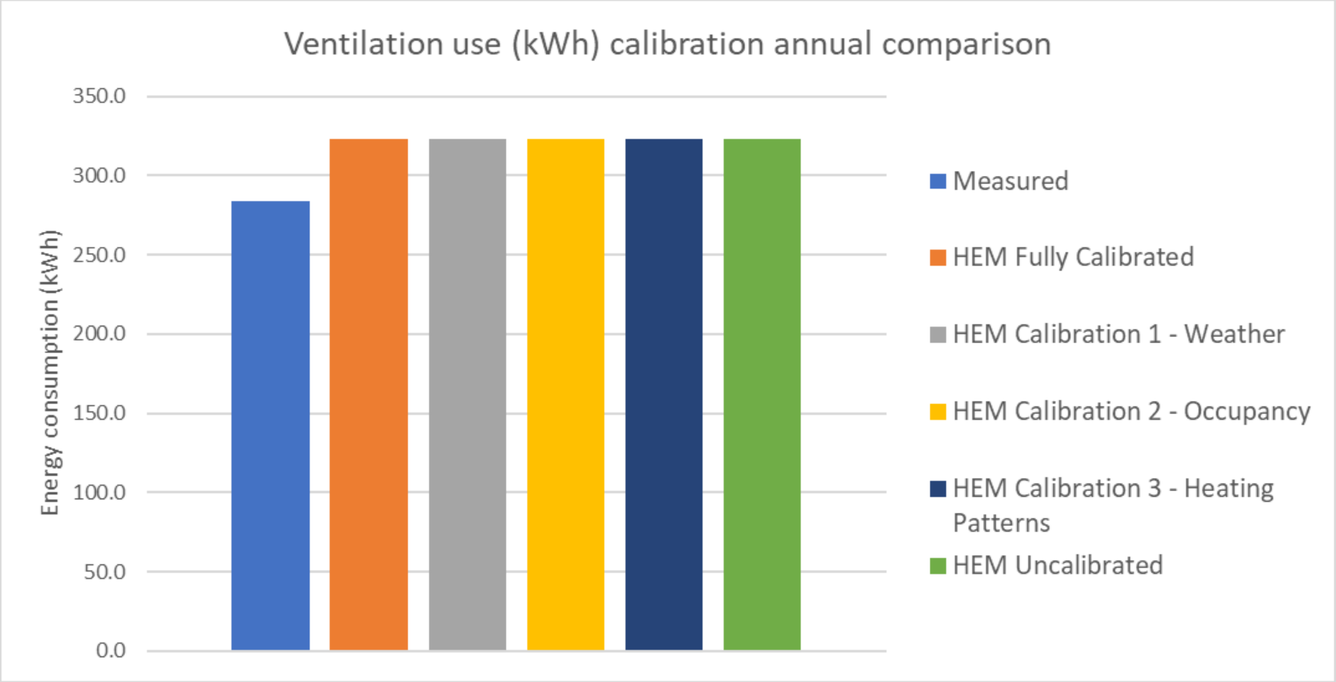


Figure 12 compares the results for annual ventilation energy consumption. As noted earlier, the fully calibrated Home Energy Model can be directly validated against measured data for MVHR consumption. All of the ventilation energy use is due to MVHR, since this is the only installed ventilation system. The difference between the fully calibrated results and the measured consumption is 8%.

The input data for ventilation used the measured specific fan power for all simulations, giving fairly close energy consumption figures between predicted and measured. The pressure loss through the ductwork is unknown, and this is not currently modelled in the Home Energy Model.

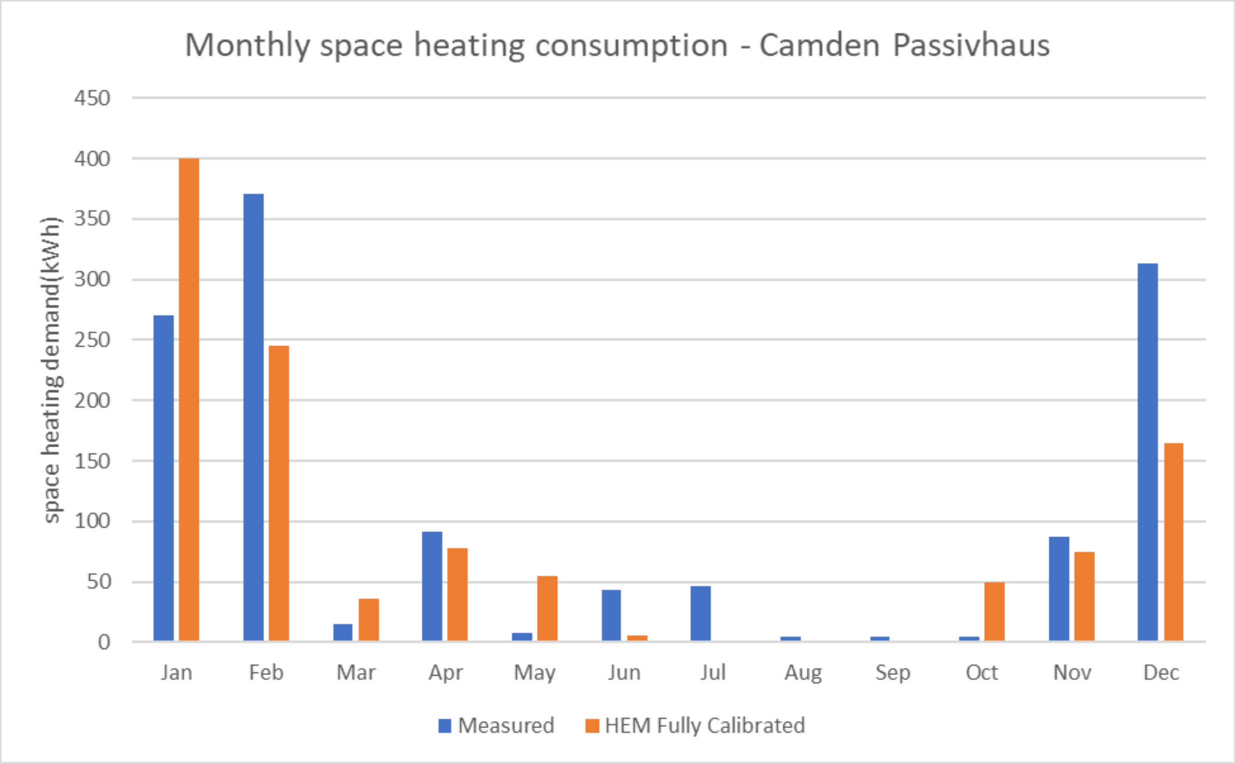
Figure 12: Annual ventilation energy consumption - Camden Passivhaus



Monthly space heating energy consumption

Figure 13 compares the fully calibrated Home Energy Model results to the measured data for the Camden Passivhaus.

Figure 13 Monthly space heating energy consumption - Camden Passivhaus



The Camden Passivhaus has very low space heating energy consumption, and is about 10% of what is typical for a UK house. As a result, small changes to solar gains and internal gains will be a much higher percentage of the space heating consumption. There are still some uncertainties about solar and internal gains, and these uncertainties can affect the predictions of space heating energy consumption. The simulations assumed a constant shading factor for the windows, but the use of blinds may have varied from month to month, thus causing unknown monthly variations in solar gain. The model assumed no window opening in the winter months, but any additional window opening could increase heating demand, and the window opening pattern may have varied in different months.

February and December have a higher space heating energy consumption than predicted, while January has lower space heating energy consumption than predicted. These variations may be due to the uncertainties discussed elsewhere around:

- Blind usage
- Window opening
- Pipework and cylinder losses
- Metabolic gains

There is some heating usage during the summer months. This is unlikely to be due to a need for heating, and instead may be due to unknown factors, such as the thermostat being set accidentally at a high temperature, or perhaps the occupants were drying towels on their towel radiators. The Home Energy Model is probably correct to predict that there should be almost no space heating energy consumption in the summer.

Internal temperature data

Figure 14 and Figure 15 compare the fully calibrated Home Energy Model results and the measured data the Camden Passivhaus for monthly internal temperature. The figures are for the living and non-living areas respectively. As noted earlier, the fully calibrated Home Energy Model can be directly validated against measured data for internal temperatures.

In Figure 14, there is general agreement between predicted and measured temperatures. The January to May and August to September predicted temperatures are about one degree higher than measured. From October to November, the predicted temperatures are two to three degrees higher than the measured temperatures.

In Figure 15, the predicted temperatures closely match the measured temperatures from January to July. From August to November, the predicted temperatures are about one degree higher than the measured temperatures.

Figure 14 Monthly average internal temperature – living area

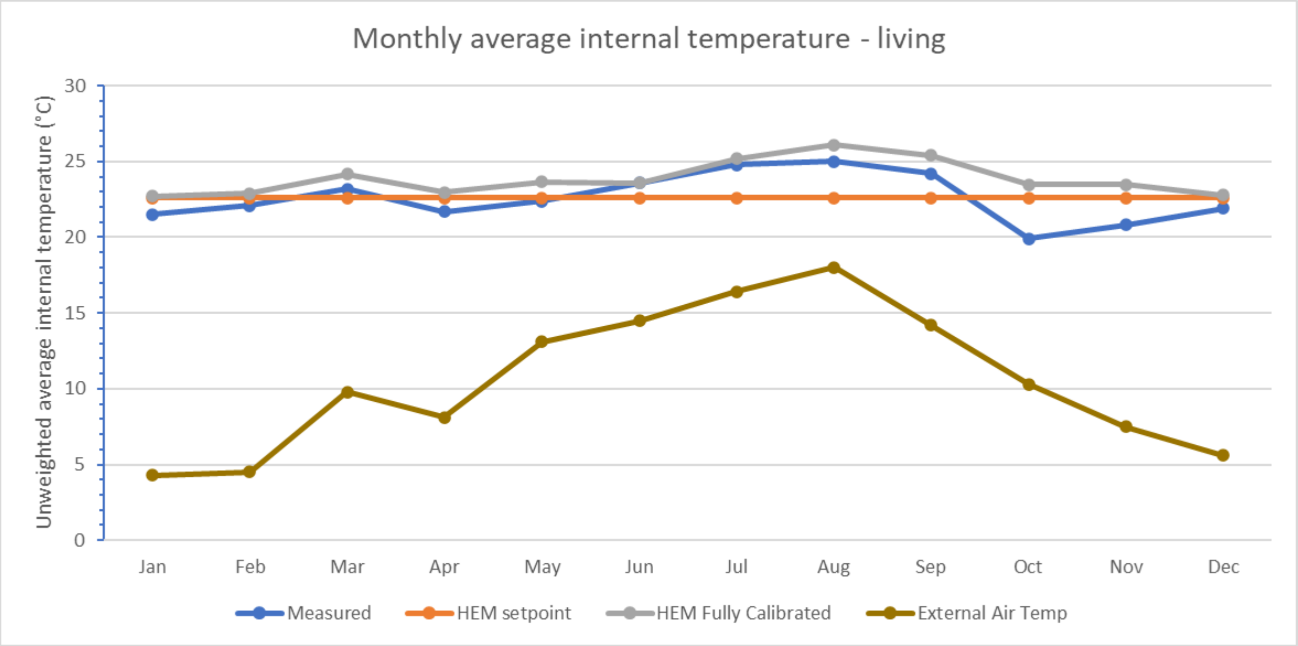
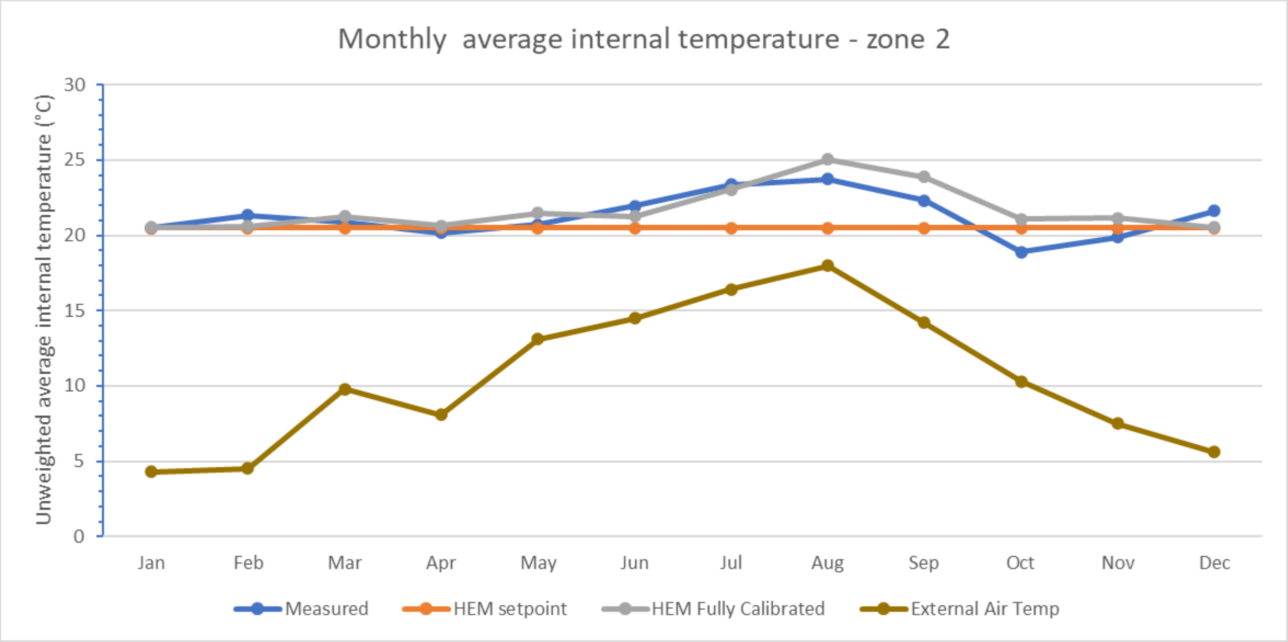


Figure 15 Monthly average internal temperature – non-living area



The measured temperatures dropped noticeably below the setpoint temperatures in April and October, for both Figures 14 and 15. Figure 14 has the greatest difference, with a 3°C difference in October. This suggests that less heating was used in these months. There are various potential explanations including: the heating setpoint was reduced in these months; they were away on holiday; or they decided to wait before turning on the heating for the winter and accepted lower internal temperatures.

In the living room, HEM predicted January to May temperatures about 1°C higher than the measured temperatures. This may be due to various factors including:

- The shading factor of the living room windows was higher than 80%
- More natural ventilation was used than assumed in the Home Energy Model
- Internal gains were lower than calculated in the model
- The modelled heating setpoint may have differed slightly from the setpoint in use
- Temperature stratification may mean that different temperatures could have been recorded depending on the location of the temperature sensor. HEM predicts the average zone temperature, while the temperature sensor is located in one place, which may not be the same as the zone average temperature.

Most of these factors also affect space heating consumption and may also contribute to the differences noted previously in the monthly consumption results (see Figure 13).

Also, in both the living room and bedroom, HEM predicted August to September temperatures to be 1°C to 1.5°C higher than the measured temperatures. This may be due to various factors including:

- The shading factor of the living room windows was higher than 80%
- More natural ventilation was used than assumed in the Home Energy Model
- The effect of MVHR summer bypass ventilation was not included
- Internal gains were lower than calculated in the model

Commentary

The case study shows that the Home Energy Model can produce plausible results that match the measured data, when averaged over a year. On an annual basis, the Home Energy Model was able to model space heating energy consumption close to the annual measured value. On a monthly basis, the space heat consumption was a less close match, and this could be due to the many uncertainties in the input variables, and the variability of occupant behaviour from month to month. These differences on a monthly basis have cancelled themselves out to show a good alignment at an annual level. The calibration was based on the annual average of the heating setpoint, and so variations in the heating setpoint in each month were not modelled, possibly explaining the better fit over an annual period.

Given the uncertainty of many of the case study conditions, it is not possible to determine if the inputs to the calibrated Home Energy Model were based on a close representation of the Camden Passivhaus during the monitoring period. Several variables have significant uncertainty, and these uncertainties have a cumulative effect leading to a total modelling error range which is very broad. Therefore, this validation study can only provide limited insight about the accuracy of the Home Energy Model.

Further work could be undertaken to both improve the modelling and better quantify the uncertainties. Possibly the Camden Passivhaus could be used as a helpful basis for an inter-model comparison with PHPP and the Home Energy Model, since PHPP is dedicated to modelling energy efficient components such as found in the Camden Passivhaus. However, it may be better to focus resources on other case studies for which the level of uncertainty is lower and are better able to validate the HEM.

The uncertainties are discussed further below.

Uncertainty analysis

Shading of windows

As explained in the occupancy calibration section, there was extensive use of window blinds which reduced solar gain. The effect of the blind usage on solar gain was not measured. However, the description of blind usage suggests that the blinds were in use most of the time. From this, a plausible range for a shading factor may be 10% to 100%. The calibration assumed a shading factor of 80% which is in the plausible range. This is a value which enables the Home Energy Model to match annual space heating energy consumption to the measured consumption. However, there is a wide range of uncertainty on the actual value, and no conclusion can be drawn that the true shading factor in use was 80%. The only confirmed data on shading were that there was some shading, and lighting electricity usage was above typical amounts for low-energy lighting, probably due to a darkened interior.

In a highly insulated home such as the Camden Passivhaus, small variations in solar gain have a higher relative impact on space heating demand. Due to its very low space heating demand, it is very sensitive to small changes in solar gains and internal gains. The validation study indicates a need to model window shading from blinds and curtains accurately to ensure realistic modelling of solar gains in low-energy homes.

Heating controls

The measured data reported the average annual temperature of the living room while the heating was in operation. This was midway between 22°C and 23°C. This gives some confidence that the living room heating setpoint was in this range on an annual average basis. However, monthly heating setpoint data was not available. The heating system was in operation for temperatures ranging from 19°C to 30°C. When the heating system is operating, the heating setpoint does not necessarily match the actual temperature in the room, since there are times when the heating system is raising the temperature from a cooler temperature up to the setpoint, or the air temperature may have overshot the setpoint. Nevertheless, this wide range of temperatures makes it difficult to narrow down what setpoints were in use, especially on a daily or monthly basis. There is also the possibility of temperature sensor measurement error. Stratification of temperatures in the living room is likely, since heated buoyant air was supplied at ceiling level through the supply air outlets in the kitchen roof, and which has a higher ceiling than the living room. This may mean that the temperature sensors were not in fact measuring the true average temperature in the living/kitchen/dining area.

This results in some uncertainty around monthly space heating predictions.

For the non-living area, there were measured average temperatures, but these did not make a distinction when the heating was in operation or not. This may result in more uncertainty for the non-living area setpoints on both an annual and monthly basis.

Pipework, cylinder and ductwork

Few details were given on lengths of distribution DHW pipework or MVHR ductwork. The insulation used for the hot water cylinder and the ductwork was not specified. A reasonable assumption was made based on a similar case study for Building for 2050. There may therefore be some uncertainty around heat losses for pipework and ductwork.

The amount of heat loss from standing water in distribution pipework is uncertain, which may affect predictions of DHW demand and the amount of heat gains from pipework. Similarly, the uncertainty around cylinder losses affects the prediction of heat losses into the house. The MVHR ductwork was very short, which would have minimised heat losses, but there is still uncertainty around the actual losses.

There was no measured data for the storage losses of the hot water cylinder used. By using the SAP 10 default value for hot water storage loss, the heat losses may be an underestimate of about 0.4 kWh/day, based on data from a similar Viessmann cylinder.

This uncertainty around DHW and ventilation heat losses increases uncertainty around internal gains, and consequently predictions of space heating energy consumption. It also impacts on identifying a plausible level of blind usage to reduce solar gains, with the intention to match space heating demand and internal temperatures.

Natural ventilation

The BPE case study noted that windows were rarely opened. It was therefore assumed that there was almost zero natural ventilation from windows. There was no measured data for window opening, so there is some minor uncertainty around the amount of natural ventilation.

If there was more natural ventilation than assumed in the model, there would be greater heat losses than predicted. This could result in the model predicting higher internal temperatures and lower space heating demand than the measured values. It may also mean that less than the assumed 80% shading from blinds would be needed to obtain a good match with the measured values.

Metabolic heat gains

The BPE case study mentioned there were 2 occupants in the house. In addition, a BBC interview mentioned that the occupants had a child and a dog, so the BPE report might not have fully documented the occupants and all sources of metabolic gains[15]. There was also no data on occupant hours spent in the house. There was a mention that the occupants took holidays at various times during the period of the BPE case study. However, the dates of the holidays were not recorded.

Due to the lack of occupancy data, the model predictions of metabolic gain relied completely on the default occupancy profile from the FHS assessment wrapper. The calibration of occupancy was limited to adjusting the default profile to use 2 occupants as an input to the default profile.

The metabolic gains are therefore very uncertain, although could be similar to the FHS predictions based on 2 occupants.

An uncertainty in metabolic gains may cause some uncertainty in predictions of space heating energy consumption and internal temperatures.

Internal heat gains

The energy used by appliances, lighting and cooking was measured. However, the percentage conversion of this energy into internal gains is unknown. Default values for gains conversion factors were used. Some uncertainty therefore remains around actual internal heat gains.

An uncertainty in these internal heat gains may cause some uncertainty in predictions of space heating energy consumption and internal temperatures. As previously mentioned, the very low

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[15] BBC Interview with Evan Davis, for BBC PM programme, 26th April 2019. Available at https://bere.co.uk/architecture/camden-passivhaus-ranulf-road/#

heat losses in the Camden Passivhaus mean that small variations in internal heat gains would have a greater impact on heating requirements than would be the case for a typical UK home.

Weather data

Due to the lack of hourly weather data from the BPE study, new hourly weather data had to be reconstructed. The actual weather conditions onsite cannot be precisely replicated in the Home Energy Model. The average monthly reconstructed temperatures, when compared to available onsite monthly data, differ with a range of -0.4°C to +0.1°C. For the global horizontal radiation, the reconstructed weather data differ from monthly average values with a range of -7 W/m^2 to 0 W/m^2. The difference for wind speed is unknown, since no wind speed data was published. These will cause some additional variation between modelled and measured space heating consumption.

Recommendations

Use of blinds and curtains

It is typical for blinds or curtains to be used on windows, especially if the occupants perceive there are privacy concerns, as in the Camden Passivhaus, or if the occupants wish to reduce glare. A typical amount of blind or curtains usage could be applied in the Home Energy Model. This could for example:

- Apply a shading factor to the glazing g-value
- Adjust the U-value of the window to include insulation effects of the blinds or curtain
- Identify a typical schedule of blind/curtain usage on an hourly basis

Shading factor

Individual windows can get additional shading from blinds, curtains, railings, fences or trees. There could be an optional input to the window definition to include an estimated shading factor for each window.

In *ISO 52016-1*, Annex E, Section E.2.2, ‘Total solar energy transmittance of transparent elements’, it contains a methodology for calculating a shading correction factor from movable shading devices. This may be a useful reference for implementing a shading factor from blinds and curtains.

Appendix A – additional analysis

Internal heat gains

A comparison is shown here of the uncalibrated and fully calibrated internal gains in the Camden Passivhaus with the Home Energy Model. Since the validation study modelled a Passivhaus, it is also informative to compare with the internal gains predictions from PHPP (Passive House Planning Package).

As shown in Figure 16 the uncalibrated Home Energy Model based on the FHS assessment wrapper predicts internal gains which are higher than the fully calibrated model which looks to better account for the actual internal gains. Occupant energy usage of appliances is highly variable between households, so a close match of the FHS assessment wrapper predictions[16] to an individual home such as the Camden Passivhaus is unlikely.

As shown in Figure 16 the uncalibrated Home Energy Model based on the FHS assessment wrapper predicts internal gains which are higher than the fully calibrated model, which looks to better account for the actual internal gains. Occupant energy usage of appliances is naturally highly variable between households, so a close match of the FHS assessment wrapper predictions to an individual home such as the Camden Passivhaus is unlikely.

However, it can be seen that the Camden Passivhaus has lower internal gains than the generic FHS assessment wrapper prediction. One potential reason for this could be the use of high-efficiency appliances, which is required by the Passivhaus standard, and this strategy was used in the Camden Passivhaus. Its entry in the Low Energy Buildings Database states:

> *“Every appliance was rigorously chosen and had to comply with the high levels of efficiency set in PHPP. Where possible the appliances are A++ rated.”*

An A++ rated appliance could have half the energy consumption of an A rated appliance[17]. In a Passivhaus, A++ rated[18] high efficiency appliances are to be expected, but for other UK homes, less efficient appliances may be more common. Either the appliances are older (being in an existing home), or the householder buys a cheaper but less efficient appliance. The trend for new appliances is for their energy efficiency to improve. This means that new homes may in general have lower appliance internal heat gains than the FHS assessment wrapper estimates, and Passivhaus new homes even lower internal gains still. To understand and quantify this effect, further analysis and study is necessary.

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[16] For further details, see the technical paper S11P-017, *Lighting, cooking, electrical appliances and incidental heat losses in the Home Energy Model: FHS assessment wrapper.* This is based on the Energy Follow Up Survey (EFUS) 2017.

[17] Carbon Footprint Ltd, *Household Energy Consumption*

[18] Note that energy labels now use a new scale from A to G. See https://www.energylabel.org.uk/the-new-label/

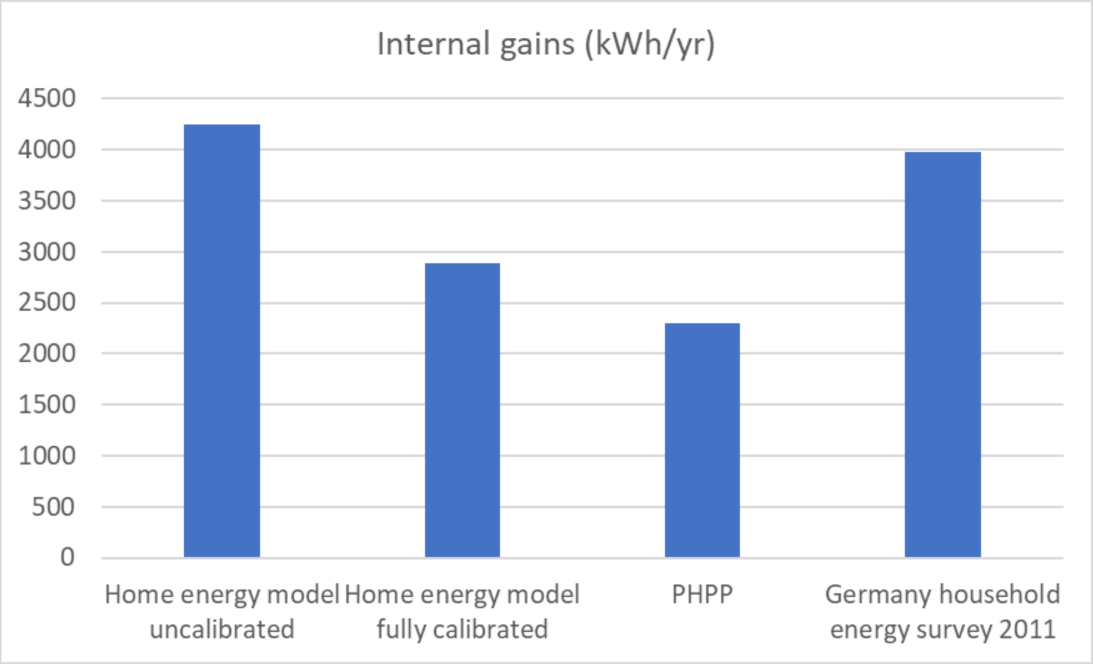
The Passive House Institute commented on Passipedia about the typical internal gains from appliances as found in a household electricity survey[19] in Germany, 2011:

> *"The PHI points out that it is not permissible at all to use such high [internal gain] values for the planning of Passive Houses. There are several reasons for this: in the first place, attention is and must be given to a high level of efficiency of electricity applications particularly in Passive House buildings"* [20]

The uncalibrated Home Energy Model predicts higher internal gains than PHPP would, when based on the PHPP internal gains formula by floor area[21].

According to the Passipedia article, PHPP would predict much higher internal gains if appliance usage was based directly on the German household electricity survey. For a 100 m^2 home, the article explains that a typical German household had around 4.5 W/m^2 of internal heat gains, taking into account the availability of dissipated heat from electricity consumption. However, the PHPP internal gains algorithm instead calculates 2.6 W/m^2 of internal heat gains for a 100 m^2 home, the same treated floor area as the Camden Passivhaus (using the PHPP Treated Floor Area definition). The impact on the annual internal heat gains is shown on the graph below, using the floor area for the Camden Passivhaus. This compares the uncalibrated Home Energy Model, fully calibrated Home Energy Model, PHPP internal heat gains algorithm, and the German household survey. (Annual energy total in kWh/yr, not W/m^2, was used to avoid confusion between different definitions of floor area.)

Figure 16: Internal heat gains in Camden Passivhaus: Home Energy Model, uncalibrated and fully calibrated, compared to PHPP and a Germany household electricity survey



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[19] *Survey: 'Where is electricity used in the household?'* NRW Energy Agency 2015.

[20] Passipedia. *Internal heat gains in relation to living area.* Section 2 'Actual electricity consumption depending on household size'

[21] Passipedia. *Internal heat gains in relation to living area.* Section 11 'Outcome: PHPP 9 approach for IHG depending on dwelling size'

For the Passivhaus standard, the PHPP algorithm for predictions of internal heat gains intentionally reduces internal heat gains to reflect the expected use of highly efficient appliances. Otherwise, an overestimate of internal heat gains could result in an underestimate of space heating demand for homes designed to Passivhaus standards, since very little space heating is required in the first place.

Consideration may also be needed for the Home Energy Model to reduce internal gains predictions in some cases, since new homes may have more efficient appliances than existing homes. This would avoid potential under-estimation of space heating demand as a result of the use of more efficient appliances, especially for homes built to high insulation levels.

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