Department for
Energy Security
& Net Zero

Comparison of HEM to IEA Annex 58 measured data

Focus on space heating consumption and internal air temperature in two test homes

December 2023

Acknowledgements

The Home Energy Model has been developed for the Department for Energy Security & Net Zero by a consortium led by the Building Research Establishment (BRE), including AECOM, Sustenic, University of Strathclyde's Energy Systems Research Unit, Kiwa Ltd., Loughborough University Enterprises Limited, Chris Martin and John Tebbit.

Quality assurance has been undertaken by a consortium led by Etude, including Levitt Bernstein, Julie Godefroy Sustainability, and UCL.

Document reference: HEM-VAL-02

Document version: v1.0

Issue date: 13/12/23

Home Energy Model version: HEM v0.24

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Contents

Introduction

This paper summarises the work undertaken and results from a comparison of Home Energy Model (HEM) calculations with measured data from two identical experimental homes from the IEA Annex 58 research project.

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

The IEA Annex 58 research project

The IEA Annex 58 research project[1] was funded by the International Energy Agency (IEA). Its goal was to "*develop the necessary knowledge, tools and networks to achieve reliable in situ dynamic testing and data analysis methods that can be used to characterise the actual energy performance of building components and whole buildings*". Subtask 4a of IEA Annex 58 focussed on the validation of Building Energy Models against in situ monitored data. For this validation of HEM calculations, the monitored dataset from subtask 4a was used as detailed below.

Two monitored experiments were conducted using two test houses, O5 and N2, situated at Fraunhofer Institute for Building Physics (IBP) in Holzkirchen, Germany. The two test houses are almost identical in terms of size, geometry, construction and systems installed. Each test house is a detached plot with a ground floor area of 89m^2, and a basement and attic space. The test houses have mechanical ventilation without heat recovery and space heating is supplied by fast response electric convector heaters. External roller blinds were installed across each window. Construction and thermal performance of both test houses is stated to be typical for houses of modern construction standards in Europe (at the time of the experiment in 2013). The layout of the test houses is shown in Figure 1.

Monitored data used for this validation exercise included:

- Total electricity consumption
- Space heating energy consumption
- Mechanical ventilation energy consumption
- Internal temperatures

Experiment 1 took place from 21st August 2013 to 30th September 2013 and included both test houses. Experiment 2 took place from 9th April 2014 to 3rd June 2014 for the O5 test house only. There were occasions during the monitoring period where space heating or internal temperature data was incomplete. This occurred in the second experiment, for the period 17th

[1] Annex || IEA EBC (iea-ebc.org)

April 2014 – 23rd April 2014 for space heating measurements in the living room and in the period 23rd May 2014 – 26th May 2014 for internal temperature measurements for the whole test house.

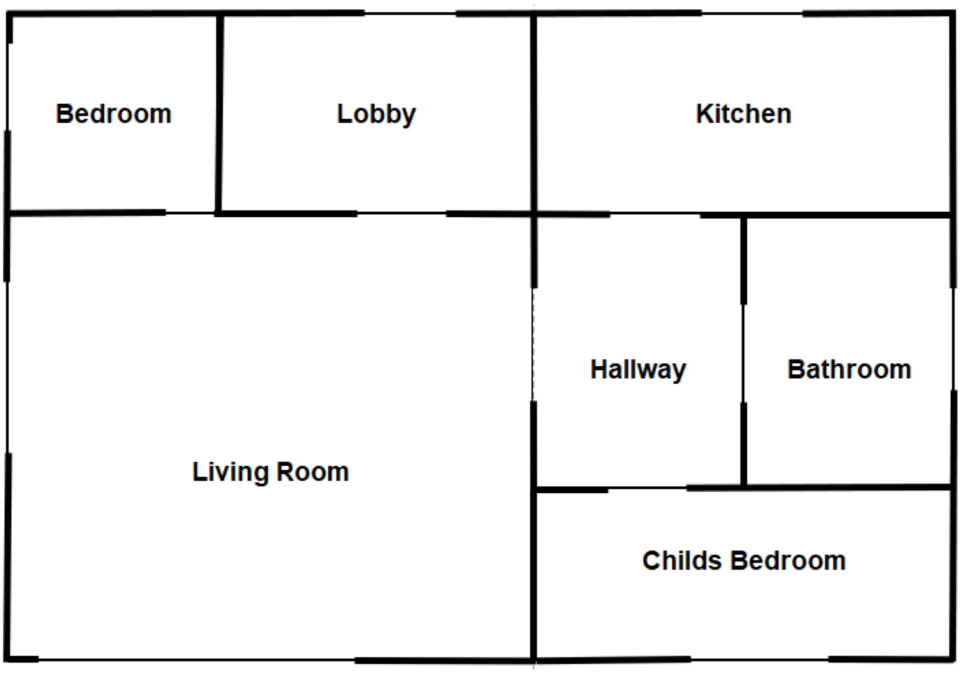
Each of the two experiments contained multiple test conditions which varied the experimental setup and boundary conditions across the monitoring period.

The test conditions in both test houses can be summarised as follows:

- *Initialisation* – A period at the start of the experiment to heat the building to a constant air temperature.
- *Constant Temperature* – A period of heating to a constant air temperature controlled by the building management system.
- *Random Order Logarithmic Binary Sequence (ROLBS)* - A period with a pseudo random sequence for heating to ensure that solar and heat inputs are uncorrelated. Heating duration is a randomised sequence ranging between 1 – 90 hours across the schedule.
- *Re-initialisation* – A period of heating to re-align both test houses to a constant air temperature.
- *Free Float* - A period without a space heating regime.

The schedule and boundary conditions for each experiment are provided in more detail in the Experimental Conditions section.

Figure 1: Floor Layout of the IEA Annex 58 O5 & N2 Test Houses



Approach to HEM modelling

This section describes the approach to the HEM modelling. It summarises:

- the information used in the building energy models, and
- the approach to calibrate the HEM analysis to better represent the actual conditions for Plots O5 and N2 during each test condition. The calibration refers to modifying assumptions that form part of the Future Homes Standard (FHS) assessment wrapper[2] so as to better represent known actual conditions - we did not modify any core HEM assumptions. For each test house, we calibrated the models for the weather and the space heating regime.

Most parameters are adequately defined by IEA Annex 58 for the purpose of the HEM modelling but, where necessary, reasonable estimates are included for the HEM inputs. The level of uncertainty in the value of the parameters is reduced due to relatively controlled experimental conditions, and the random influence of occupant behaviour has been excluded by experimental design. This gives a greater confidence in the measured parameters for the purpose of validating simulations of building fabric performance.

HEM version 0.21 was used for the modelling presented in this report. There are no substantive differences between this version of the HEM and the one issued for consultation, in regard to the modelling carried out in this report.

Based on the measurement data available, the following aspects of HEM listed below can be directly validated against measured data in this validation exercise for each test condition:

- Internal air temperature predictions
- Space heating energy usage

The following aspects of the HEM can be indirectly validated against measured data, since they are part of the calculations for those aspects of the HEM listed above:

- Geometrical building definition from input data
- Building construction elements thermal response
- Solar gains calculation

As specified in the IEA Annex 58 specification, the ground floor of each test house has two heating zones. In experiment 1, zone 1 is defined as the living room and zone 2 is defined as all other ground floor rooms. In experiment 2, zone 1 refers to the living room, hallway, child's bedroom and bathroom. Zone 2 refers to the kitchen, lobby and bedroom. HEM was set up to replicate the heating zones in both experiments to ensure alignment with monitored data.

[2] The FHS assessment wrapper is a separate software package to the HEM. It specifies the inputs and outputs of the core engine to demonstrate compliance with the FHS (i.e. it wraps around the core engine). On the input side, this includes factors such as standardised assumptions around occupancy and setpoint temperatures.

Currently, in the Home Energy Model, heat transfer between zones is not modelled. In a real house, heat can easily flow between zones, since there is airflow between zones and some heat transfer through internal walls. The use of MVHR also requires airflow between zones, which may increase interzone heat transfer compared to a home with natural ventilation.

The test houses undergo a pre-run of a few days before each test condition starts to ensure the starting conditions of each test condition aligns with the measured data.

In all test conditions, the average dwelling internal air temperatures predicted by HEM are compared to the measured data. There are some test conditions where the heating regime is different in the two zones. Further work could be undertaken to compare the average air temperatures by zone which may provide additional insight.

Information used in the HEM models

Dimensional data from architectural drawings from the IEA Annex 58 project 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 provided by the IEA Annex 58 project. This was based on the building energy modelling specification provided. The provided information included fabric U-values, calculations for the thermal mass of opaque elements, information on the shutter blinds and mechanical ventilation system and detailed calculations for the thermal bridges. The specification also provided information on the heating system and the defined setpoint temperatures for the experiments.

Some further details of the performance values used for the building components are provided below [3].

It should be noted that the IEA Annex 58 dwellings are test houses with no occupancy. Therefore, all inputs related to occupancy (e.g., domestic hot water, appliances, lighting, cooking) were set to zero.

Thermal mass

The thermal mass of the external walls, roof and floor was calculated using the areal specific heat capacity "kappa value" calculations for opaque elements. The areal specific heat capacity is defined for the full depth of each opaque element. The thickness, specific heat capacity and density of each layer in an opaque element is provided in the IEA Annex 58 specification. The thermal mass of internal walls was included in the HEM to better represent the actual thermal mass of the dwellings.

[3] In addition, Section 5.5 'Uncertainty Analysis', from the report of Subtask 4a (Strachan et al; http://www.iea-ebc.org/Data/publications/EBC_Annex_58_Final_Report_ST4a.pdf) discusses the level of uncertainty around the performance values set out in the modelling specifications by IEA Annex 58 for the building components.

Thermal bridging

Thermal bridge psi-values were calculated by Fraunhofer IBP for each junction[4]. Internal dimensions were used for the calculations. The psi-values used as inputs in the HEM are shown in Table 1.

Table 1: Thermal bridges psi-values by junction

Junction	Psi-value W/m·K
External Wall - Floor	0.110
External Wall - Ceiling	0.089
External Wall – External Wall	0.093
Internal Wall - Floor	0.204
Internal Wall - Ceiling	0.378
Windowsill	0.140
Reveal	0.080
Lintel	0.050

Ground Floor / Basement U-value

The floor U-value was calculated by Fraunhofer IBP according to EN ISO 6946 using insulation conductivities supplied by the manufacturer. The floor U-value was calculated as 0.29 W/m^{2}K.

The ground floor was above a basement which was unheated in both the O5 and N2 buildings for Experiment 1 (see further details in section on experiment conditions). The unheated basement had an average air temperature of 18.5°C during Experiment 1.

A correction factor was applied by BRE to the floor U-value to account for the higher temperature in the basement than the external air temperature. This correction factor follows the methodology in BS EN 12831-1:2017, ‘Energy performance of buildings - Method for calculation of the design heat load’, section 6.3.2.5 ‘Temperature adjustment factor’.

$$Temperature\ adjustment\ factor = \frac{Internal\ temp - \ temp\ of\ adjacent\ space}{Internal\ temp - external\ temp}$$

The adjusted U-value for the floor is 0.16 W/m^{2}K. This value was used in the modelling.

[4] *Empirical Whole Model Validation Modelling Specification*, section 3.7. Thermal bridges, IEA ECB Annex 58

Wall U-value

The wall U-value was calculated by Fraunhofer IBP according to EN ISO 6946, using insulation conductivities supplied by the manufacturer. The wall U-value varied between 0.19-0.27 W/m^2K due to differences in the insulation material used on different facades. The U-value used for each façade is shown in Table 2.

Table 2: External Wall U-value by Facade

External Wall Orientation	U-value $W/m^2 \cdot K$
South	0.21
West	0.27
North	0.20
East	0.19

Window U-value

For windows, the Fraunhofer IBP calculated U-value (according to EN ISO 10077-1) of 1.2 W/m^2K was used for all windows.

Under some test conditions (see further detail in the Experimental Conditions section), external metal shutter blinds were closed over the windows. The shutter blinds were filled with PUR foam insulation with a conductivity of 0.023 W/m·K. The U-value of windows was adjusted by BRE to reflect this when the shutter blinds were drawn, according to ISO/TR 52022-2:2017. The U-value in this case is 0.33 W/m^2K. An outline of this adjustment is shown in Table 3. In the scenarios where shutter blinds were drawn, this was treated as an opaque element with a g-value of 0.

Table 3: Adjusted U-value for windows with shutter blinds

Parameter	Value
Window U-value ($W/m^2.K$)	1.20
Window Resistance ($m^2.K/W$)	0.83
Shutter Blind Resistance ($m^2.K/W$)	2.17
Total Resistance ($m^2.K/W$)	3.00
Adjusted U-value ($W/m^2.K$)	0.33

Glazing g-value

The manufacturer stated the glazing g-value as 0.602. A 5% correction factor for dirt on the windows was included by BRE, for a final g-value of 0.572.

Air permeability

Pressurisation tests at 50Pa were performed on the ground floor before the start of the experiments. The O5 building was 3.85 $m^3/h \cdot m^2$ and the N2 building was 4.05 $m^3/h \cdot m^2$.

Electric Heaters

Dimplex AKO K 810/K 811 heaters were used in the test houses. The electric heaters have a maximum output of 2kW. The IEA Annex 58 specification gives the convective/radiative split as 70%/30%.

Upon investigation by BRE, an alternative convective/radiative fraction was used to that provided by the manufacturer. According to BS EN ISO 15316-2:2017 for convector heaters, the typical convective/radiative split is 95%/5%. This had minimal impact on the total space heating consumption predicted by HEM but resulted in the HEM results better aligning with the measured profiles.

One electric heater was installed in each room of both test houses (excluding the hallway).

Zone Control for Heating Systems

Zone control for heating systems was based on two zones. Zone 1 refers to the living room, hallway, child's bedroom and bathroom. Zone 2 refers to the kitchen, lobby and bedroom.

The heating setpoints varied for each test condition and were set to the stated air temperatures in these zones as defined by the specification (see the Experimental Conditions section for more explanation).

In the IEA Annex 58 test houses, the heating setpoints were controlled by the air temperature measured at the mid-height of the room. Therefore, the reported results from HEM are air temperatures to ensure alignment with the measured data.

Mechanical Ventilation

Mechanical ventilation was installed in both test houses. Limited information was provided on the type and manufacturer of the ventilation system. The Specific Fan Power (SFP) of the mechanical system was not provided by IEA Annex 58. For this project, the mechanical ventilation system has an assumed SFP of 2 W/l·s as a default assumption for balanced mechanical ventilation without heat recovery. The 2.8m duct in the cellar is insulated with aluminium covered with 3cm rock wool (conductivity 0.035 W/m·K) as stated in the IEA Annex 58 specification.

Mechanical ventilation supplied an air flow rate of 120 m^3/h in Experiment 1 to both test houses and 60 m^3/h in Experiment 2 to the O5 test house.

Table 4: Mechanical Ventilation Properties

	Experiment 1	Experiment 2
SFP (W/ls) (assumed)	2.0	2.0
Air Flow Rate (m^3/h)	120	60
Ductwork Length (m)	7.5	7.5

Experimental Conditions

The purpose of this analysis was to validate space heating predictions from HEM, along with the modules that support these predictions. Hence, the HEM modelling was calibrated to be reflective of the actual case study conditions during the monitoring period, with the actual boundary conditions found onsite. Five runs were undertaken for each test house in Experiment 1 and four runs for one test house, O5, in Experiment 2 under different test conditions as detailed below. In each test condition, the starting point for the HEM internal air temperature was calibrated to the measured data.

Experiment 1: O5 & N2 Test Houses

This adopted the actual conditions of the case study and the local weather data as monitored on site. Experiment 1 was conducted in both test houses in the period 21st August 2013 – 30th September 2013. There was onsite monitored external temperature data available for this period. The other weather data parameters provided were direct solar radiation, diffuse solar radiation, and wind speed. This data was combined into a custom weather data file for the IEA Annex 58 location during the monitoring period.

The experimental schedule was split into five different test conditions across the monitoring period. The test conditions were the same in each test house except for some variation between houses to southern shutter blinds. The conditions under which each test was performed are outlined in Table 5. Experiment 1 was focussed on the ground floor of each test house where the test conditions were applied. Both the attic space and the basement were unheated for the duration of the experiment.

The position of the shutter blinds was varied in the O5 test house only. The shutter blinds on the south façade were either fully open or closed depending on the test condition. In the N2 test house, shutters blinds on the south façade were closed for the duration of Experiment 1. All other windows in O5 and N2 had the shutter blinds open.

The ROLBS heating regime was provided in the modelling specification. This outlined the sequence (both timing and duration) for the number of hours the heating system was switched on/off during the test condition. For this test condition there was no thermostat setpoint and in the HEM, the heating system was specified to be on/off continuously for the defined number of hours. The heating system was set to 500W when on.

Table 5: Experiment 1 test condition schedule

Test condition	Period	Heating Regime	Shutter Blinds*
1. Initialisation	21/08/2013 00:00 - 22/08/2013 23:59	30°C in all ground floor rooms No heating in attic or basement	N2 south blinds down O5 south blinds down
2. Constant Temperature	23/08/2013 00:00 - 29/08/2013 23:59	30°C in all ground floor rooms No heating in attic or basement	N2 south blinds down O5 south blinds up
3. ROLBS (Random Order Logarithmic Binary Sequence)	30/08/2013 00:00 - 13/09/2013 23:59	Pseudo random heating sequence in living room** There is no heating setpoint. Instead, the temperature is allowed to free float according to the heat input supplied. No heating in other ground floor rooms, attic & basement	N2 south blinds down O5 south blinds up
4. Re-initialisation	14/09/2013 00:00 - 19/09/2013 23:59	25°C in all ground floor rooms No heating in attic or basement	N2 south blinds down O5 south blinds up
5. Free Float	20/09/2013 00:00 - 30/09/2013 23:59	No heating input	N2 south blinds down O5 south blinds up

*Shutter blinds on the south side of the test houses were open/closed for the duration of the test condition. All other windows in both test houses had shutter blinds open.

**The heating system output was set to 500W in the living room when on for the ROLBS sequence

Experiment 2: O5 Test House

As for Experiment 1, this adopted the actual conditions of the case study and the local weather data as monitored on site. Experiment 2 was conducted on the O5 test house only in the period 9th April 2014 – 3rd June 2014.

Experiment 2 was focussed on the ground floor of the O5 test house where the test conditions were applied. Both the attic space and the basement were heated to 22°C for the duration of the experiment and were treated as boundary conditions. Zone 2 was also heated to 22°C for the duration of the experiment.

The position of the shutter blinds was varied in the O5 test house. Shutter blinds in zone 2 were closed for the duration of the experiment. All other windows in O5 had shutter blinds open.

The experimental schedule was split into four different test conditions across the monitoring period. The conditions under which each test was performed are outlined in Table 6.

Table 6: Experiment 2 test condition schedule

Test Condition	Period	Heating Regime	Shutter Blinds
1. Constant Temperature	09/04/2014 00:00 - 29/04/2014 00:59	30°C in Zone 1 22°C in Zone 2, attic & basement	Zone 1 blinds up Zone 2 blinds down
2. ROLBS (Random Order Logarithmic Binary Sequence)	29/04/2014 01:00 - 14/05/2014 00:59	Pseudo random heating sequence in Zone 1** There is no heating setpoint. Instead, the temperature is allowed to free float according to the heat input supplied. 22°C in Zone 2, attic & basement	Zone 1 blinds up Zone 2 blinds down
3. Re-initialisation	14/05/2014 01:00 - 20/05/2014 00:59	30°C in Zone 1 22°C in zone 2, attic & basement	Zone 1 blinds up Zone 2 blinds down

4. Free Float	20/05/2014 01:00 - 03/06/2014 23:59	No heating input in zone 1 22°C in zone 2, attic & basement	Zone 1 blinds up Zone 2 blinds down

*Zone 1 refers to living room, hallway, child's bedroom & bathroom. Zone 2 refers to kitchen, lobby and bedroom.

**The heating system output was set to 2.8kW in zone 1 when on for the ROLBS sequence

Results

High-level analysis across all experiments

Table 7 compares the total energy consumption by energy end-use and average internal air temperature for the ground floor of Plots N2 and O5 for each test condition. It also shows the percentage difference between the HEM and measured data. The homes are all-electric and so the energy consumption is all electricity consumption.

Table 7: Average hourly electricity consumption and average hourly internal air temperature for test conditions

Plot	Space heating electricity consumption (kWh per hr)			Ventilation electricity consumption (kWh per hr)			Average internal air temperature (°C per hr)		
	Measured	HEM	% change from Measured	Measured	HEM	% change from Measured	Measured	HEM	Difference (°C)
Experiment 1 Test Condition 1 (Initialisation - 30°C heating both zones)									
N2	1.75	1.61	-8.1%	0.105	0.068	-35.0%	30.1	30.0	-0.1
O5	1.66	1.60	-3.7%	0.082	0.068	-17.2%	30.0	30.0	0
Experiment 1 Test Condition 2 (30°C heating both zones[5])									
N2	1.79	1.72	-4.1%	0.094	0.068	-27.5%	30.0	29.7	-0.3
O5	1.43	1.46	2.0%	0.084	0.068	-19.0%	30.1	30.1	0
Experiment 1 Test Condition 3 (ROLBS heating zone 1, no heating zone 2)									
N2	0.24	0.24	-2.6%	0.083	0.068	-18.4%	23.2	25.3	2.1
O5	0.25	0.24	-3.5%	0.081	0.068	-16.0%	25.3	27.5	2.2
Experiment 1 Test Condition 4 (25°C heating both zones)									
N2	2.07	1.85	-10.3%	0.088	0.068	-22.8%	24.9	25.0	0.1
O5	1.78	1.97	11.0%	0.083	0.068	-18.5%	24.9	25.0	0.1
Experiment 1 Test Condition 5 (no heating both zones)									

[5] The Plot O5 shutter blinds configuration in Experiment 1 Test Condition 2 differs from the configuration in Experiment 1 Test Condition 1 as described in Table 5.

Plot	Space heating electricity consumption (kWh per hr)			Ventilation electricity consumption (kWh per hr)			Average internal air temperature (°C per hr)		
	Measured	HEM	% change from Measured	Measured	HEM	% change from Measured	Measured	HEM	Difference (°C)
N2	0.00	0.00	N/A	0.083	0.068	-18.0%	18.6	18.6	0
O5	0.00	0.00	N/A	0.078	0.068	-13.3%	20.3	20.1	-0.2
Experiment 2 Test Condition 1 (30°C heating zone 1, 22°C heating zone 2)									
O5	1.17	1.20	3.1%	0.024	0.038	57.1%	24.2	24.1	-0.1
Experiment 2 Test Condition 2 (ROLBS heating zone 1, 22°C heating zone 2)									
O5	1.36	1.33	-2.5%	0.026	0.038	43.8%	25.7	27.0	1.3
Experiment 2 Test Condition 3 (30°C heating zone 1, 22°C heating zone 2)									
O5	1.64	1.72	5.3%	0.020	0.038	86.1%	24.8	24.7	-0.1
Experiment 2 Test Condition 4 (no heating zone 1, 22°C heating zone 2)									
O5	0.10	0.20	102.5%	0.019	0.035	81.7%	21.1	21.3	0.2

Table 7 shows that space heating electricity consumption predictions in HEM vary from the measured data from –10.3% to 11%, with HEM typically underpredicting the measured space heating consumption. The exception is Experiment 2, Test Condition 4 which had limited heating and a difference in results above 100%, albeit the absolute difference was similar to other test conditions. The cause of this is explored in the Evaluation for each test condition section below.

The ventilation electricity consumption comparison depends on the experiment. For Experiment 1, HEM underestimated the measured consumption by up to 35%. In contrast, for Experiment 2, HEM overestimated the measured consumption by up to 86%. Note the ventilation electricity consumption is an order of magnitude smaller than the space heating electricity consumption. The Specific Fan Power (SFP) is critical for determining ventilation energy consumption; as the SFP was not known, this limits the validation of ventilation energy consumption.

The average internal air temperature predictions in HEM vary from the measured data by -0.3°C to +2.2°C. As noted in the approach section, this is dwelling average internal air temperatures. Further work could investigate how average zone temperatures vary between the HEM and the measured data.

The reasons for the differences in the results are explored further below where each test condition is examined in more detail.

Evaluation for each test condition

This section details the average electrical power consumed and internal air temperature for both test houses, both measured and HEM, under the test conditions previously detailed. We have focussed on presenting the key features in the results rather than presenting here all of the results for each plot and test condition. The overall summary for each test condition is presented above.

Experiment 1, Test Condition 1 & 2

Figure 2 and Figure 3 show the average hourly electricity consumption for Plot N2 space heating and ventilation respectively during Experiment 1 Test Condition 2. Whilst not shown here, the results are similar for Experiment 1 Test Condition 1 as both have a similar set-up with heating being supplied to control the internal temperature to 30°C for both test conditions. Similarly, the equivalent graphs for Plot O5 show similar features and are not shown here.

Figure 4 and Figure 5 show the average hourly internal air temperature for Plots N2 and O5 respectively which have different solar shading conditions.

Figure 2: Average space heating hourly electricity consumption, Plot N2, Experiment 1, Test Condition 2

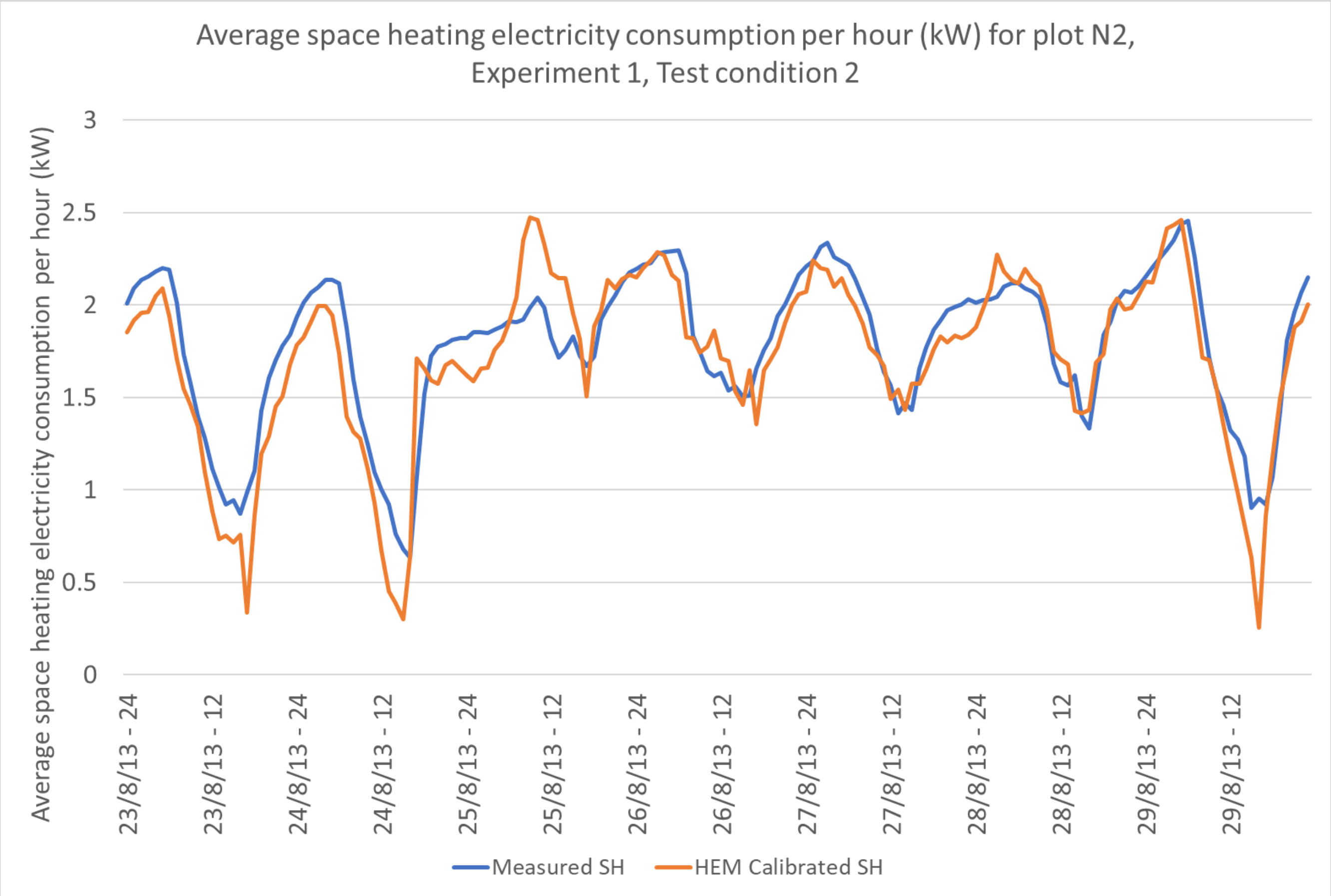


Figure 3: Average ventilation hourly electricity consumption, Plot N2, Experiment 1, Test Condition 2

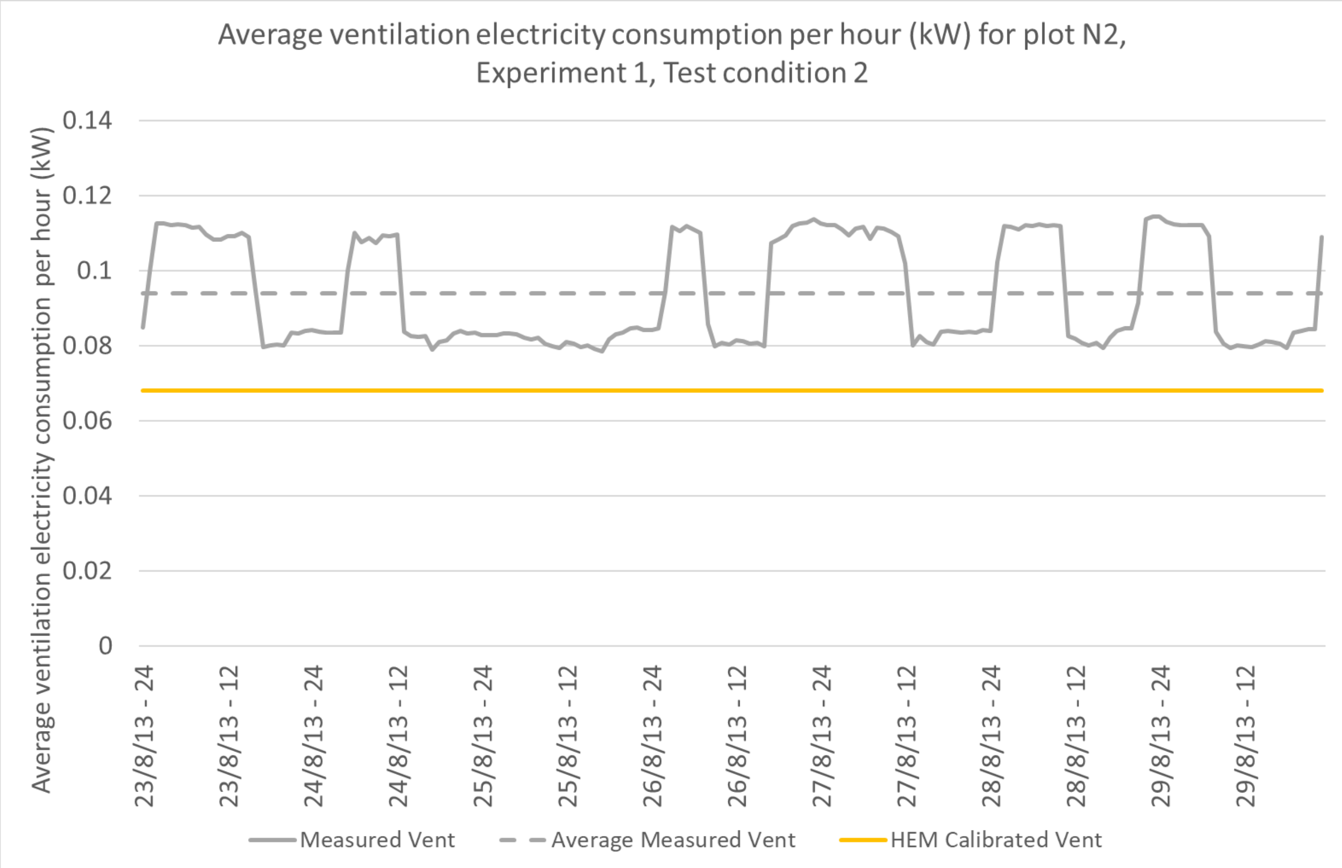


Figure 4 : Average hourly internal air temp., Plot N2, Experiment 1, Test Condition 2

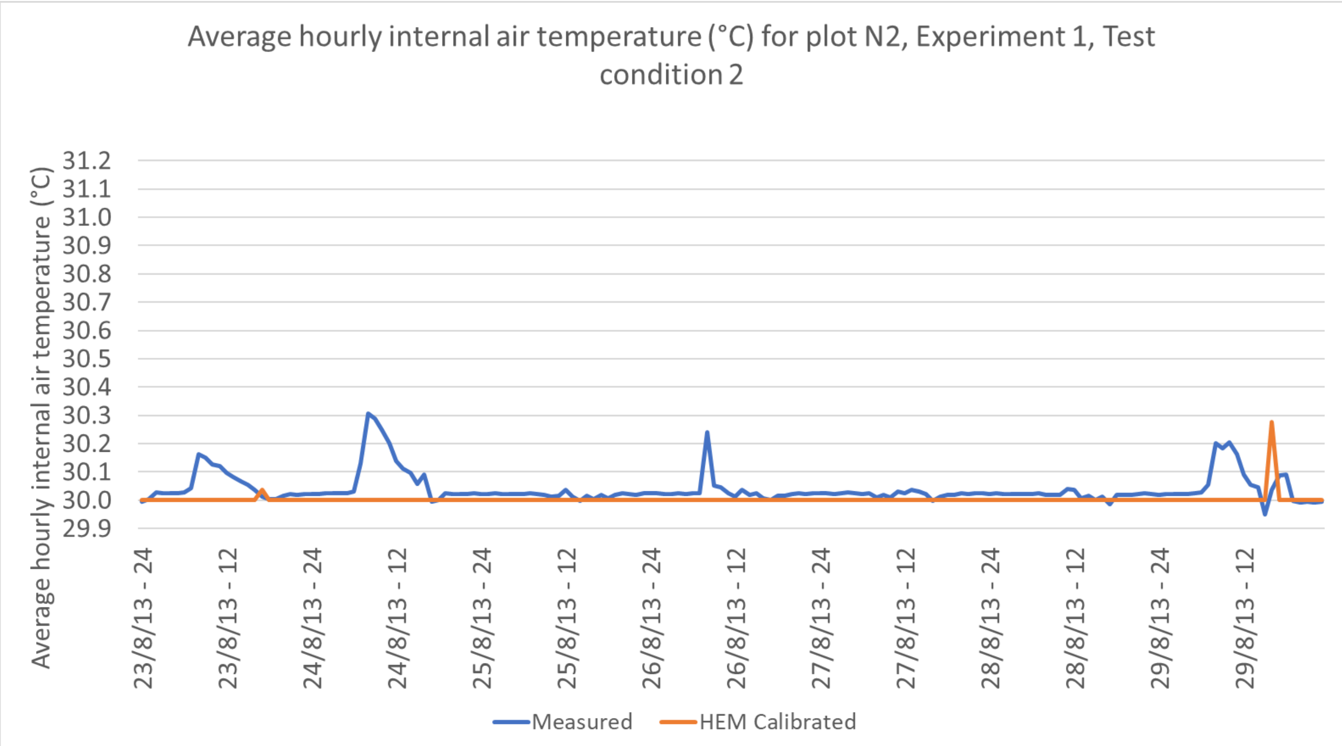


Figure 5: Average hourly internal air temperature, Plot O5, Experiment 1, Test Condition 2

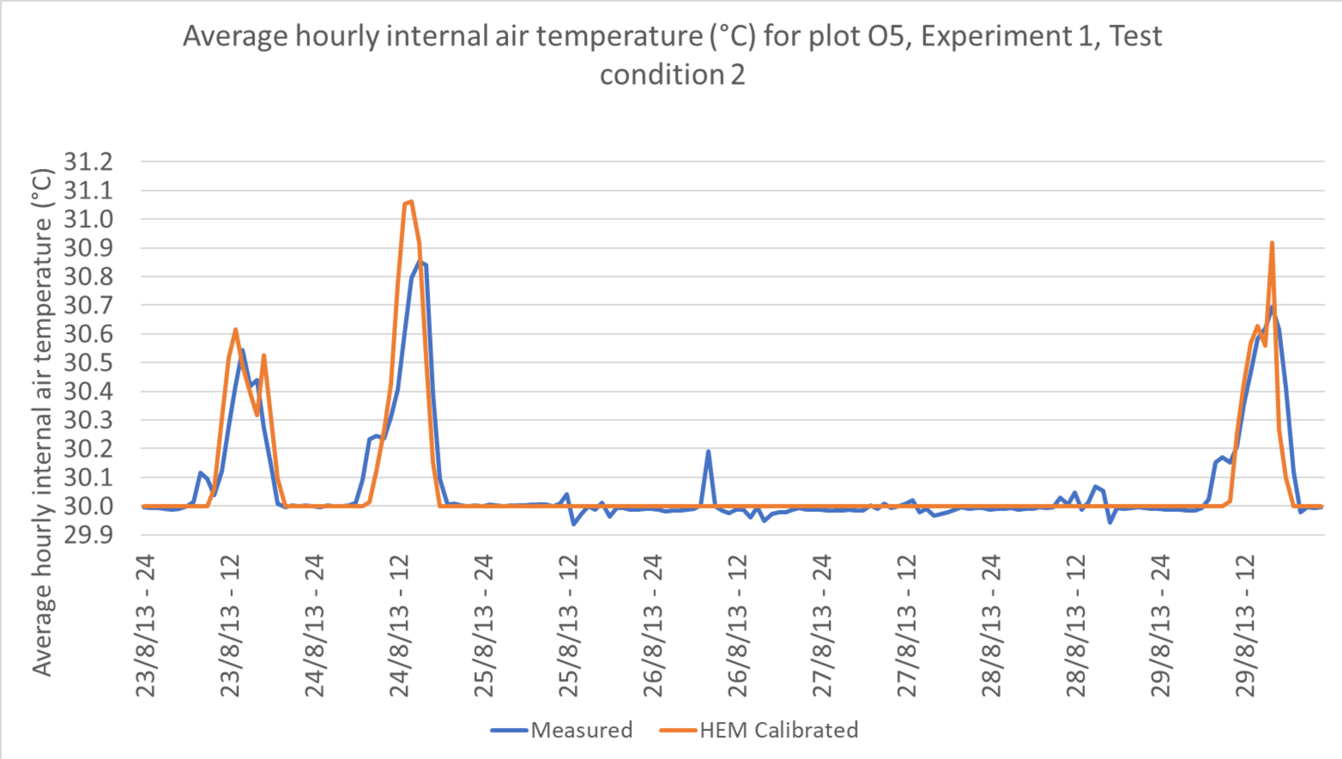


Figure 2 shows that space heating electricity consumption peaks and troughs align between measured and HEM results; troughs typically occur in the afternoon with peak solar gains. It appears that the HEM model reduces the heating to a greater extent than the measured, suggesting that the HEM space heating requirements are more sensitive to a change in solar gains and resulting increased internal temperature. This results in the HEM space heating electricity consumption being lower than measured as shown in Table 7.

Figure 3 shows that ventilation electricity consumption in HEM is constant and overall lower than the measured data. The measured data varies over time in an irregular pattern with peaks and troughs of the same amplitude. The peaks in the measured data could arise from a boost function (e.g. linked to relative humidity levels) that is operating for some of the time in the experiment which we do not have details of and was not modelled in HEM. The systematic difference between the HEM results and the measured baseline (of around 0.03kW on average) may relate to two causes: (i) the level of uncertainty in the measured air flow rate, and (ii) the project team needing to make a reasonable estimate of the efficiency of the mechanical ventilation system given limited data from IEA Annex 58 documentation. This could be tested further through sensitivity analysis. The issues identified here were reflected in the ventilation electricity consumption results for the whole of the Experiment 1 and no additional analysis is presented for the other test conditions.

Figure 4 and Figure 5 show that HEM and the experimental set-up both broadly meet the intent of achieving a 30°C internal temperature. The peaks in internal air temperature shown in Plot O5 are believed to relate to the additional solar gain heat transfer from south facing blinds being up. It is noted that HEM appears to marginally over-predict these solar gains which aligns with the under-prediction of space heating electricity consumption during the same periods.

Overall, there is considered to be a good fit between the modelled and measured space heating energy consumption and internal temperature data averaged over the experiment as shown in Table 7, as well as in the profiles shown in Figure 2 to Figure 5. Ventilation energy consumption is the only exception, which is likely to relate to uncertainties associated with the installed mechanical ventilation system and the test conditions.

Experiment 1, Test Condition 3

For Experiment 1, Test Condition 3, heating is turned on and off at random times for periods of random length. Figure 6 and Figure 7 show the average hourly electricity consumption for Plot N2 and Plot O5 space heating respectively. Note for both plots, which have identical heating patterns, there is a close match between the predicted and measured electricity consumption such that it is generally difficult to see the measured data on the plot.

Figure 8 and Figure 9 show the average hourly internal air temperature for Plots N2 and O5 respectively. The plots have different solar shading arrangements.

Figure 6: Average space heating hourly electricity consumption, Plot N2, Experiment 1, Test Condition 3

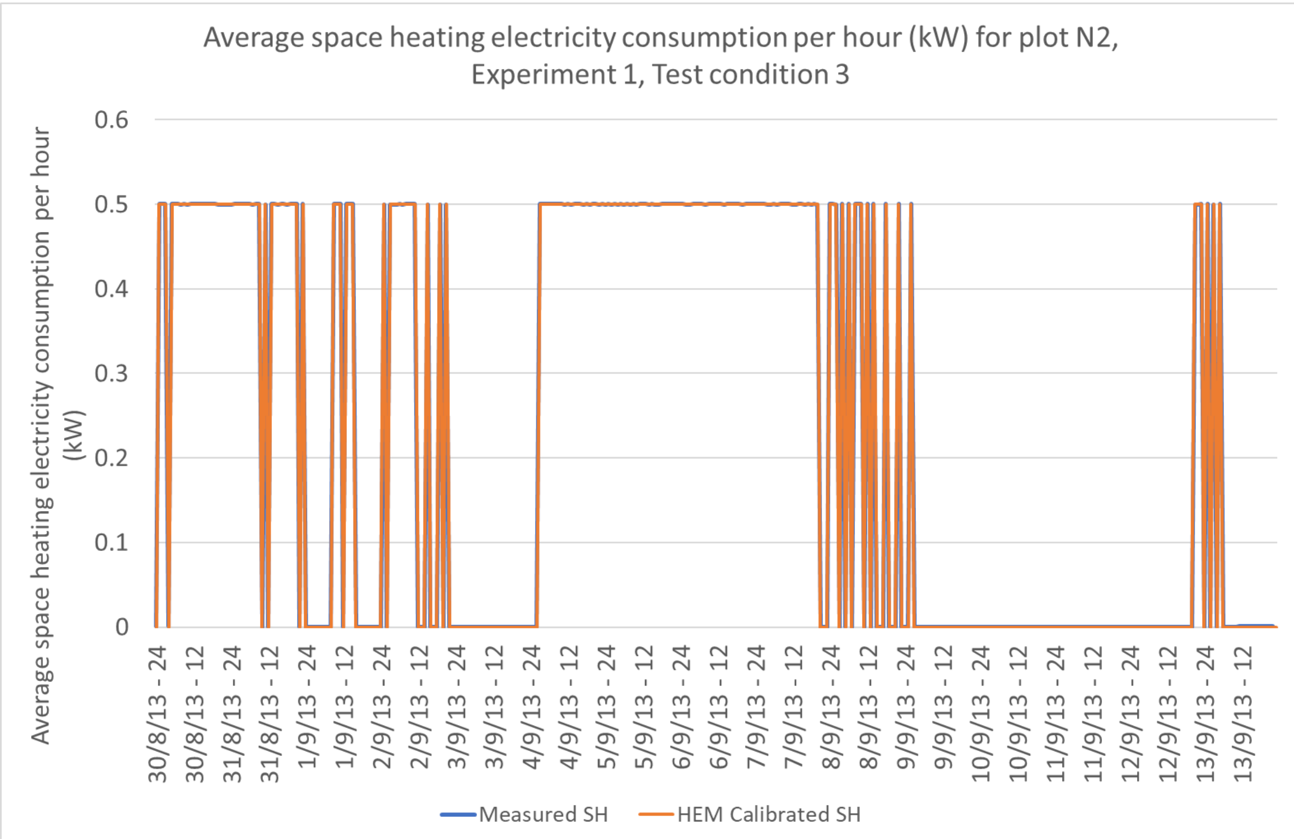


Figure 7: Average space heating hourly electricity consumption, Plot O5, Experiment 1, Test Condition 3

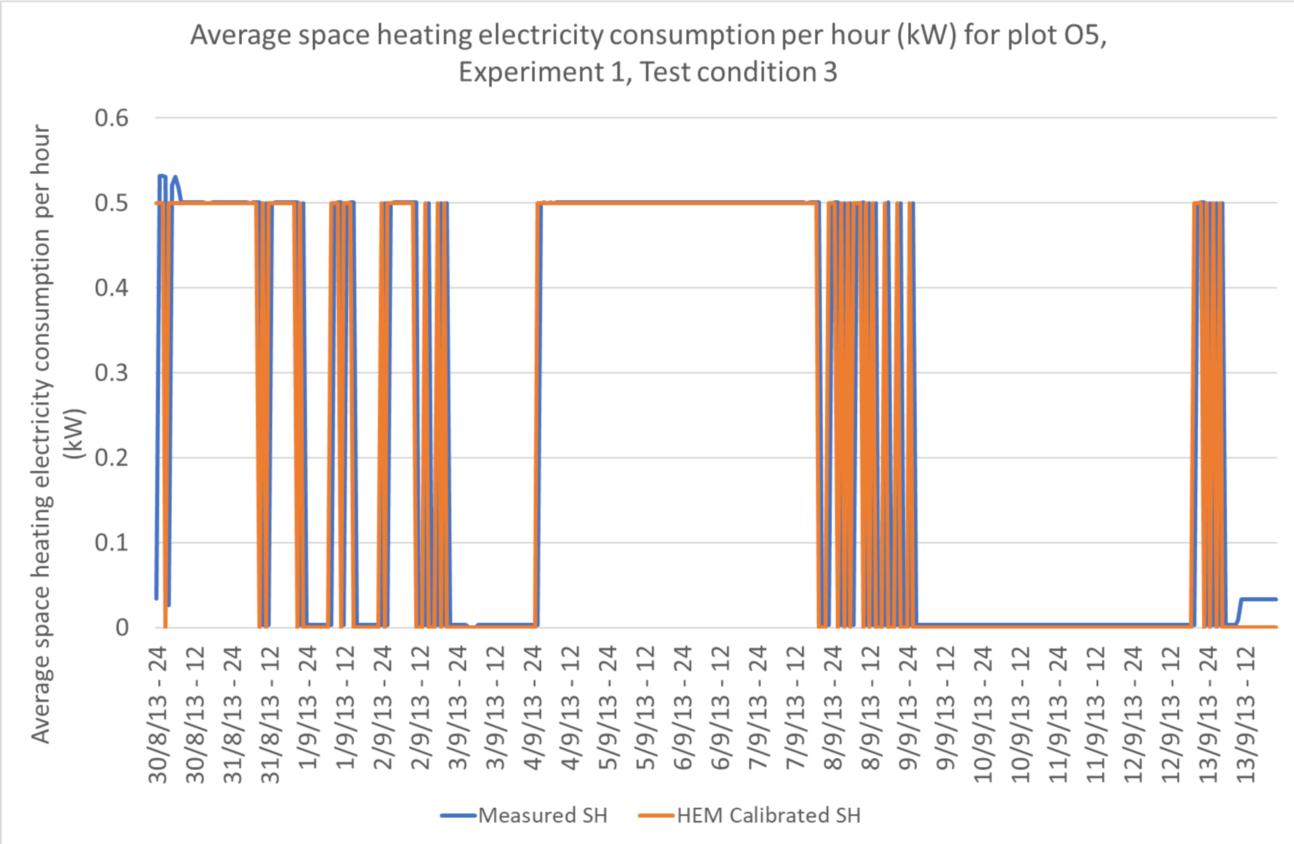


Figure 8: Average hourly internal air temperature, Plot N2, Experiment 1, Test Condition 3

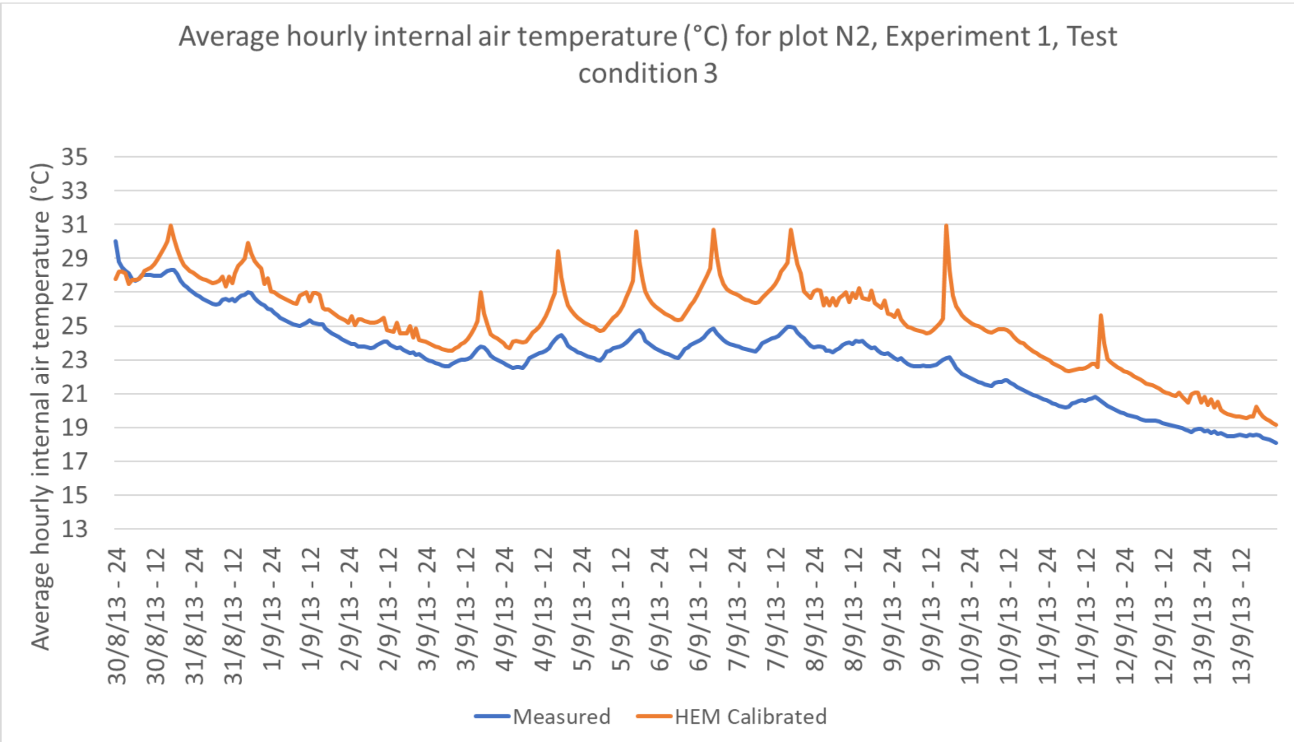


Figure 9: Average hourly internal air temperature, Plot O5, Experiment 1, Test Condition 3

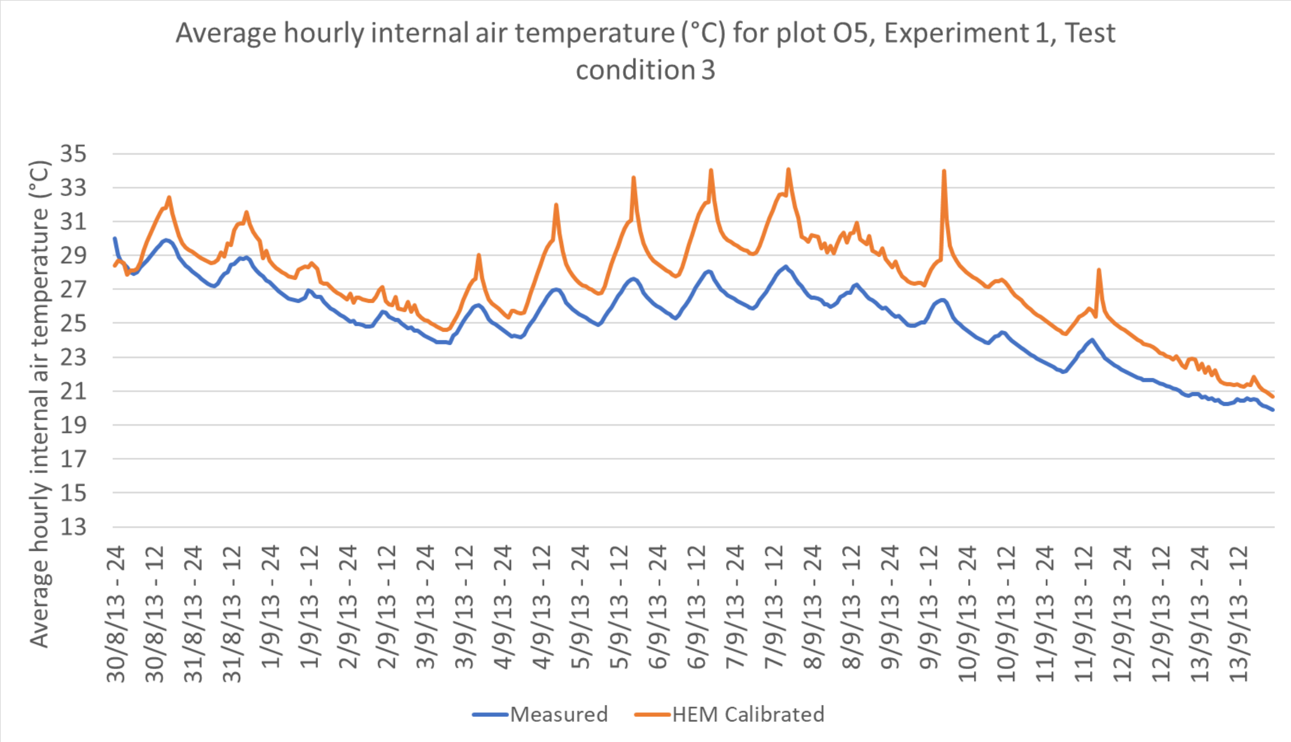


Figure 6 and Figure 7 highlight that the space heating electricity consumption for both the measured and HEM modelled plots are very close, which shows that the complex heating pattern was correctly set up in the model. Figure 8 and Figure 9 do show differences in internal temperatures – the timing of these peaks appears to imply that they primarily relate to solar gains and with contribution from external air temperature; the peaks consistently occur in late afternoon, lagging these sources of gains, as would be expected.

Contributors to solar gains related differences may include the following:

- The manufacturer's value for the window g-value was used, which was 0.602. In the IEA Annex 58 research, it additionally provided calculation from a window modelling software package called Window 6.3, which referred to standard physical properties of glazing panes from the International Glazing Database, with calculations of g-value according to EN-410[6]. The g-value from this calculation was 0.571, which is 5% less than the manufacturer's value. This may cause some variance between the modelled and measured solar gains.
- The test houses have white painted walls and no furniture inside the rooms. This may result in a significant amount of solar gain being reflected straight back outside through the windows, and not being converted into heat. This would have a similar effect to reducing the g-value of the glazing and would result in reduced effective solar gains in the measured house compared to the modelled house. In the HEM, the assumption is that all radiation passing through the glazing is absorbed inside the building. It does not model short-wave radiation being reflected back through the glazing.
- The g-value of glazing is based on solar energy transmittance when solar radiation is normal to the glazing surface. However, the angle of the radiation to the glazing varies continuously throughout the day. The g-value depends on the angle of incidence, and glancing angles result in more reflection and absorption of the radiation, causing a

[6] BS EN 410:2011. *Glass in building. Determination of luminous and solar characteristics of glazing*

reduction in the g-value. ISO standard 52016 has a default 10% reduction of the glazing g-value, which approximates the average reduction in g-value across the day[7]. This 10% reduction is also applied in the HEM model. The actual reduction of g-value in the experiments may differ from 10%, which again may cause some variance between the modelled and measured solar gain.

Variance in thermal mass between HEM and the test houses may be a secondary contributing factor to the differences observed. The HEM models thermal mass according to ISO 52016-1:2017, with thermal mass distributed in three layers, according to whether the thermal mass was externally facing, inside the element itself, or internally facing[8]. A "mass distribution class" is then assigned to select how the thermal mass is distributed in the element. This is a simplified model, which may not be able to reflect all aspects of thermal energy storage in the construction element, and in some circumstances the modelled temperatures could diverge from reality.

The impact of solar gains appears to be greater in O5 compared to N2, likely because of the south facing blinds in O5 being up. Solar gain differences also appear to be driving divergence between the datasets during the longer periods of constant heating, for instance the period starting on 4/9/13. HEM's increased solar gains appear to accumulate between the daily cycles to increase and maintain the difference from measured data.

When the heating system was forced to follow the ROLBS pattern, the modelled internal temperature demonstrated all the features of the modelled data, however, with higher temperatures (additional gains) and larger amplitude. These differences may be explained by aspects related to the solar gains and thermal mass not being sufficiently well reflected in the inputs to the model. However, the relative contribution of these factors and potential for contributions from other factors remains uncertain.

Experiment 1, Test Condition 4

Test Condition 4 re-initialised the experiment to a constant set-point of 25°C. It resulted in similar results for the measured and HEM model, with measured electricity consumed reasonably accurately recreated in the HEM results, however, the variances are the largest for space heating amongst the dataset as shown by Table 7. These largely occur during the initial period, which involves an irregular spike in heating in order to reheat the dwellings to 25°C, following the final period of the previous test condition which had no heating. A closer match might be obtained if further calibration was undertaken, but the existing fit is considered to be reasonable in this context and no further work is proposed. As both plots had south facing blinds down, the internal air temperature for plots N2 and O5 aligned with the 25°C heating

[7] BS EN ISO 52016-1:2017. *Energy Performance of Buildings - Energy Needs for Heating and Cooling, Internal Temperatures and Sensible and Latent Heat Loads - Part 1: Calculation Procedures.* 'Table B.43 — Factors related to the solar energy transmittance'.

[8] BS EN ISO 52016-1:2017. *Energy Performance of Buildings - Energy Needs for Heating and Cooling, Internal Temperatures and Sensible and Latent Heat Loads - Part 1: Calculation Procedures*. Section 6.5.7 'Type of construction dependent properties of the nodes'

setpoint, although slight variance in the measured temperature may be caused by solar gains in other parts of the building where blinds were up.

There is a reasonable fit between the modelled and measured space heating energy consumption and average internal temperature data averaged over the experiment as shown in Table 7.

Experiment 1, Test Condition 5

For Experiment 1, Test Condition 5, the heating was turned off and so there is no space heating energy consumption data. Figure 10 and Figure 11 show the average hourly internal air temperature for Plots N2 and O5 respectively.

Figure 10: Average hourly internal air temperature, Plot N2, Experiment 1, Test Condition 5

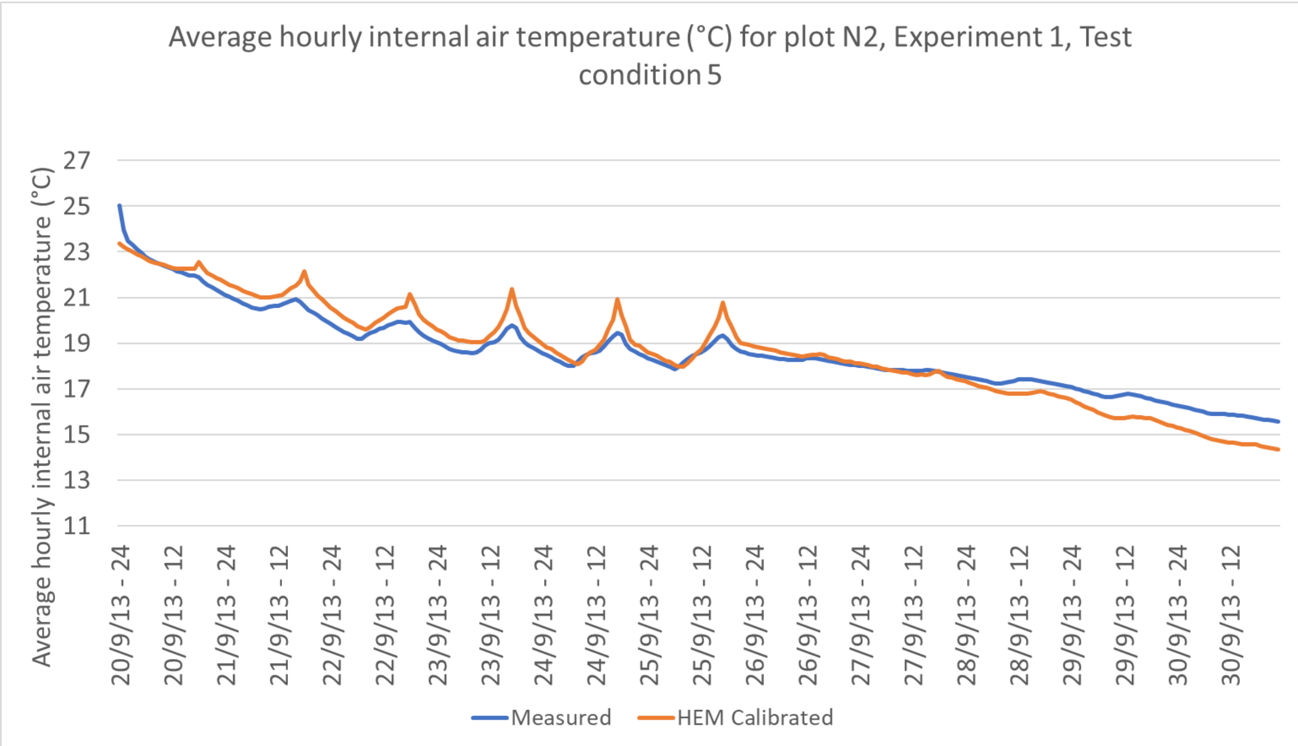
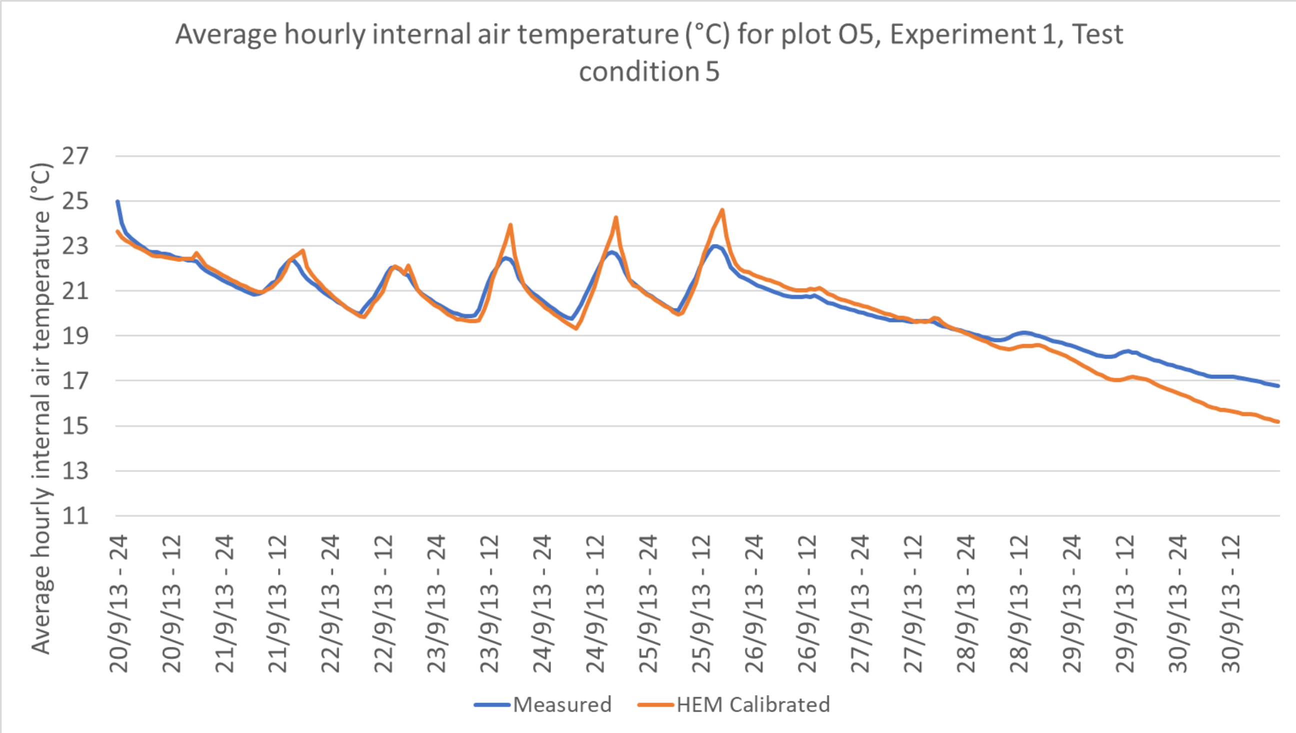


Figure 11: Average hourly internal air temperature, Plot O5, Experiment 1, Test Condition 5



The air temperature initially shows daily oscillations during periods of relatively high solar heat gains. For both plots, the HEM oscillations are greater than that of the measured data – as in previous test conditions, HEM is predicting a greater impact of solar gains.

After this period, the temperatures continue to fall, and the HEM data and the measured data appear to diverge towards different temperatures around 1°C-2°C apart. By comparison to Experiment 2 Test Condition 4, as shown by Figure 13, it can be inferred that the unheated basement treatment in the HEM model may be primarily responsible for the divergence; the main difference in conditions is that the basement is unheated in this case and Figure 13 shows a better fit when the basement is heated.

The unheated basement is an unheated space, which is partially protected from outside weather. As highlighted earlier, the model allowed for the basement by modifying the ground floor U-value to account for the higher temperature in the basement than the external air temperature. This correction factor was based on the unheated basement having an average air temperature of 18.5°C during Experiment 1. One possible source of uncertainty is that Experiment 1 extended from 21st August 2013 to 30th September 2013. Hence, during this test condition, the air temperature in the basement may have differed from the average and hence the corrected U-value should be different for this period.

Furthermore, the internal air temperatures have different starting conditions with HEM around 1°C-2°C below the measured data at the beginning of the test condition.

There is a good fit between the modelled and measured average internal temperature data averaged over the experiment as shown in Table 7. The differences in temperature towards the end of the test condition are expected to principally arise from an unheated

basement in the test house which was only indirectly accounted for in the model through modification of the ground floor U-value. However, the relative contribution of this factor and potential for contributions from other factors remains uncertain.

Experiment 2, Test Condition 1

Note that Experiment 2 was applied to Plot O5 only.

Experiment 2, Test Condition 1 was similar to Experiment 1 Test Condition 1. It produced similar data for the measured and HEM model, with measured space heating energy consumed reasonably accurately recreated in the HEM results. The internal air temperature of zone 1 (set to 30°C) and zone 2 (set to 22°C) averaged over the ground floor to around 25°C as anticipated.

The ventilation electricity consumption has similar characteristics to the data in Experiment 1, with HEM data constant and the ventilation data variable; however, in contrast to Experiment 1, HEM overpredicts rather than underpredicts the ventilation electricity consumption. As for Experiment 1, this difference is likely to relate to differences in air flow and ventilation efficiency between the model inputs and the actual experimental set-up. The issues identified here were reflected in the ventilation electricity consumption results for the whole of the Experiment 2 and no additional analysis is presented for the other test conditions.

There is a good fit between the modelled and measured space heating energy consumption and average internal temperature data averaged over the experiment as shown in Table 7.

Experiment 2, Test Condition 2

Experiment 2, Test Condition 2, shows similar features to Experiment 1, Test Condition 3, with the heating turned on and off at random times for periods of random length.

The space heating electricity consumption for both the measured and HEM modelled plots are close. The air temperature data shows solar gains driving oscillations in internal air temperature, which are accentuated in HEM indicating its increased sensitivity. During longer periods of heating, the solar gains drive divergence between the HEM data and measured data, which last for the majority of the period. Potentially reasons for this difference were discussed in Experiment 1.

When the heating system was forced to follow the ROLBS pattern, the modelled internal temperature demonstrated all the features of the modelled data, however, with higher temperatures (additional gains) and larger amplitude. As discussed in Experiment 1, this may be due to inputs to the HEM not accurately representing features which affect solar gains and thermal mass.

Experiment 2, Test Condition 3

Experiment 2, Test Condition 3, was similar to Experiment 1 Test Condition 4, and specified reinitialising the experiment to a 30°C heating setpoint for zone 1, with zone 2 set to 22°C. It produced similar data for the measured and HEM model, with measured space heating energy consumed reasonably accurately recreated in the HEM results.

There is a good fit between the modelled and measured space heating energy consumption and average internal temperature data averaged over the experiment as shown in Table 7.

Experiment 2, Test Condition 4

Experiment 2, Test Condition 4, was similar to Experiment 1 Test Condition 5, with heating turned off. However, in Experiment 1 all of the heating was turned off whilst in Experiment 2 heating to the main southern zone was switched off only, with the northern rooms and basement still heated to 22°C. Figure 12 shows the average hourly electricity consumption for space heating. Figure 13 shows the average hourly internal air temperature.

Figure 12: Average space heating hourly electricity consumption, Plot O5, Experiment 2, Test Condition 4

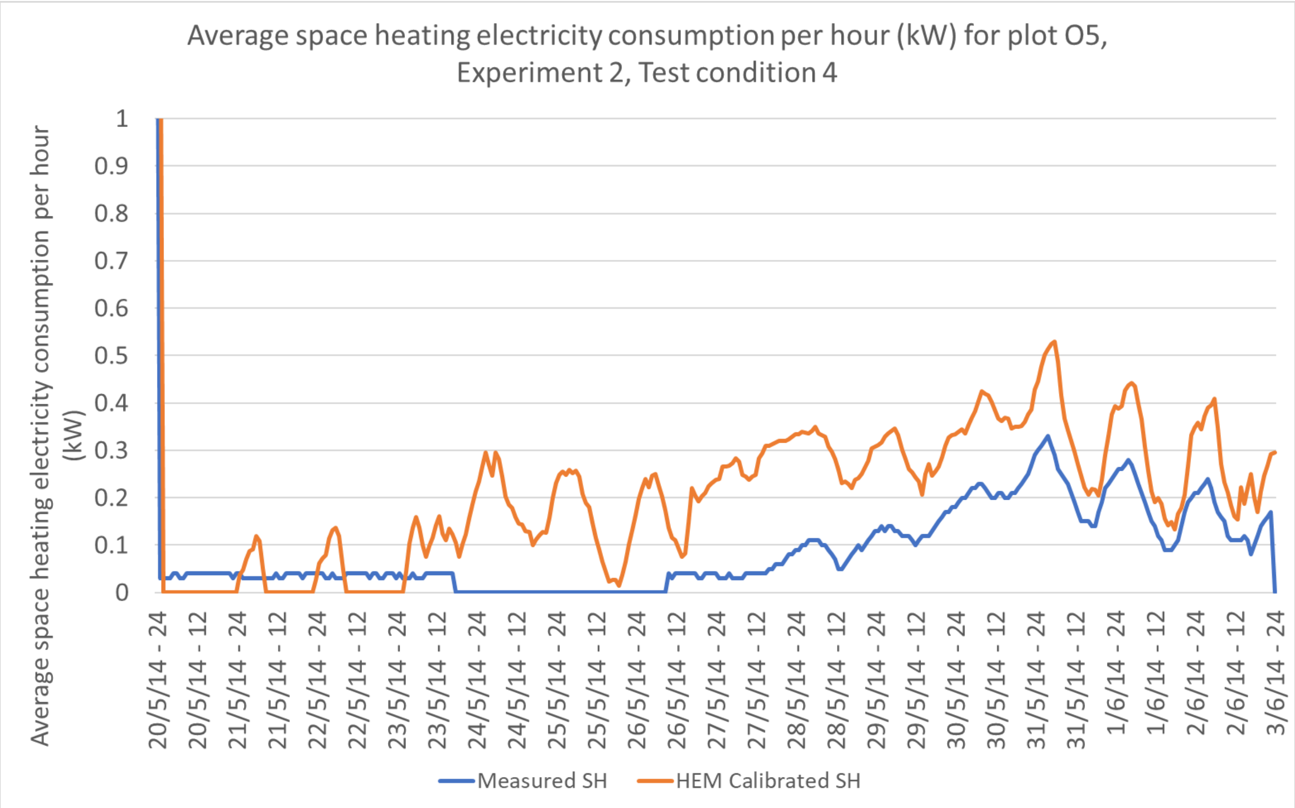


Figure 13: Average hourly internal air temperature, Plot O5, Experiment 2, Test Condition 4

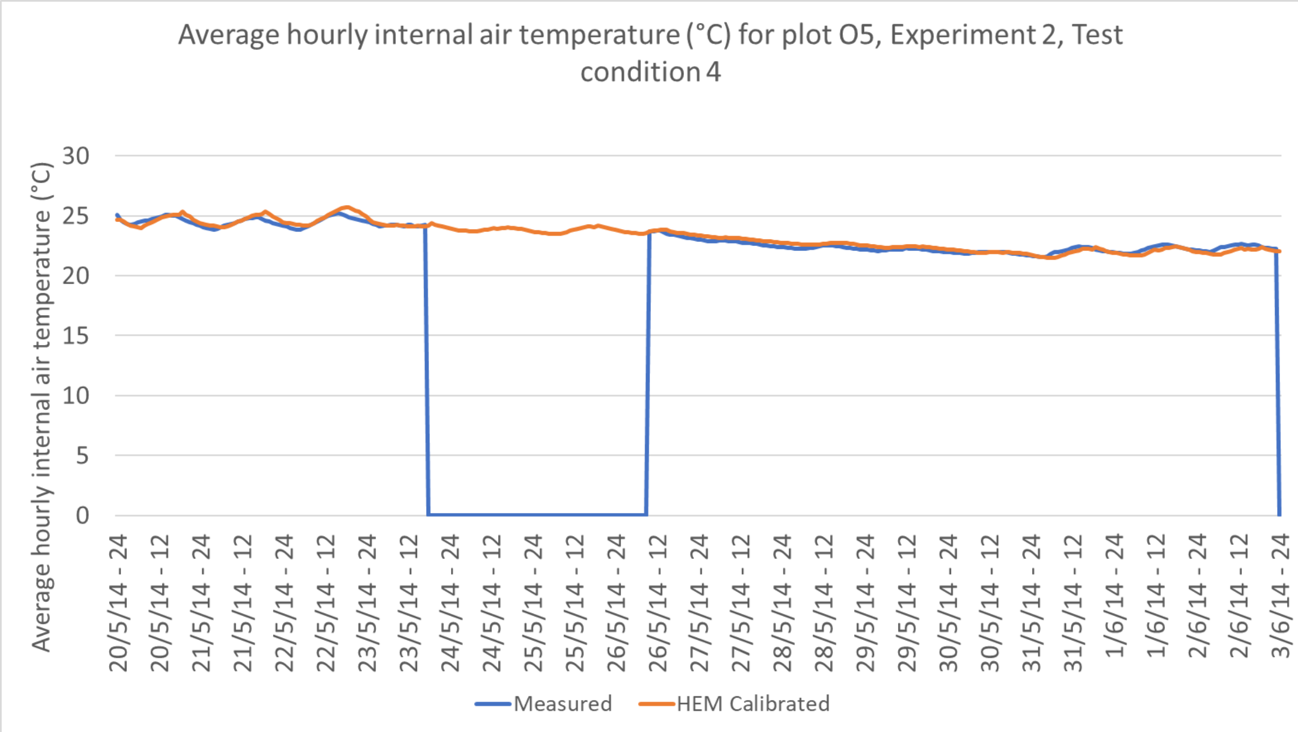


Figure 12 shows that the electricity consumption for heating differs significantly between HEM and measured data. The heating appears to regularly increase during the night, into the early morning, and so may relate to external temperature drops which trigger heating in Zone 2. It appears that the HEM model is more sensitive to this than the measured data, which may relate to thermal mass or other heat transfer issues, such as the lack of interzonal heat transfer. It is noted that the electricity consumption is an order of magnitude smaller than the previous test conditions and the absolute difference here between modelled and measured data is similar to the other test conditions. Figure 13 shows good alignment in air temperature between HEM and measured data (noting the period of measured data loss from 23/05/14 to 26/05/14).

As noted earlier, average dwelling air temperatures are compared between HEM and the measured data. Further work to compare the average zone temperatures could help identify sources of the discrepancy between the HEM predicted and the measured heating consumption.

There is a good fit between the modelled and measured average internal temperature data averaged over the experiment as shown in Table 7. The space heating energy consumption varies by a similar absolute difference to other test conditions, indicating a reasonable match, however, the relative difference is large. This difference may relate to thermal mass or heat transfer assumptions. However, the relative contribution of these factors and potential for contributions from other factors remains uncertain.

Summary across all experiments and conclusions

DESNZ is validating the Home Energy Model (HEM) to ensure its accuracy and reliability in predicting the actual performance of homes. This comprises a range of validation activities covering different aspects of the HEM. This paper describes one of these validation activities.

It is not possible within this validation activity to confirm that HEM correctly predicts the real building performance in the two test houses. Despite the experiments being well-controlled, uncertainties remain, including the accuracy of the input data entered into the model and the accuracy of the measured data. As a result, there will be uncertainties associated with both the HEM predicted results and the comparison measured values. Available information relating to the size of the uncertainties is discussed below. What we can say is that if the uncertainty ranges for both the modelled and measured results overlap, then the results are consistent with the HEM correctly predicting the real building performance in the test houses.

Within the scope of the uncertainties associated with this case study, there is considered to be a good fit between the modelled and measured space heating energy consumption data and the internal temperature data. As confirmed by Table 7, the modelled and measured space heating electricity consumption were within 11% or 0.1kWh/hr[9]. The modelled and measured average internal air temperature were within 2.2°C for the worst matched test conditions, and for the majority of test conditions the agreement was significantly better. The authors consider that such differences could reasonably reflect aspects related to the solar gains, thermal mass and the unheated basement not being sufficiently well entered into the model. See the "Evaluation for each test condition" section for further detail on underlying reasons for differences relating to solar gains and thermal mass (Experiment 1 Test Condition 3) and the unheated basement (Experiment 1 Test Condition 5). Furthermore, the IEA Annex 58 research team estimated the experimental uncertainty in the room averaged air temperature to be in the order of 1°C which limits the fit expected between the predicted and measured data.

The modelled and measured ventilation electricity consumption varied by up to 86%. The differences could be explained by the limited available data on the installed ventilation system which resulted in the model being inaccurately set-up.

The differences identified here could be investigated through further analysis. For example, sensitivity analysis could be undertaken to assess the impact of the uncertainties in the input data on HEM results and confirm that these uncertainties could reasonably explain the differences identified in this study. Data could also be analysed by heating zone, which may inform differences related to the lack of interzonal heat transfer in HEM. Furthermore, we recommend engaging with those involved in the original IEA Annex 58 research who may be able to improve on our understanding of the experimental conditions and model input data.

It is important to note that no model is a perfect representation of reality. The aim is that HEM sufficiently well represents real-world performance for applications of interest.

[9] For Experiment 2 Test Condition 4, the modelled & measured space heating electricity consumption were 102.5% different. However, the absolute difference was only 0.1kWh/h which is a similar magnitude to other test conditions.

This publication is available from: https://www.gov.uk/government/publications/home-energy-model-validation-documentation