Department for
Energy Security
& Net Zero

Comparison of the Home Energy Model to Building for 2050 measured data

Focus on space heating consumption in three 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-04

Document version: v1.0

Issue date: 13/12/23

Home Energy Model version: HEM v0.24

© Crown copyright 2023

This publication is licensed under the terms of the Open Government Licence v3.0 except where otherwise stated. To view this licence, visit nationalarchives.gov.uk/doc/open-government-licence/version/3 or write to the Information Policy Team, The National Archives, Kew, London TW9 4DU, or email: psi@nationalarchives.gsi.gov.uk.

Where we have identified any third-party copyright information you will need to obtain permission from the copyright holders concerned.

Any enquiries regarding this publication should be sent to us at: homeenergymodel@energysecurity.gov.uk

Contents

Introduction

This paper summarises the work undertaken and results from a comparison of the Home Energy Model (HEM) calculations with measured data from three homes that participated in the Building for 2050 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. For comparison purposes, SAP 10.2 calculations have also been carried out.

DESNZ requested that homes monitored in the Building for 2050 research project were used for this validation exercise. The Building for 2050 research project was not designed to validate building simulation models, and as such the data gathered is not detailed enough to provide a comprehensive comparison with the HEM. However, it forms part of a wider comparison exercise with measured data that has both helped with the development of the HEM and highlighted particular sensitivities in the model. The intention is to continue the validation process and identify further case studies better suited to validating the Home Energy Model.

The Building for 2050 case study

The Building for 2050 project[1] was funded by BEIS and is a study of the construction of low-cost, low-carbon homes. One element of this project was the physical monitoring of four case study housing developments. For this validation exercise, three homes were recruited from the Marmalade Lane Cohousing development in Cambridge and the developer and households gave permission for their data to be re-used for this analysis. The other three case study housing developments were considered less suitable for this validation exercise.

The Marmalade Lane development comprises 42 dwellings, a mix of flats and houses, with a shared ‘Common House’ facility. It deploys a fabric-first design with offsite timber panels for houses and paired ‘Tyneside’ type flats, and prefabricated Cross-Laminated Timber (CLT) panels for the main block of flats and the Common House. Low carbon features include a triple-glazed panel system, Air Source Heat Pumps (ASHPs) to supply heating and hot water, and Mechanical Ventilation with Heat Recovery (MVHR). The details of the scheme, including individual heating systems for houses and paired ‘Tyneside’ type flats, are shown in Figure 1. The main block of flats was supplied by a communal heating system with ASHPs. Residents of some homes chose to install solar PV post-completion.

---

[1] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1121448/Building_for_2050_Low_cost_low_carbon_homes.pdf

The Marmalade Lane development is considered to be low carbon relative to the developments built to Part L 2021 and hence may not be representative of the majority of new build homes built to that standard; a key difference is likely to be the use of ASHPs rather than gas boilers supplying heating and domestic hot water.

Eight of the Marmalade Lane households participated in the physical monitoring. Four of these households lived in houses or paired 'Tyneside' type flats, with individual ASHPs which the data suggests were functioning broadly as expected over the monitoring period with no major faults identified. The recruitment for this HEM validation focused on these four homes. Three of the four households agreed for the use of their data for this HEM validation analysis – these are referred to as Plot A, Plot B and Plot C in this paper. Plot A and Plot C are mid-terrace houses with floor areas of 110 to 120m². Plot B is a mid-terrace ground floor flat with a floor area of 50m².

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

- total electricity consumption, from a secondary incoming electricity meter.
- sub-metered electricity consumption for five separate energy uses: (i) total space heating and hot water, (ii) lighting, (iii) ventilation, (iv) cooking and (v) appliances, and
- internal temperature data.

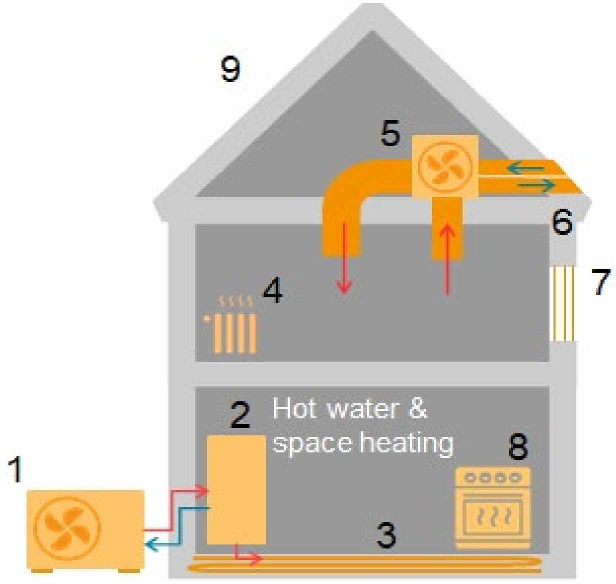
An estimate was made of the split between the electricity consumption for space heating and hot water from the sub-metered data. This is described in Appendix A. The appendix also assesses the uncertainty for this estimated split. The estimate of electricity consumption for hot water includes for storage losses.

Post-occupancy data was typically available for an 18-month period from February 2019 to August 2020 and August 2019 to July 2020 was selected as the annual period for analysis in this report. PV panels were installed at plots A and C and monitoring data was supplied by the residents, using the manufacturers' monitoring systems; however, this has not been included in the analysis, as the data is not as robust and because validating PV generation was not prioritised at this stage of the validation programme. The electricity consumption measured is the electricity used in the homes, whether it comes from PV or the grid. For Plot A only, there was a period of incomplete total space heating and hot water electricity consumption data between March 2020 and July 2020 and data from corresponding months from 2019 was used. The estimated split of hot water consumption from the prior year was used directly, while the estimated split of space heating was adjusted by Heating Degree Days[2] (see the approach in Appendix B) to reflect the differing external temperatures between 2019 and 2020.

---

[2] Heating Degree Days predict the relative change of space heating demand over time periods, accounting for the length of time and the difference between the external temperature and a reference external temperature at which point no heating is assumed to be required.

Figure 1: Marmalade Lane development (houses and paired 'Tyneside' type flats)



1. Air source heat pump
2. Cylinder and buffer tank
3. Underfloor heating
4. Radiators in upper storeys with thermostatic radiator valves (TRVs)
5. MVHR unit
6. Timber frame
7. Triple glazing
8. Electric cooking
9. Plots A and C have PV (installed post-construction)

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 A to C during the monitoring period. The calibration refers to modifying assumptions

that form part of the Future Homes Standard (FHS) wrapper[3] so as to better represent known actual conditions - we did not modify any core HEM assumptions. For each plot, we independently calibrated for weather, occupancy, and space heating regime, and then combined the three separate calibrations into a fully calibrated model.

The Building for 2050 monitoring study was not developed with the intention to validate HEM. Hence, reasonable estimates are included for HEM inputs as necessary. Most inputs were based on measured data or manufacturer's data. Where data was considered unreliable or unavailable, default SAP 2012 values (in line with the Building for 2050 team approach) were used instead. Default values were used for the following inputs:

- Thermal bridging
- MVHR specific fan power
- MVHR HR efficiency

An estimate was also made for the heat pump flow temperature (see section on air source heat pump for details).

Other than the calibrations specified in this paper, no inputs were amended later in order to improve the agreement with the measured data.

HEM version 0.22 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 regards to the modelling carried out in this report.

Information used in the HEM models

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

A feature in HEM allows modelling of the opening and closing of windows for temperature control. A standard control was included in all models where windows are allowed to open outside of the heating season to maintain a 24°C set point. The set point was chosen based on measured internal air temperature in the summer months. Windows are assumed to remain closed during the heating season.

Details of the performance of the building components were provided by the Building for 2050 project. This was based on the developer's SAP input files. This information was modified by available information on the actual performance of the building components. This comprised a combination of observations of the development during construction and completion and measurements on other plots in the development by the Building for 2050 project team (as-built airtightness measurements and infra-red thermography for 2 plots, a co-heating test for 1 plot, heat flux measurements for 2 plots for different fabric elements to provide U-values,

---

[3] 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.

mechanical ventilation flow rates for 2 plots). There were no post-completion testing results measured by the Building for 2050 project team for any of the 3 plots (Plots A to C) aside from the air tightness testing and ventilation commissioning undertaken by the developer to satisfy Building Regulations.

Some further details of the performance values used are provided below. A potential future analysis would be to evaluate the impact of the uncertainty in many of these parameters on HEM results as these parameters were not directly measured for the three plots. This may help explain differences identified later between the HEM calculated results and the measured data.

Thermal mass

Thermal mass is the default value assumed by HEM, plus the thermal mass of the internal walls.

- HEM 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)
- Default values of areal heat capacity of the walls for timber construction were used, as taken from Table 21 “Default values for internal effective heat capacity”, BS EN ISO 52016-1:2017. There was insufficient data on the wall construction to calculate directly.
- Although the convention in HEM predecessors such as SAP was not to include internal walls, the thermal mass of internal walls was included to better represent the actual thermal mass of the dwellings. A more accurate thermal mass produces better predictions of hourly temperature profiles, and can improve prediction of space heating demand. A better prediction of temperature profiles could be necessary for energy flexibility modelling, indicating the times of day when heating is needed. It also provides a better comparison and validation of HEM with the Building for 2050 real-world data.

Thermal bridging

Thermal bridging at Marmalade Lane was assessed by the developer and reflected in the developer’s SAP input files with y-values for Plots A, B and C of 0.096 W/m²K, 0.082 W/m²K and 0.133 W/m²K respectively. Additional thermal bridging issues were observed by the Building for 2050 project team on site. As a result, the HEM models used the SAP default y-value of 0.15 W / m² K.

Floor U-value

The onsite measured floor U-value of 0.17 W / m² K for a plot built to the same construction was used. This was measured by the Building for 2050 project team. The ground floor is a solid floor. The external perimeter and the U-value were together used to derive the other parameters needed for the ISO ground floor thermal transmittance calculations.

Wall U-value

The onsite measured external wall U-value of 0.17 W / m² K for a plot built to the same construction was used. This was measured by the Building for 2050 project team. Party walls were assumed to have a U-value of 0 W / m² K, since there is expected to be no significant heat flow across the party walls in the type of construction used.

Window U-value

For windows, the manufacturer's factory measured U-value of 1.2 W / m² K was used.

Glazing g-value

For glazing g-value, the manufacture value of 0.57 was used. The HEM models did not include corrections for dirt on glazing, or for the use of curtains and blinds.

Air permeability

Air permeability was taken from a sample house measured at 6.5 m^3/hm^2 @ 50Pa. This was taken by the Building for 2050 project team from a different plot of the same development. It was assumed that all plots A, B and C had the same air permeability, but there is some uncertainty due to lack of project team controlled air permeability tests for the individual plots.[4]

Air source heat pump

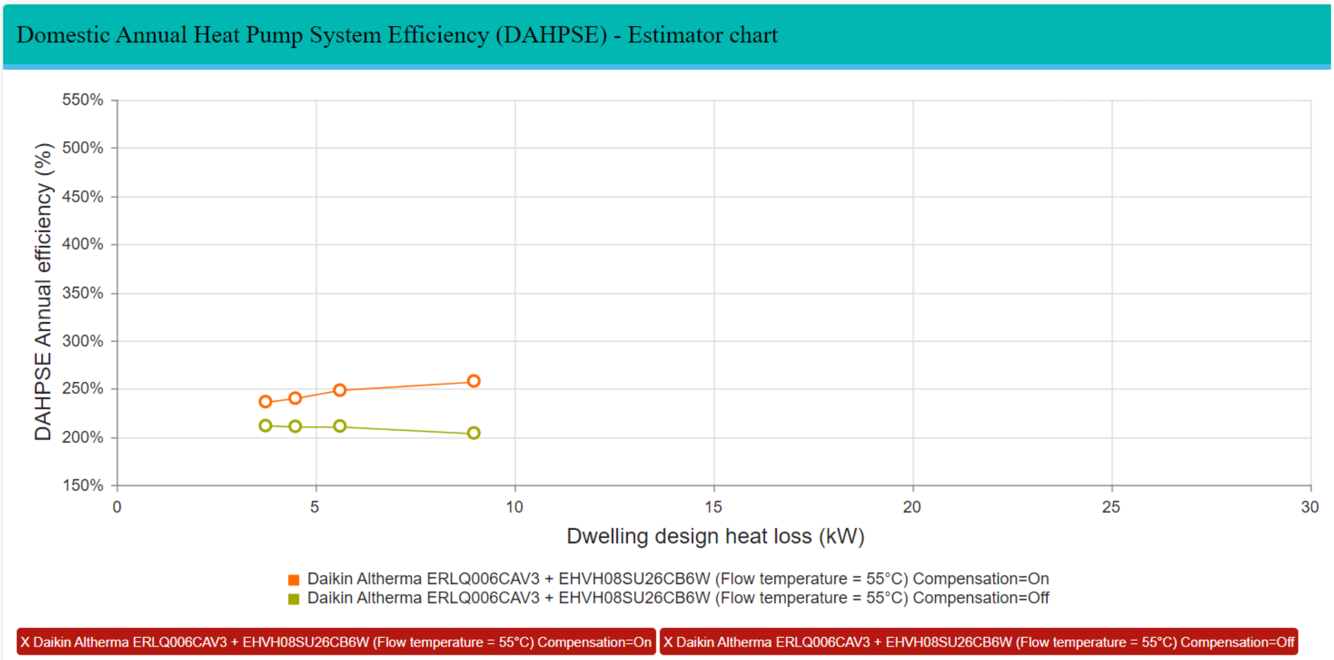
The modelling team attempted to obtain PCDB configuration data to use in HEM for the exact heat pump used in the homes, which was ERLQ006CAV3 + EHBH08CB3V, 5.223 kW, PCDB entry 102242. However, this was not available at the time, and so the installed Daikin Altherma air source heat pump was matched to the closest available product in the Product Characteristics Database (PCDB)[5]. The heat pump used for modelling had the same outdoor unit, but a different indoor unit, with a lower maximum output of 4.490 kW (i.e. 0.73kW lower). The flow temperature was 55°C based on design review. It should be noted that the differences between the manufacturers data as reflected in the PCDB and the actual operational conditions is a potential source of significant uncertainty.

In the BRE tool, Domestic Annual Heat Pump System Efficiency (DAHPSE), it shows an Estimator Chart for this heat pump model. The chart below shows a potential range of efficiencies with the expected seasonal efficiency at around 250%. If weather compensation is not correctly set up, its efficiency could be lower, by up to 50% (around 200% seasonal efficiency). The impact of potential variation in actual air source heat pump efficiency could be investigated in future uncertainty analysis as identified earlier.

---

[4] The Developer's air permeability tests were also available for each plot, but these tests differed from the measurement taken at the sample house. The Building for 2050 project team therefore suggested that the sample test be used for this comparison exercise.

[5] The actual installed heat pump model is not available in the PCDB, so could not be used for HEM modelling. For the HEM model, a similar substitute model was used, which is: Daikin Altherma ERLQ006CAV3 + EHVH08SU26CB6W. The PCDB record is at https://www.ncm-pcdb.org.uk/sap/pcdbdetails.jsp?pid=31&id=102654&type=362&mid=020045.



Emitters

The number of radiators and area of under floor heating available in architectural drawings were used to derive the emitters thermal mass (kWh/W), constant and exponent from characteristic equations of emitters as defined under BS EN 442 tests. The HEM uses these input values to determine the heating output power of each emitter type. A summary of the inputs is provided in table below.

Table 1: Summary of emitters type and associated HEM inputs

	Plot A		Plot B		Plot C	
Zone	Living	Rest of dwelling	Living	Rest of dwelling	Living	Rest of dwelling
Emitter type	Underfloor heating	Radiators and underfloor heating	Radiators	Radiators	Underfloor heating	Radiators and underfloor heating
Thermal mass (kWh/K)	0.984	0.102	0.046	0.029	1.068	0.138
Exponent	1.100	1.314	1.340	1.340	1.100	1.310
Constant	0.063	0.033	0.020	0.012	0.068	0.040

The Exponent and Constant are values that determine the heating power output of the emitter. The relevant ASHRAE equation is for ‘Corrections for Nonstandard Conditions’:

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

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. 1.1 for floor heating, 1.2 for cast-iron radiators, 1.42 for convectors

Zone control for heating systems

Zone control for heating systems was based on two zones, for living and non-living areas. The heating setpoints were set to observed temperatures in these zones. (See section on heating calibration for more explanation.)

MVHR

Within the Building for 2050 study, air flow rates for the MVHR units were measured by the Building for 2050 project team in two other homes on the development. For one of the homes, the minimum Part F requirements were met. For the other home, the air flow rate was measured as 10% below the minimum Part F requirements. For this modelling exercise, the MVHR air flow rate for each plot was based on the minimum requirement in Part F.

The installation of MVHR included some complicated and lengthy duct work. As a result, for the purpose of this analysis, a Specific Fan Power (SFP) of 0.85 W/l·s and an efficiency of 70% were used i.e. SAP default values. There is some uncertainty due to lack of specific data for these plots and the use of default values. Plot C has much shorter intake and exhaust ducts than Plots A and B, so it is possible that Plot C in particular had greater MVHR efficiency than assumed here.

The MVHR model installed is the Nuaire MRXBOXAB-ECO4[6]. The stated SFP and efficiency from its PCDB entry is respectively 0.66 W/l·s and 93% for Plots A (three wet rooms), 0.62 W/l·s and 93% for Plot B (two wet rooms), and 0.79 W/l·s and 92% for Plot C (four wet rooms).

The values used for each plot are shown in the table below. The actual lengths of the MVHR ductwork were input into the HEM model. All ductwork in the plots was inside the dwellings. Plot B had long ductwork due to the MVHR unit location in the centre of the flat with various duct bends before reaching the outside. Insulation thermal conductivity values for the specified ductwork insulation were also input. Note that the efficiency drop from design of supply and extract ducts are not modelled in HEM.

---

[6] Its PCDB entry is at https://www.ncm-pcdb.org.uk/sap/pcdbdetails.jsp?pid=34&id=500502&type=323&mid=020003.

Table 2: MVHR parameters used for Plots A, B and C

	Plot A	Plot B	Plot C
Required Part F ventilation rate (l/s)	37	19	41.73
MVHR SFP (W/l.s)	0.85	0.85	0.85
MVHR efficiency	0.7	0.7	0.7
Intake duct length (m)	1	7.5	1.5
Exhaust duct length (m)	1	5.75	1.5

Hot water pipework

The actual lengths of the primary hot water pipework between the ASHP internal unit and the domestic hot water cylinder were input into the HEM model. Insulation thermal conductivity values for the specified pipework insulation were also input.

Lengths of distribution hot water pipework from the cylinder to hot water outlets were estimated from architectural drawings. In the absence of further information, the same insulation thermal conductivity and insulation as primary pipework was input for the secondary hot water distribution pipework.

Table 3: Hot water pipework length

	Plot A	Plot B	Plot C
Primary pipework length (m)	13.25	7.5	13.25
Secondary distribution pipework length (m)[7]	21.0	8.0	48.0

Calibration

HEM calculations and predecessors such as SAP 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, in the FHS assessment wrapper, the weather is based on the CIBSE Leeds weather file, and this can significantly differ from local conditions.

---

[7] Secondary distribution pipework length includes the total length of pipework between the cylinder and each hot water outlet.

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 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.

Run 2: Weather calibration

The UK average weather data was replaced with a customised hourly local weather data file for the monitoring time period of the Building for 2050 study.

- The Building for 2050 project measured the external temperature. There was onsite monitored external temperature data available for most of this period. There were a few gaps in the temperature data which were sourced from Meteomatics Ltd, for the Cambridge weather station. It is noted that the monitored average external temperature in the winter was 7.86°C during the monitoring period of 1st August 2019 to 31st July 2020. The default weather file used for the FHS assessment wrapper is the CIBSE Test Reference Year for Leeds. By comparison, it has an average winter temperature of 4.50°C which is 3.36°C lower than that of the Building for 2050 data.
- The other weather data parameters needed were direct solar radiation, diffuse solar radiation, and wind speed. This data was also sourced from Meteomatics Ltd, for the Cambridge weather station.

The external shading factors for the Building for 2050 site were identified during the weather calibration, and so were added to the weather calibrated and fully calibrated runs. The uncalibrated run does not have this shading in the model. The amount of distant shading can be considered to be reasonably low, and therefore would have a small impact on the results. The external shading factors were estimated from shading obstacles seen on the site plan.

Run 3: Space heating regime calibration

Heating set-points and temperature regimes were specified to be more reflective of the observed conditions within the three Plots.

Daily profiles of internal air temperature measurements averaged over the winter months (November to March) were used to determine set point temperature controls (see Figure 2, Figure 3 and Figure 4). Air temperature measurements were available for the Living area and Master Bedroom for all plots and Bedroom 2 for Plots A and C. In Figure 2 and Figure 4, “ROD” is “Rest Of Dwelling”, which averages daily internal air temperature measurements for the Master Bedroom and Bedroom 2. Relatively sharp increases in temperatures were interpreted as a change in heating set point controls. Slow increases in temperature during the day light hours (around 7am to around 5pm) were attributed to solar and internal gains.

The heating set-point temperatures adopted for different times of day and location are shown in Table 4. This is compared to the standard HEM assumptions. Some potential further review and refinement is suggested in the Summary and Conclusions section.

Table 4: Heating set-point regime

	HEM FHS assessment wrapper	Plot A	Plot B	Plot C
Living area	21°C weekdays between 7am and 9:30am, 4:30pm to 10pm, and weekends between 8:30am and 10:30pm No setback temperature	20.6°C between 6pm and 11pm 19.4°C the rest of the time	20.4°C between 7pm and 1am 19°C the rest of the time	21.7°C between 5pm and 10pm 20.4°C the rest of the time
Rest of dwelling (based on measured data from bedrooms)	18°C weekdays between 7am and 9:30am, 4:30pm to 10pm, and weekends between 8:30am and 10:30pm No setback temperature	19.5°C between 6pm and 11pm 18.6°C the rest of the time	21°C between 7pm and 1am 19.5°C the rest of the time	20.4°C between 5pm and 10pm 19.6°C the rest of the time

Figure 2: Average internal winter temperature for Plot A

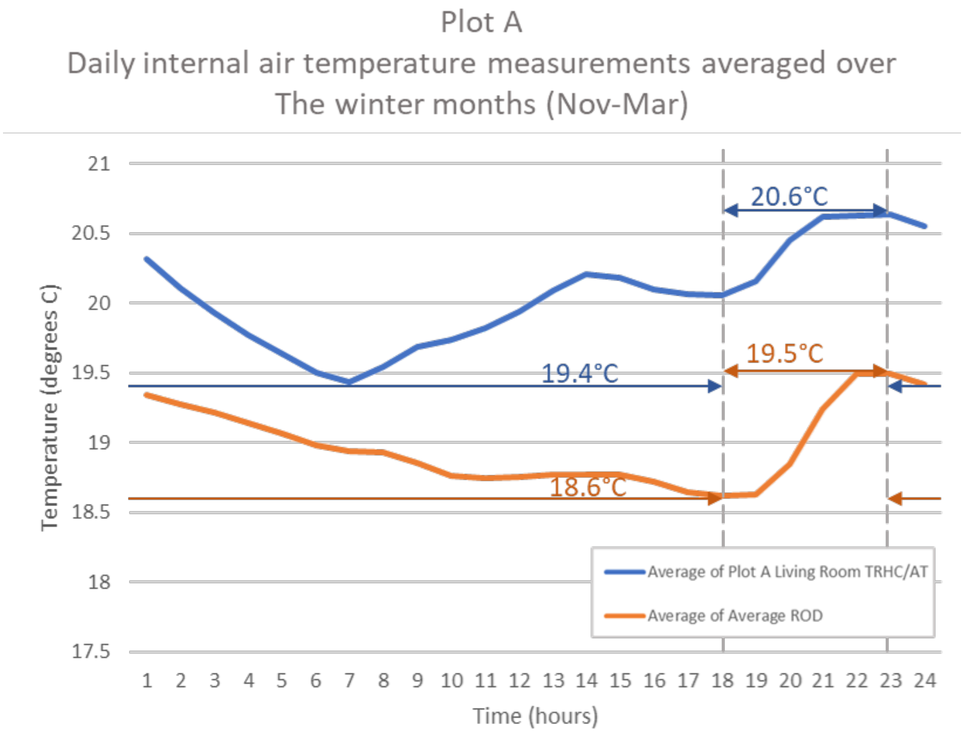


Figure 3: Average internal winter temperature for Plot B

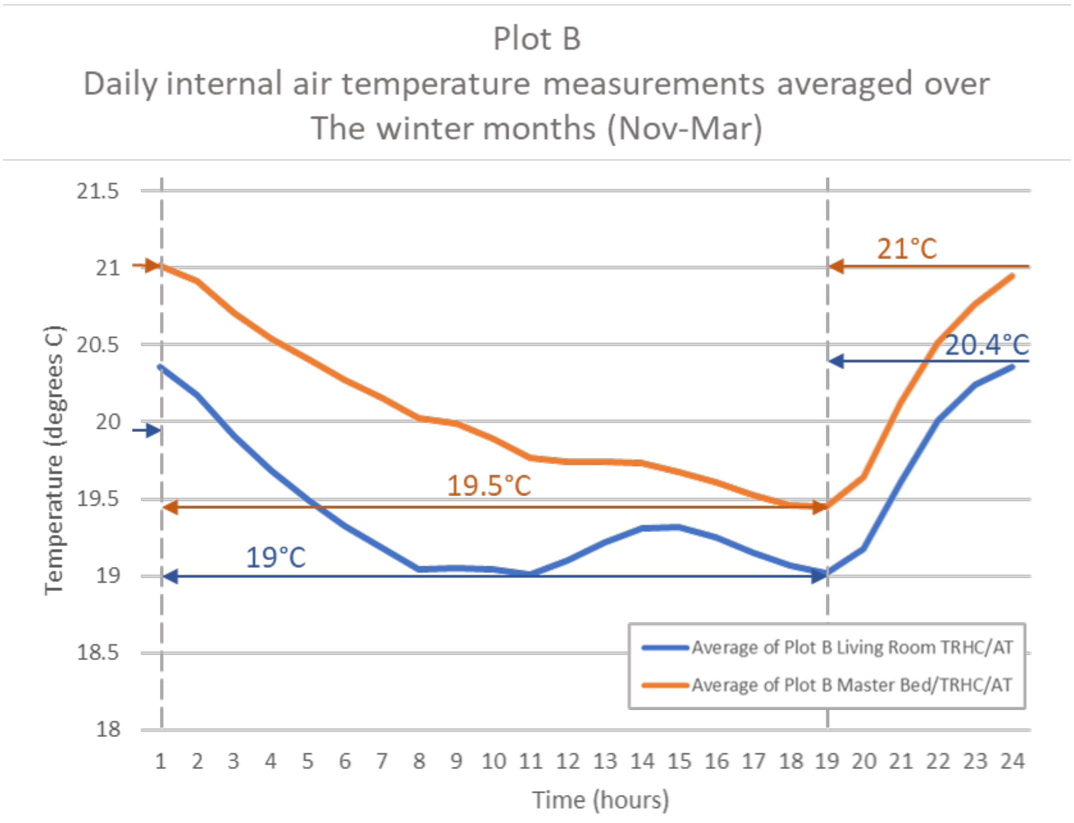
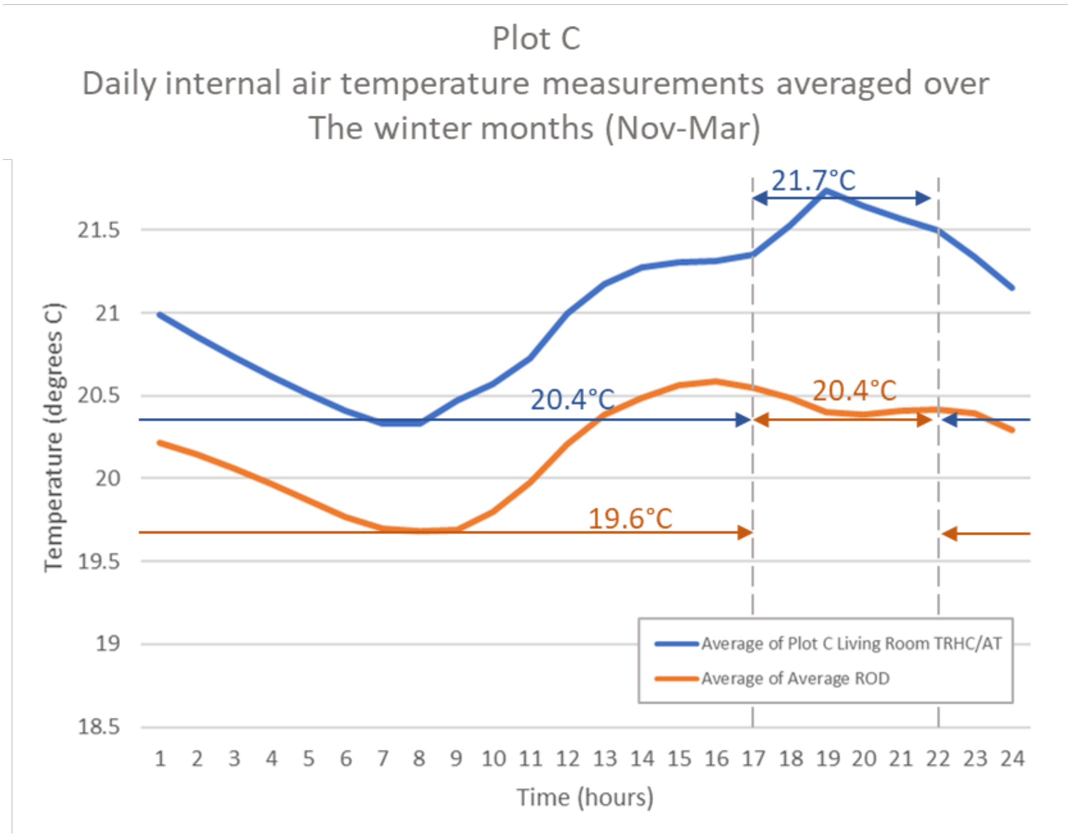


Figure 4: Average internal winter temperature for Plot C



Run 4: Occupancy calibration

Occupants directly influence the energy use in a building through:

- 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

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.

Part L adopts standardised assumptions for occupancy and their related energy uses. In practice, occupant behaviour is very variable between dwellings and can be significantly different from these standard assumptions. It would be necessary to monitor a large population of homes to obtain statistically significant validation regarding whether these standardised assumptions are reasonable.

For the purpose of this validation exercise, to assess the space heating demand predictions in HEM, 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.

The first approach to calibrate for occupancy was to simply change the occupant number, and to let that adjust the associated energy uses and internal heat gains automatically in the HEM algorithms. However, the results from this initial calibration were far from the actual energy usage. Therefore, the simple occupancy number adjustment approach was not used in the final calibration. Instead an approach was taken which calibrates all occupancy-related parameters. The occupancy number then was used only in the metabolic internal heat gains calibration, while other parameters were adjusted based on occupant-specific energy usage.

There have been suggestions that for predecessors to HEM (i.e. SAP), when applied to very low-energy homes, it predicts higher internal gains than used in reality. This suggestion tends to be from anecdotal experience from some low energy homes. These higher internal gains could then sometimes result in SAP predicting that little additional space heating is needed. When higher levels of insulation are in place, space heating demand is reduced. This then automatically means that internal heat gains become a greater percentage of total heat gains from all sources. The impact of small variations in the internal heat gains could therefore be very significant in the Building for 2050 plots. It is therefore even more essential that the HEM models are calibrated with actual internal heat gains, so that validation of space heating usage does not become invalidated by high uncertainty of the internal heat gains.

Details of the approach to calibration are detailed below.

Metabolic gains

The metabolic gains from HEM were adjusted using the actual number of occupants as a parameter to the metabolic gains algorithm as implemented in HEM. However, to simplify update to the metabolic profile in the HEM inputs file, the gains profile was flattened so that gains were defined per month instead of per hour. The monthly input to internal gains was still the same as if an hourly profile was used. The average metabolic gain for each occupant was around 43 W. This resulted in the following metabolic gains for each plot.

- Plot A (4 occupants): 171 W
- Plot B (2 occupants): 86 W
- Plot C (3 occupants): 129 W

There has been an update to the HEM metabolic gains algorithm since these adjusted values were calculated, and the current version may produce slightly different values when adjusting the number of occupants. However, the actual metabolic gains in the plots are unknown, since there was no record of occupancy hours. Hence there is significant uncertainty about the actual metabolic gains.

Cooking energy usage

The actual sub-metered cooking energy use was entered into the HEM model. The HEM engine then calculates the internal heat gains from the actual cooking usage with the cooking usage algorithm. The adjustment was based on the measured values of cooking energy usage, which were reported as a single value averaged for each month.

Appliance energy usage and internal heat gains

The actual sub-metered appliance energy use was entered into the HEM model. Appliances includes all white goods except for cooking appliances. The HEM engine then adds appliance energy use to the internal heat gains based on the measured values of appliance energy usage, which were reported as a single value averaged for each month.

The Home Energy Model does not include all the appliance energy usage as internal gains, since it is assumed that some is lost as waste heat. The appliance gains factor in HEM is 75%, which means that 75% of the appliance energy becomes internal gains.

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. There is no easy way to adjust this, such as varying an input value. Instead, both the temperature of the hot water and the duration of each hot water event were decreased or increased on a trial-and-error basis, until reaching an annual DHW use as close as possible to the estimated energy use. 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 cold water feed profile from the uncalibrated version was kept unchanged. Note that this may mean that exact DHW energy calibration may not be possible. The HEM 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 HEM results to compare to the Building for 2050 measured data.

The following aspects of HEM 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

These aspects of HEM listed below can be indirectly validated against predictions of the above, since they are part of the calculations for them:

- Geometrical building definition from input data
- Building construction elements thermal response
- Solar gains calculation
- Air source heat pump energy usage

Comment on the calibration

The case study plots can help validate both the space heating and ventilation demand predictions in HEM. The domestic hot water, lighting and appliances (including cooking) energy demands were modified in HEM to align with the actual energy use. There is insufficient case study data to separately validate these latter energy uses[8].

The core HEM engine does not make any assumptions about energy consumption, and can use any value for energy-related inputs. Instead assumptions that affect energy consumption are made by the FHS assessment wrapper, and the uncalibrated run uses the FHS assessment wrapper assumptions. The calibrated model takes the measured energy consumption as direct inputs, and therefore cannot indicate how lighting and appliance parameters might influence predictions of energy consumption. These parameters might be inputs such as light efficacy, required illumination levels or appliance energy efficiency. For example, there might be a desire to start with a required illumination level and then validate the prediction of the energy consumed as a result. In this case, measurements of both illumination levels and lighting energy consumption would be needed. For this calibration, only lighting energy consumption was available, so such a validation was not possible. There is however

---

[8] The FHS assessment wrapper calculations includes standardised predictions of usage of hot water, lighting and appliances. For effective validation of the standardised predictions, it would need a large sample of homes from a comprehensive survey of household usage patterns.

some potential for indirect validation of conversion of lighting and appliance energy usage to internal heat gains.

Appliance energy consumption is an input parameter to HEM, which is not modified by the engine. In the outputs file, the appliance energy consumption per timestep is based on this unmodified input parameter. Note that HEM does apply a conversion factor to convert appliance energy consumption into internal gains, and the appliance internal gains are then used in the calculation of space heating consumption.

Approach to SAP 10.2 modelling

Information used in the SAP 10.2 models

Much of the information provided under section “Information used in the HEM models” also applies to the SAP 10.2 modelling. Exceptions are provided below.

Note that SAP 10.2 is a monthly model, which means that some calibration elements used in the HEM calibration do not apply here. Furthermore, SAP 10.2 has a pre-defined set of inputs which may not always enable calibration in the same way as used with HEM.

Heat pump

SAP10 uses the same heat pump model and flow temperature as HEM, which means the SCOP efficiency value is the same in both models.

Floor thermal transmittance

SAP 10.2 does not calculate the effect on floor thermal transmittance of seasonal changes in ground temperature below the floor, and therefore does not need to know the underlying soil type.

Zone control for heating systems

Default SAP 10.2 set points were calculated by the engine based on the selected heating controls: smart controls (code 2207 from SAP 10.2 table 4e).

MVHR

As per developer SAP calculations conducted for the Building for 2050 study, the MVHR unit with a PCDB index number 500502 was selected.

The Specific Fan Power given in Table 5 was entered as a measured value. Efficiency, SFP in-use factor and ventilation rate were obtained from PCDB, based on the number of wet rooms and the duct type (rigid).

The inputs and resultant SFP, efficiency and flow rate are summarised in the table below. It is noted that there are some differences to the HEM modelling because SAP 10 has a slightly different approach to HEM, such as defining an ‘in-use’ factor.

Table 5: Summary of MVHR model inputs for SAP10 models

	Plot A	Plot B	Plot C
Number of wet rooms	3	2	4
Ventilation rate used (SAP10 default)	0.5 ACH	0.5 ACH	0.5 ACH
Heat exchanger efficiency (associated with number of wet rooms + value differs to HEM input)[9]	93%	93%	92%
SFP	0.85	0.85	0.85
SFP in-use factor	1.1	1.1	1.1

Hot water pipework

Actual lengths of hot water pipework are not an input in SAP 10.2.

Occupancy

It is only possible to vary the number of occupants as an input into occupancy algorithms. The standardised SAP 10.2 occupancy behaviour profile is still used, which is likely to be very different from the case study homes. In particular, this did not allow for any matching of actual internal gains from appliances, cooking and lighting.

Calibration

Run 1: Uncalibrated model

This adopted the standard assumptions and the UK average weather data as would be used for the current Part L compliance assessment.

Run 2: Weather calibration

Monthly average solar, wind and external temperature profiles were derived from the same weather dataset used for the HEM calibrations.

---

[9] The PCDB efficiencies were used here, unlike the HEM model which used the less efficient default value of 70%. This could be changed to be the same as used in HEM if the models are re-run, but note that the true efficiency in use is uncertain, and could differ from both PCDB and default values.

Run 3: Space heating regime calibration

SAP10 calculates space heating demand based on the average monthly internal air temperature of the house. In a real home, heating will have varying temperatures depending whether the heating is on or off. SAP10 takes an average of these varying temperatures over a whole month, and so internally the calculations in SAP10 do not use on or off heating periods.

The dwelling is divided in two zones: the living area, and the rest of the dwelling. Two different internal air temperatures are calculated for each zone.

The monthly average internal air temperature is influenced by heating controls, as described in SAP 10.2 Table 9, "Heating periods and heating temperatures"[10]. As no existing controls allow us to reproduce the measured internal air temperature, we devised a smart control, allowing us to tweak the heating hours-off and temperature set points to obtain similar monthly average internal air temperatures as those observed in the measured data (Table 6). This method did not allow to obtain a perfect fit; the resultant average monthly air temperatures are summarised in Table 6.

Table 6: Summary of measured and modelled internal air temperatures for the winter months

	Plot A		Plot B		Plot C	
	living area	rest of dwelling	living area	rest of dwelling	living area	rest of dwelling
Monitored average internal air temperatures in degrees C (Oct-Mar)	20.1	19.1	19.6	20.22	21.0	20.4
Modelled average internal air temperatures in degrees C (Oct-Mar)	20.4	19.2	19.6	20.3	20.9	20.4

---

[10] Standard Assessment Procedure (SAP 10), available at https://bregroup.com/sap/sap10/

Run 4: Occupancy calibration

In SAP 10.2, occupancy related gains and hot water usage are derived based on the number of occupants estimated based on floor area. For this calibration, the exact number of occupants was forced upon the calculation.

Run 5: Full calibration

All of the adjustments included in Runs 2 to 4 were combined. This is the main set of SAP10 results to compare to the Building for 2050 measured data. Note that for this run, ‘Full calibration’ is not the same as in the HEM model, since the internal heat gains from appliances, cooking and lighting could not be adjusted to the measured values. Instead, ‘Full calibration’ means as fully calibrated as it was possible to do so by adjusting inputs in the SAP10 models.

Results

Annual energy use

Figure 5, Figure 6 and Figure 7 compare the annual energy consumption for Plots A, B and C respectively. The homes are all-electric and so the energy consumption is all electricity consumption. Each figure shows the uncalibrated and fully calibrated SAP 10.2 results, all five of the HEM 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 the percentage difference of the total annual electricity consumption to that of the Building for 2050 measured results. In particular, this set of graphs shows the impact of each stage of the calibration. The SAP 10.2 output data does not include cooking or appliances; therefore, the percentage difference is not provided as this would not be a like-for-like comparison.

These figures show the impacts of the HEM calibrations, which are described here:

- The weather calibration has milder winter weather than the HEM default weather. As a result, all plots show a similar drop in space heating demand when calibrated for weather.
- For all three plots, the heating pattern calibration tends to predict a slightly higher level of space heating compared to the uncalibrated run. This is expected to be due to differences between the HEM standard heating profile and the calibrated heating profiles (see comparison in Table 4). The heating calibration assumptions were determined by analysing measured internal temperatures (relating to actual occupant heating patterns), which appear to have resulted in the use of more energy on average than the HEM standard profiles. See January weekly average internal temperature profiles in Figure 17, Figure 18 and Figure 19, which provide a visual indication of the level of alignment of the heating profile calibration with the measured data. From these figures it appears that some of the occupants have chosen to adopt a relatively more continuous heating profile than is assumed in the standard profile. As shown by Table 4, some occupants have set higher temperatures outside the living area than is assumed in the standard profile. The occupants do appear to set similar temperatures to the standard assumption for the living area.
- The occupancy calibration results in a significant reduction in electricity consumption. This is largely because the calibration adopts the measured electricity consumption for domestic hot water, lighting and appliances[11]. The corresponding internal gains from these energy uses impacts upon the resulting space heating electricity consumption; in these cases, the reductions in energy loads for these uses and associated internal gains results in increased space heating demand. The space heating system with the calibrated

---

[11] The approach does not achieve an exact match for domestic hot water as discussed in the Approach to HEM modelling section.

occupancy has to input more heat to make up for the reduced amount of heat coming from internal gains.

Note that this is a co-housing development with many residents with a particular interest in being sustainable (co-housing group members were involved in the initial specification and targeted a sustainable design). The residents are expected to be more energy conscious than typical occupants and more likely to have acquired efficient lighting and appliances and used their home in an energy efficient manner.

- The HEM fully calibrated case includes all three of these calibrations and results in the best match for measured space heating electricity consumption. It is also noted that the fully calibrated space heating electricity consumption is fairly similar to the uncalibrated version; this is considered by the authors to be coincidental in this case, with the impacts of progressive calibrations on space heating electricity consumption cancelling each other out.

A comparison of the fully calibrated HEM and SAP 10.2 results are discussed below.

Figure 5: Annual electricity consumption Plot A, August 2019 to July 2020

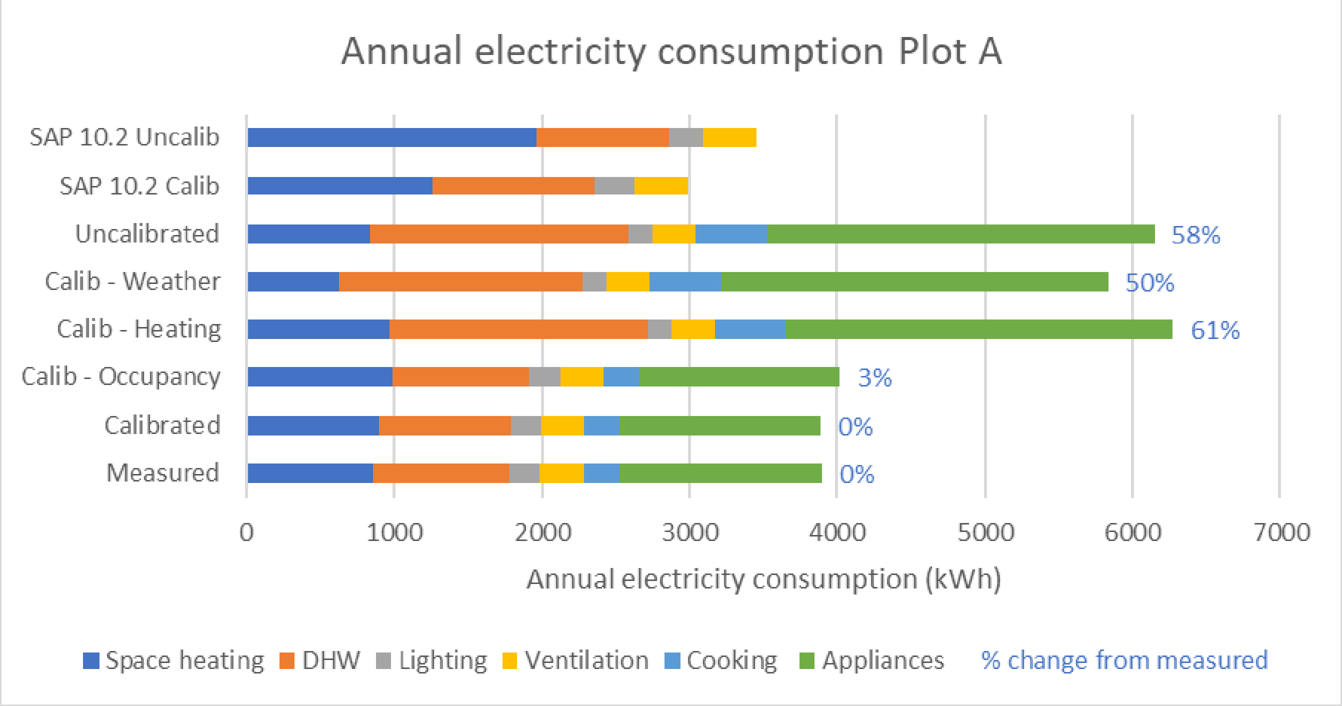


Figure 6: Annual electricity consumption Plot B, August 2019 to July 2020

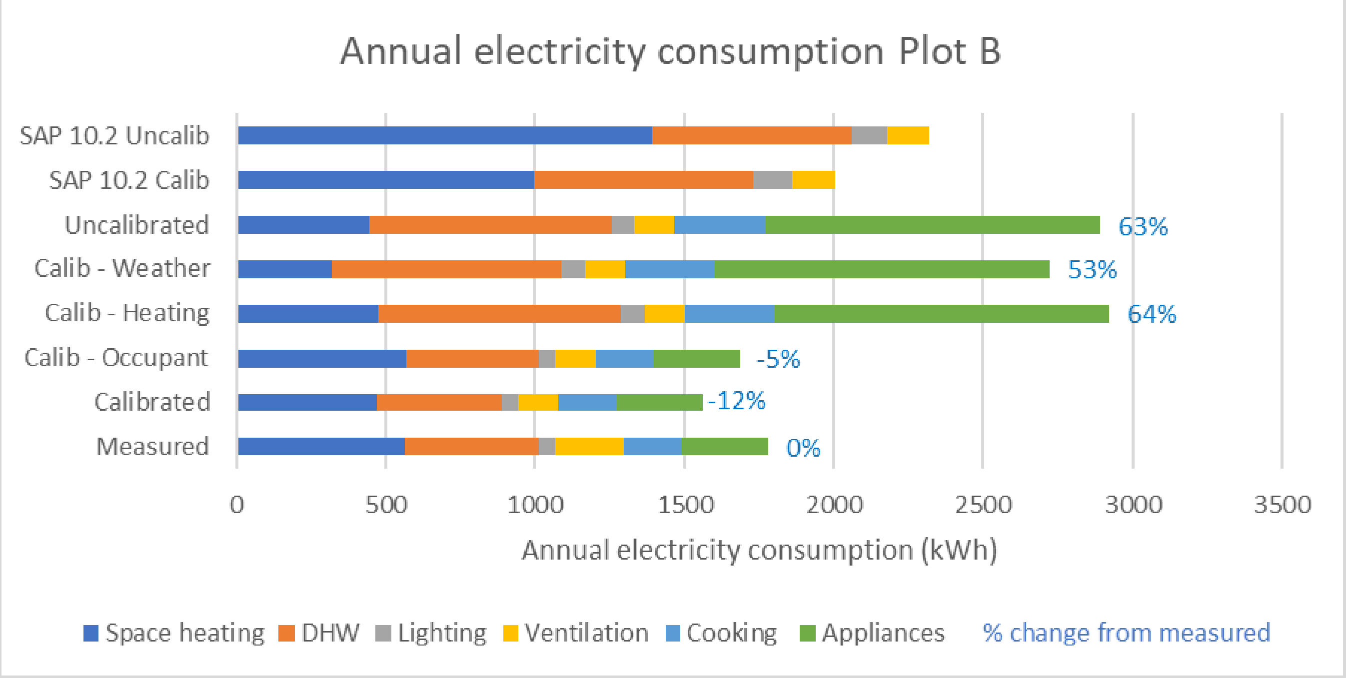


Figure 7: Annual electricity consumption Plot C, August 2019 to July 2020

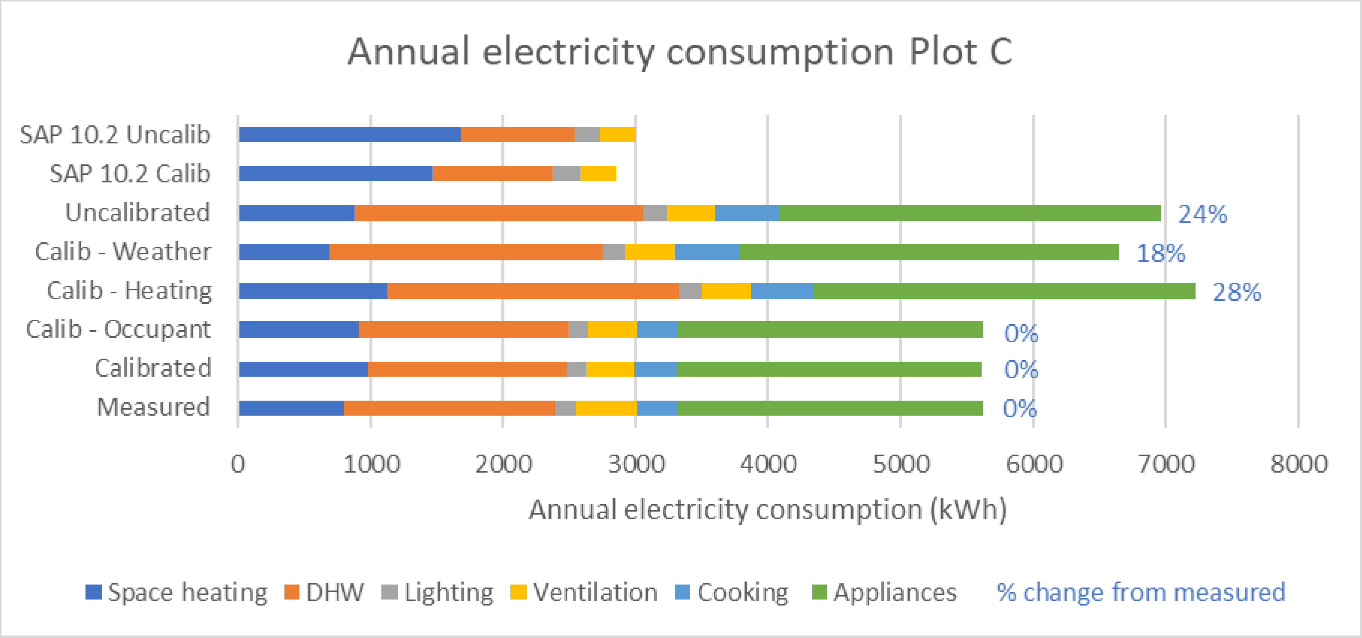


Figure 8, Figure 9 and Figure 10 compare the results for Plots A, B and C respectively for Part L regulated energy use only. They compare the fully calibrated SAP 10.2 and HEM results with the measured data.

The HEM space heating electricity consumption ranges from being around 20% below to 20% higher than the measured data. In contrast, the SAP 10.2 space heating electricity consumption is between around 50% to 80% higher than the measured data.

In all cases, the HEM space heating electricity consumption is a closer match than SAP 10.2 to the measured data. However, this does not necessarily infer that the HEM results are more reliable than SAP 10.2.

- This may partly be a reflection of the HEM having additional functionality and higher granularity compared to SAP 10.2, which is not capable of undertaking the same level of calibration as HEM. The differences in the calibration approaches are outlined in the Approach to SAP 10.2 modelling section.
- The main focus of this validation exercise has been in defining and calibrating HEM rather than in defining and calibrating SAP 10.2, which may contribute to the differences in results. If further work was undertaken on the SAP 10.2 model set-up and calibration, the SAP 10.2 results may potentially be better aligned with the measured values and HEM results. It is considered that SAP 10.2 model or calibration elements with potential for further adjustment (that may result in better alignment) are: heating setpoints, pipework heat losses, internal gains from appliances, cooking and lighting, and MVHR model inputs.

The Home Energy Model when adjusted with measured internal temperatures and metered electricity consumption and associated gains produced results that plausibly match the measured data. The differences identified could be explained by the uncertainties associated with the measured space heating consumption data (see Appendix A) and uncertainties associated with those SAP/HEM input values that input on space heating consumption e.g. the thermal performance of the building fabric and heating system efficiency. Ideally, further validation case studies will have lower levels of uncertainty. It is important to note again that the Building for 2050 project was not designed to support validation of the Home Energy Model.

The HEM ventilation electricity consumption is around 0% to 40% below that measured depending on the case study plot. In contrast, the SAP 10.2 ventilation electricity consumption ranges from being 40% below to 20% higher than the measurements.

It is plausible that the differences identified between the HEM results and the measured ventilation electricity consumption data arise from limitations in the information from the case study and this could be investigated further. Contributing factors could include:

- HEM assumes that the ventilation rate reflects the Part F “low” flow rate which is recommended for typical conditions. Either intentionally or unintentionally, the MVHR system may be on a boost flow rate for a significant proportion of the time which has been observed by case study authors in other projects. The measured data can be reviewed to assess whether there are significant periods of high ventilation electricity consumption which may reflect a high ventilation rate being used.

- Higher measured electricity consumption could reflect inadequate maintenance of the ventilation system. The measured data can be reviewed to assess whether there are longer-term trends of increasing ventilation electricity consumption during the monitoring period which may be reflective of inadequate maintenance.

Sensitivity analysis could be undertaken to consider the impact of uncertainties associated with the values for specific fan power and heat recovery efficiency input to the HEM.

Figure 8: Annual regulated electricity consumption Plot A, August 2019 to July 2020

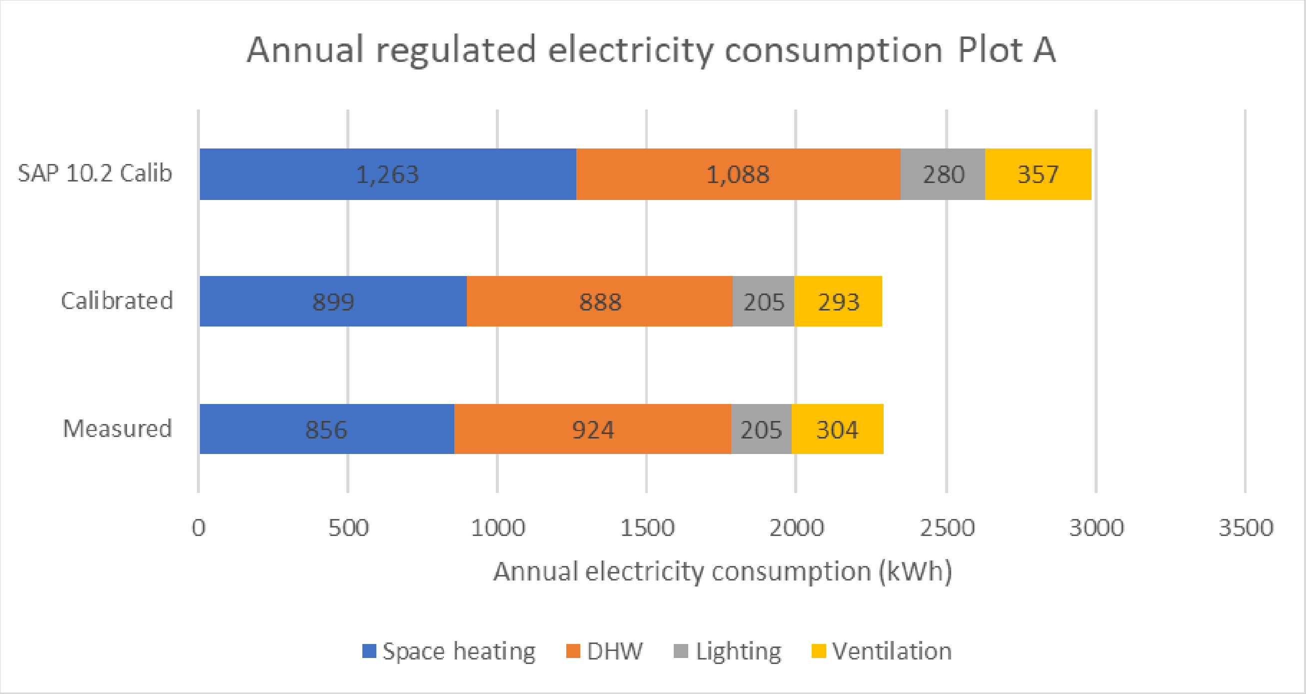


Figure 9: Annual regulated electricity consumption Plot B, August 2019 to July 2020

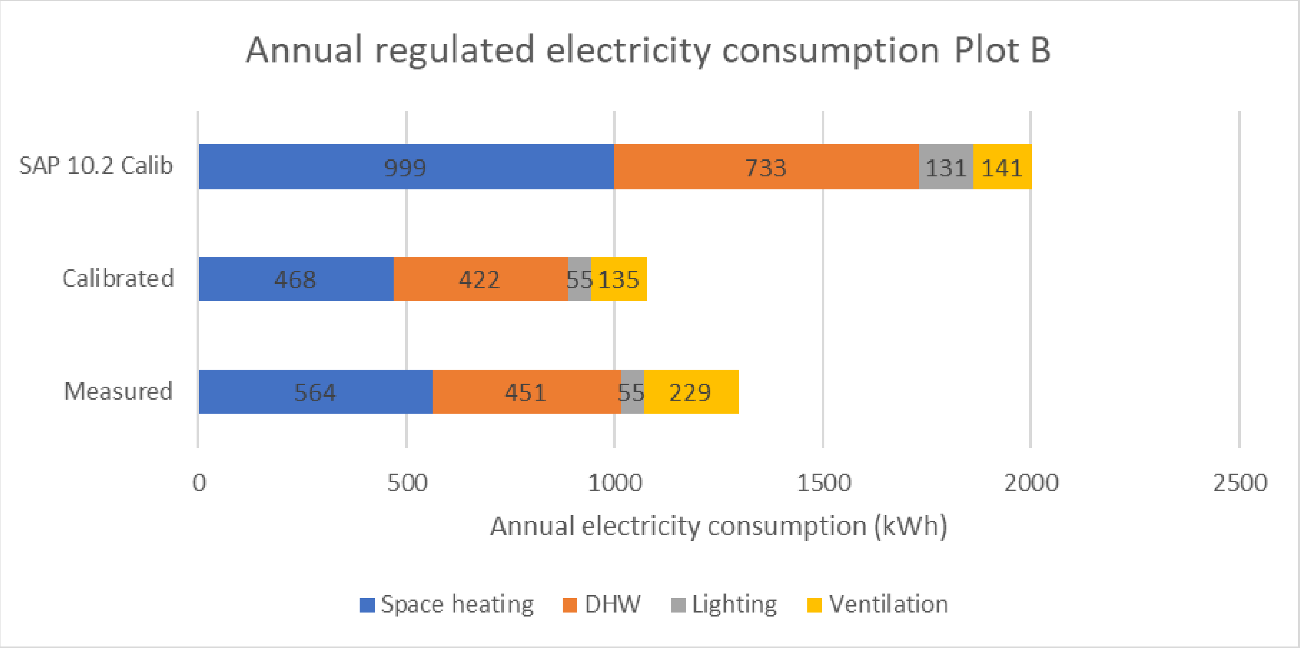
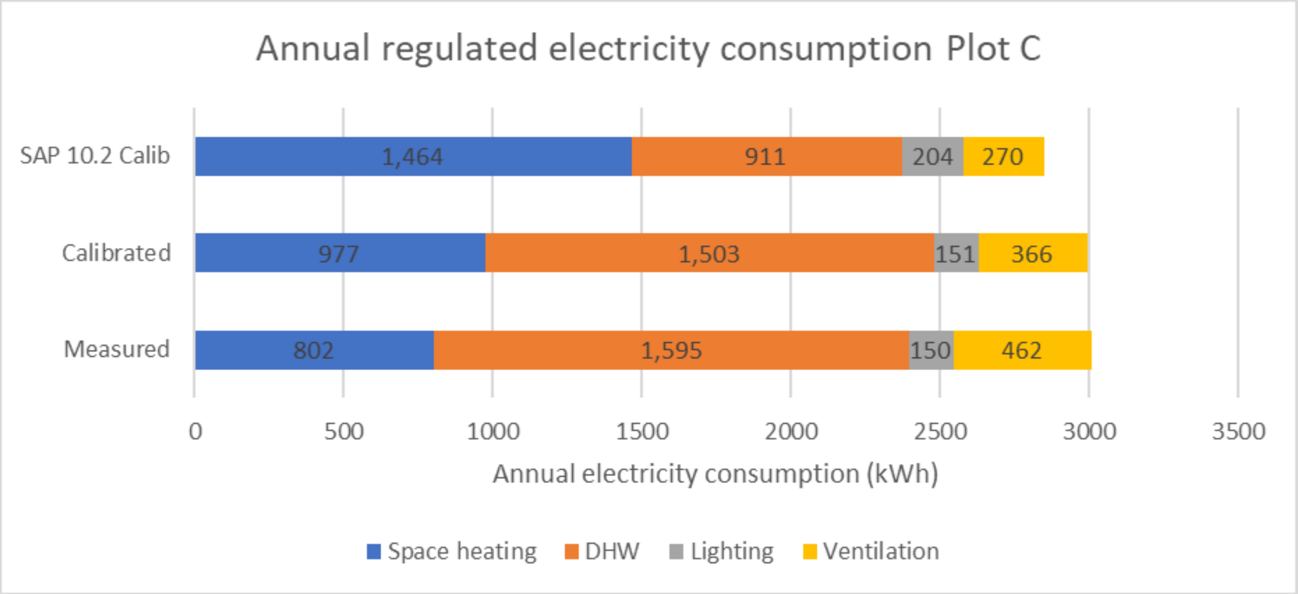


Figure 10: Annual regulated electricity consumption Plot C, August 2019 to July 2020



Monthly space heating electricity consumption

Figure 11, Figure 12 and Figure 13 compare the fully calibrated HEM results to the measured data for Plots A, B and C respectively. The period of analysis is August 2019 to July 2020. The figures reorder these months from January to December to show a typical annual profile.

- Plot A: The measured results tend to be similar to or lower than that predicted during the winter period. However, the March measurements are around 60% lower than predicted.
- Plot B: The measured results tend to be higher than that predicted through winter. In particular, the March and November measurements are 100% and 50% respectively higher than predicted.
- Plot C: The measured results tend to be lower than that predicted, by up to around 40%. However, again, the measured March and November results differ and are higher than predicted.

In reviewing these results, it is important to put them into context of conditions at the time. The first Covid-19 lockdown was announced on the 23rd March 2020 with many people restricting travel before this date. The relatively high electricity consumption in March observed in some of the plots may be related to more time spent indoors during the Covid-19 lockdowns. However, the majority of the heating season data was prior to the Covid-19 lockdown, including the winter peak months of December, January and February.

A single combined heating calibration was undertaken across all winter months, and this may be improved upon by calibrating for each month separately to account for potential changes in occupancy and heating patterns during this period. It is noted that of the three plots, Plot A only had measured space heating below that predicted in March which may be, at least partially, explained by the data being adjusted from the previous year’s March energy data which was prior to Covid-19 (see further details in the Building for 2050 Case Study section). However, for example, Plot C shows a large discrepancy between measured and modelled space heating in January 2020, pre-pandemic. Care is therefore needed interpreting the monthly data. From this analysis it is not possible to conclude that HEM provides a reliable prediction of monthly space heating energy use.

The measured electricity consumption data for space heating and hot water indicates a potential use for some space heating energy outside the SAP assumed heating season. During cooler summer periods, the internal temperature may dip below the space heating set-point, triggering low levels of space heating electricity consumption. This is somewhat replicated by the HEM. It also may reflect the uncertainty in the split between space heating and hot water electricity consumption which was described previously. Figure 11 for Plot A suggests a continuous inferred monitored space heating use during summer. This likely reflects uncertainties in the split assumed in this analysis between hot water and space heating.

Figure 11: Monthly space heating electricity consumption Plot A, August 2019 to July 2020, (reordered to January to December profile)

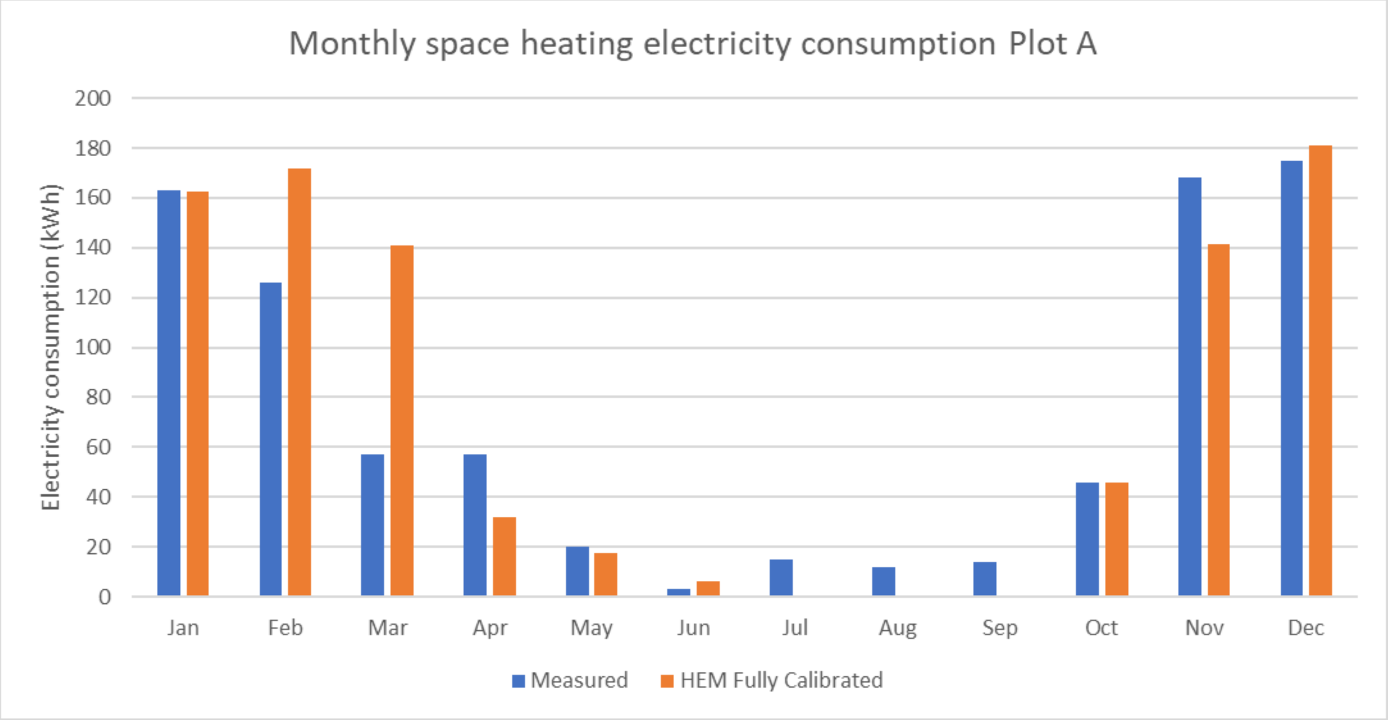


Figure 12: Monthly space heating electricity consumption Plot B, August 2019 to July 2020 (reordered to January to December profile)

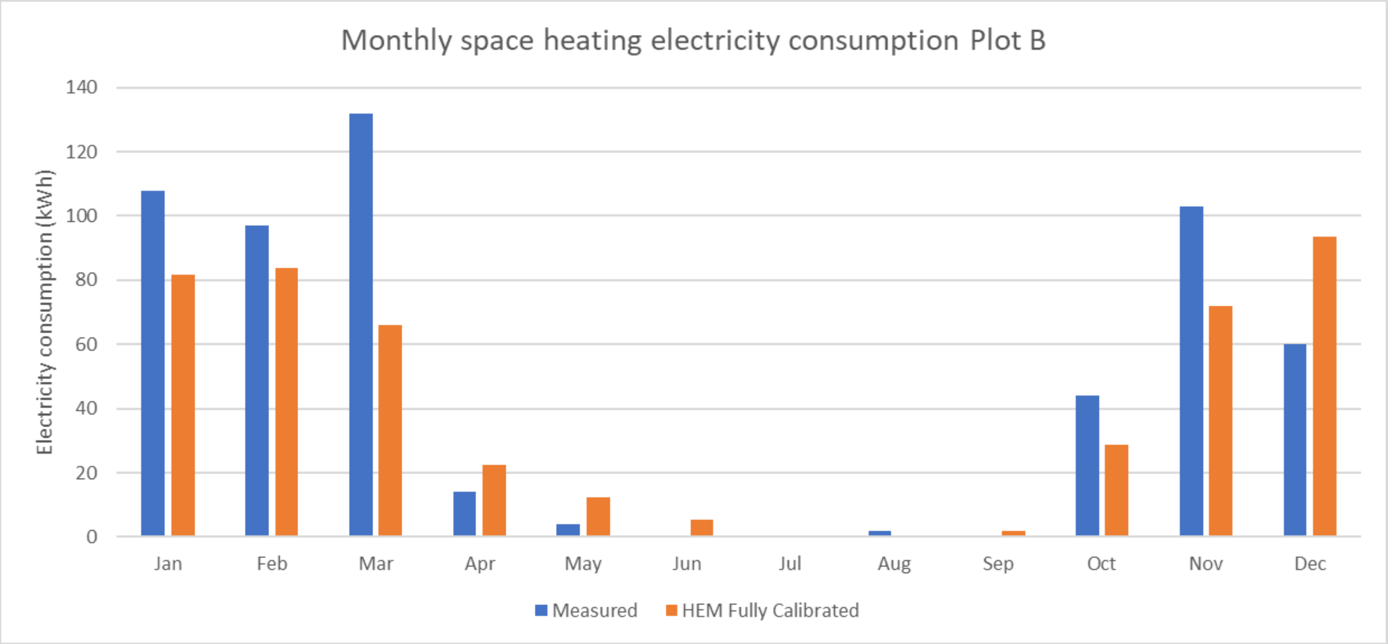
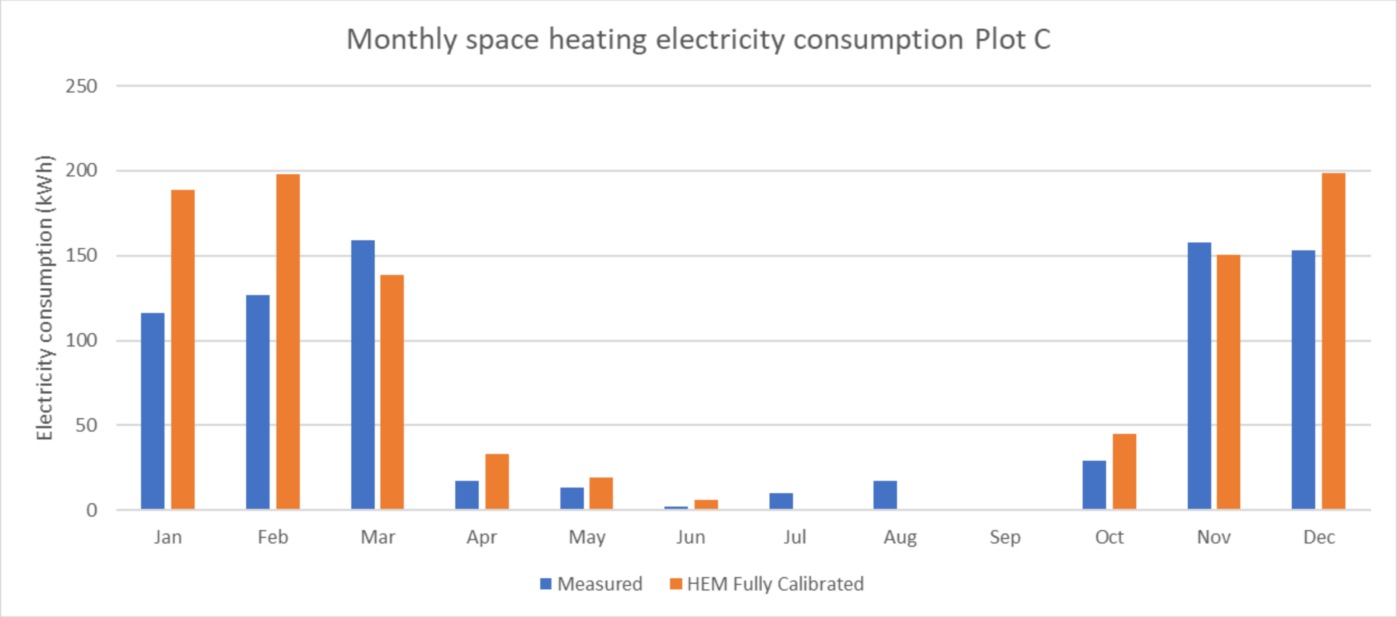


Figure 13: Monthly space heating electricity consumption Plot C, August 2019 to July 2020 (reordered to January to December profile)



Internal temperature data

Figure 14, Figure 15 and Figure 16 compare the fully calibrated HEM results and the measured data for Plots A, B and C respectively for monthly internal temperature. The measured data and HEM data are both air temperature, and not the operative temperature, and does not account for radiative effects and humidity. The period of analysis is August 2019 to July 2020. The figures reorder these months from January to December to show a typical annual profile.

The data is a relatively close match throughout the year. Plots A and B show a divergence of up to around 1°C during the summer months. In addition for Plot B, the November measurements were higher than predicted and the December measurements were lower than predicted, which may reflect variances in typical occupancy during this period; this is a relatively small flat and the internal conditions will be particularly sensitive to occupancy.

Figure 14: Monthly unweighted average internal temperature Plot A, August 2019 to July 2020 (reordered to January to December profile)

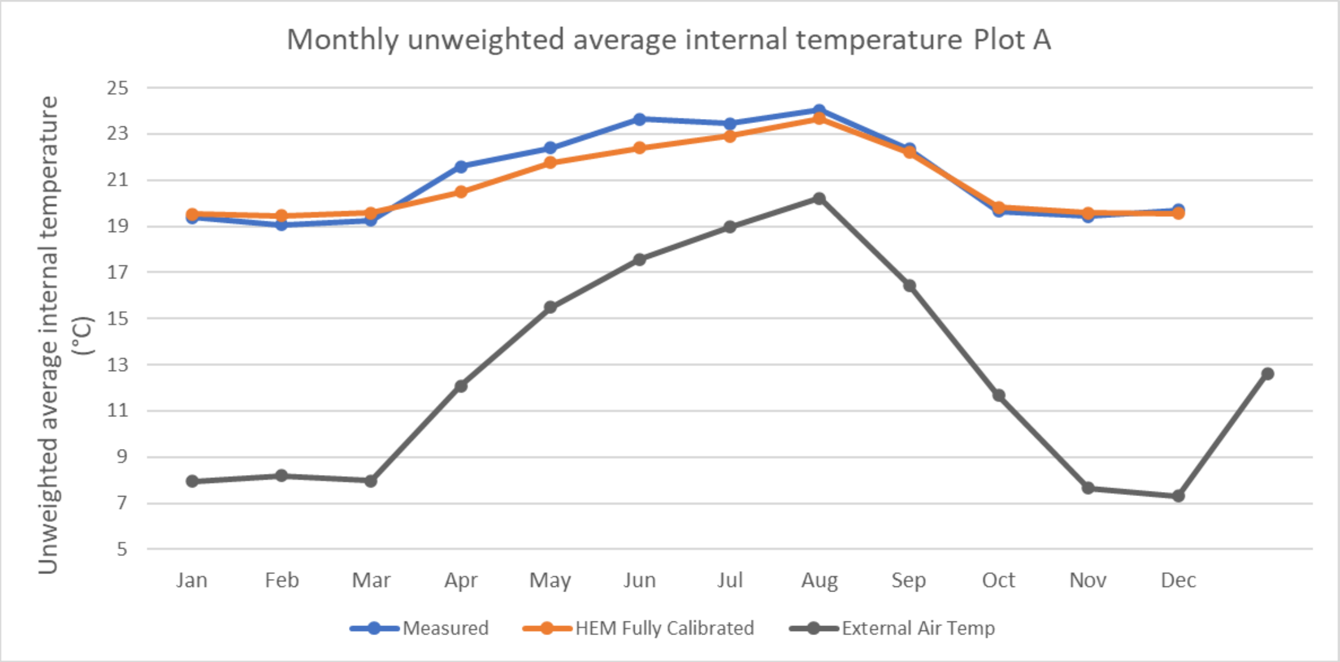


Figure 15: Monthly unweighted average internal temperature Plot B, August 2019 to July 2020 (reordered to January to December profile)

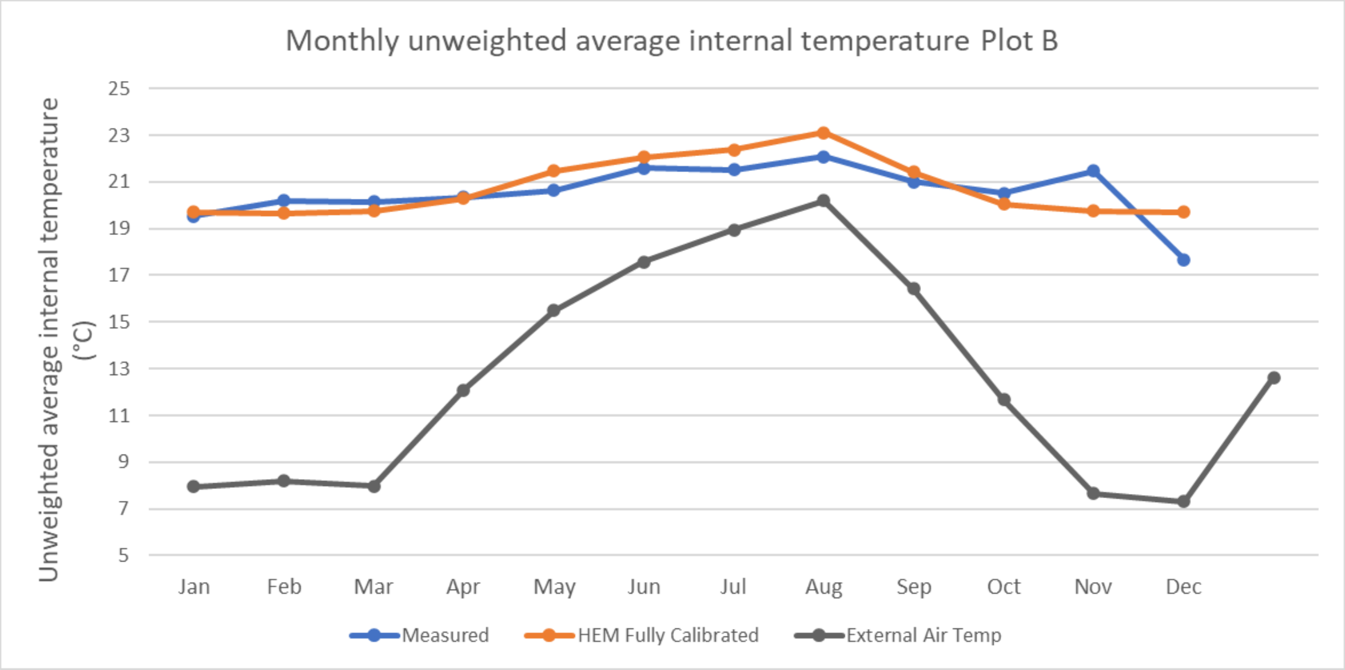


Figure 16: Monthly unweighted average internal temperature Plot C, August 2019 to July 2020 (reordered to January to December profile)

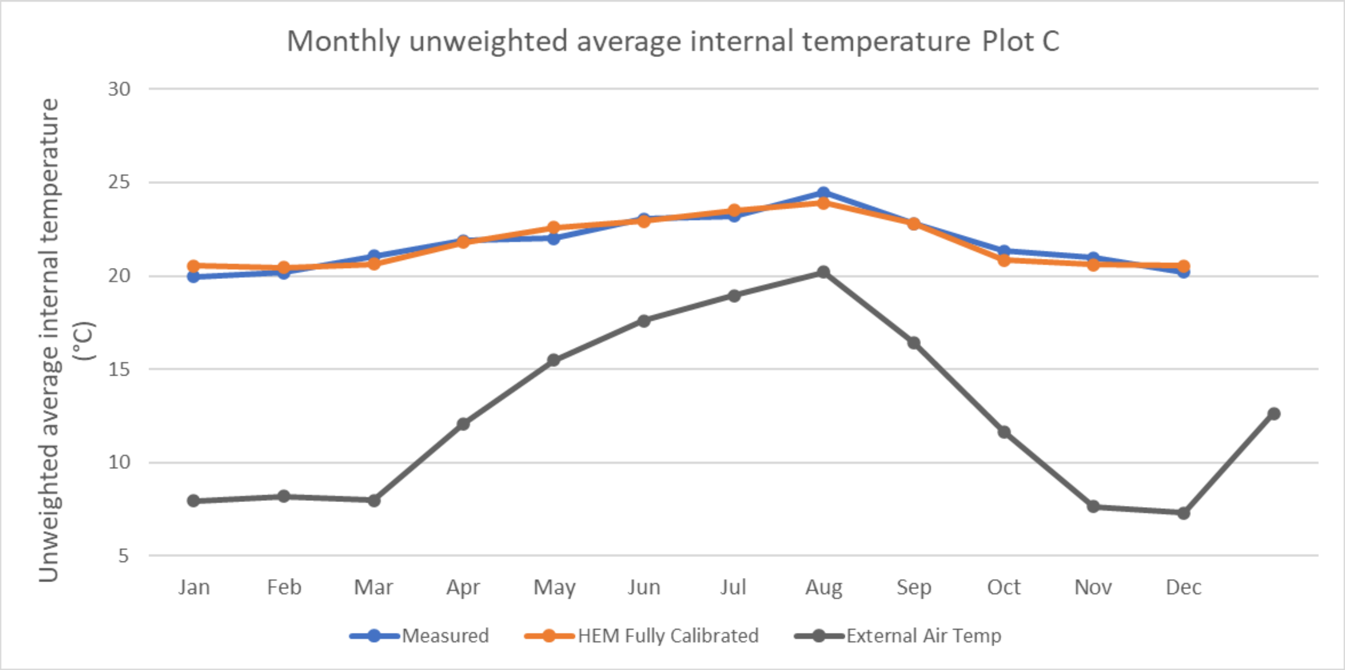


Figure 17, Figure 18 and Figure 19 compare the fully calibrated HEM results to the measured data for Plots A, B and C respectively for an average week during January 2020. This is based on averaging all data in January 2020 for the same day and time of the week e.g. the data for 4pm on Monday is an average of all of the measurements at 4pm on Monday during January 2020.

There is again a relatively close match between the HEM results and the measured data. This is to be expected as the internal air temperature measurements were used to specify the set point temperature controls in the HEM.

It is noted, particularly for Plots B and C, that the measured temperature data shows a slower rate of change than the HEM results. There are a number of potential explanations, for example:

- This may be that the temperature sensors were located close to internal walls and hence the temperature measured may be influenced by the slower rate of temperature change that occurs in internal walls due to their thermal mass than the room air temperature.
- There may be differences in relation to thermal mass between the HEM model assumptions and that of the constructed homes
- There may be differences in the heating pattern between the HEM model assumptions and occupant heating control settings.

For some of the data there appears to be a potential small offset that may also relate to these factors.

As necessary, these issues could be explored further.

Figure 17: Weekly January 2020 unweighted average internal temperature Plot A

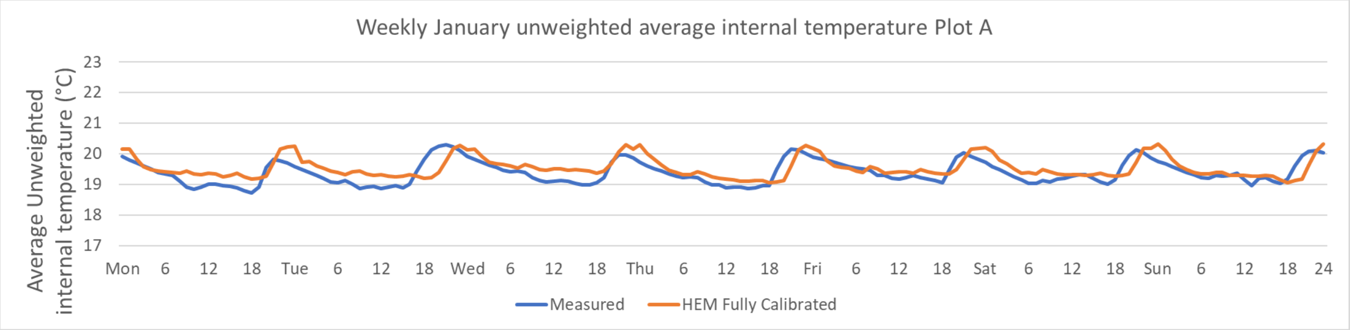


Figure 18: Weekly January 2020 unweighted average internal temperature Plot B

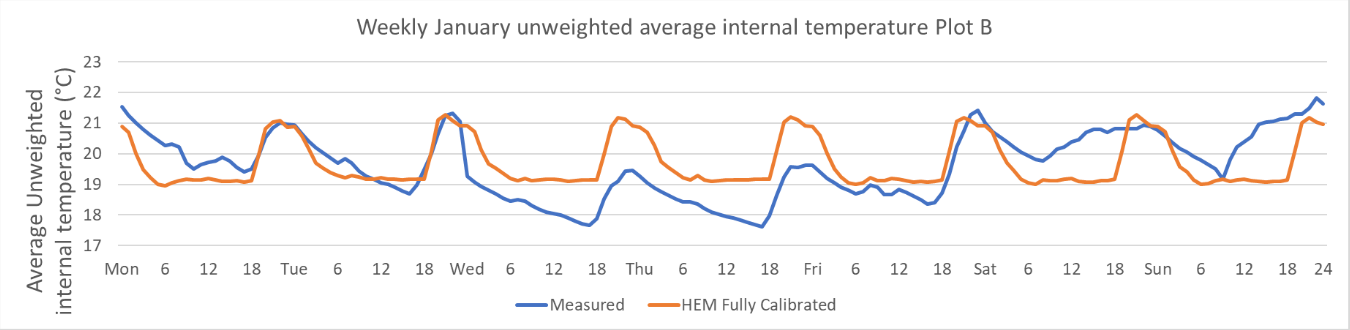


Figure 19: Weekly January 2020 unweighted average internal temperature Plot C

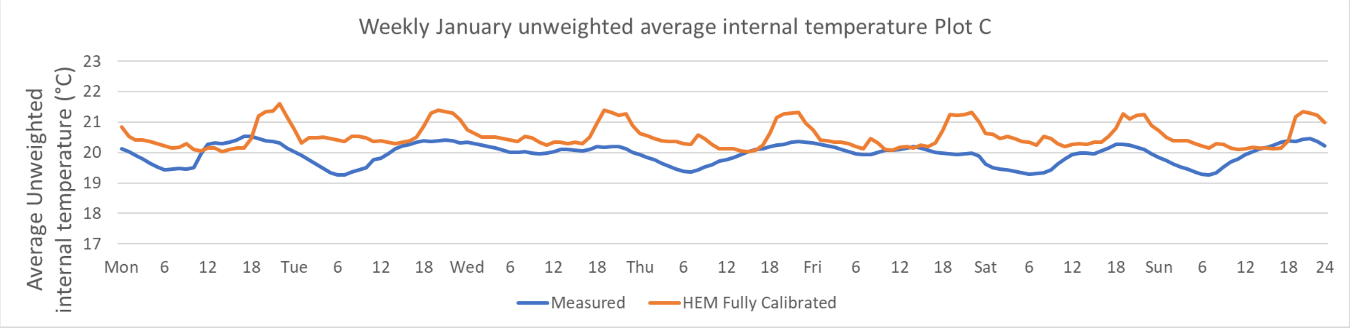


Figure 20, Figure 21 and Figure 22 compare the fully calibrated HEM results to the measured data for Plots A, B and C respectively for an average week during July.

The HEM predictions are broadly aligned with the measurements. The temperature varies most during peaks, by up to around 2°C, with Plot B showing the most divergence; this may be due to Plot B being more sensitive to gains being a small flat with a small area exposed to external temperatures, and the other plots being large houses with a large area exposed to external temperatures. Where data diverges, this is expected to relate in part to solar gains and external air temperature; the modelled peaks consistently occur in late afternoon, lagging these sources of gains, as would be expected. Thermal mass and occupancy factors (e.g. window opening behaviours) are also likely to contribute to the differences between modelled and measured data.

Contributors to solar gains related differences may include that 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 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[12]. 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. The use of internal or external shading devices by residents may also reduce the solar gains retained within homes, thereby affecting the measured data. Furthermore, although external shading by external buildings and landscape features was accounted for in the model, the reality may differ from the model assumptions.

Variance in thermal mass between HEM and the modelled houses units 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 various layers, according to whether the thermal mass was externally facing, inside the element itself, or internally facing[13]. 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.

Interzonal heat transfer may be another contributing factor to the differences. Currently, in the Home Energy Model, heat transfer between zones is not modelled, since implementing this would have increased the runtime of the models in the consultation version. 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.

There is limited data available relating to occupancy factors, including the use of shading devices as suggested above, but also relating to window opening profiles, periods of occupancy, and occupant behaviours that might influence internal gains.

Also, the installed MVHR systems include a summer bypass which is not as yet modelled in HEM. This issue can be considered further in the coming months as such functionality is included in HEM.

---

[12] 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’

[13] 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’

Figure 20: Weekly July 2020 unweighted average internal temperature Plot A

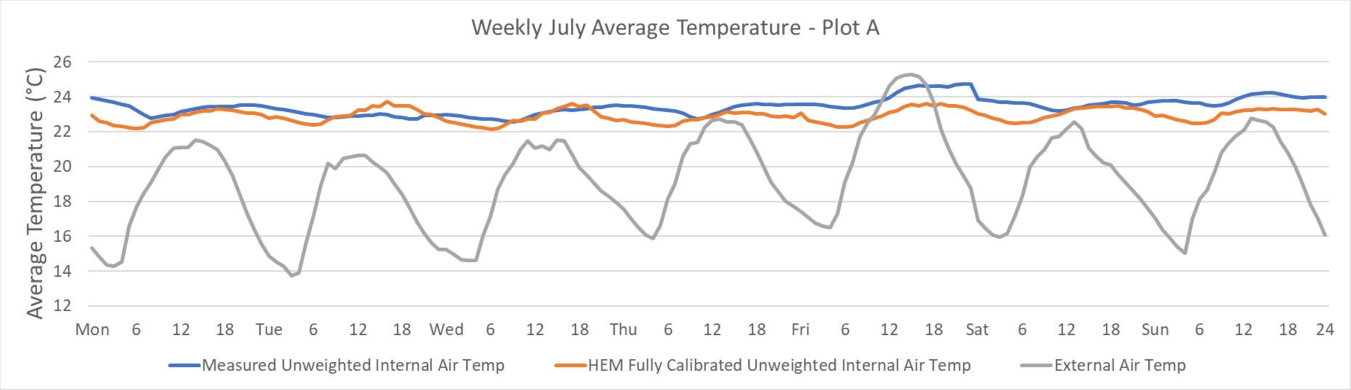


Figure 21: Weekly July 2020 unweighted average internal temperature Plot B

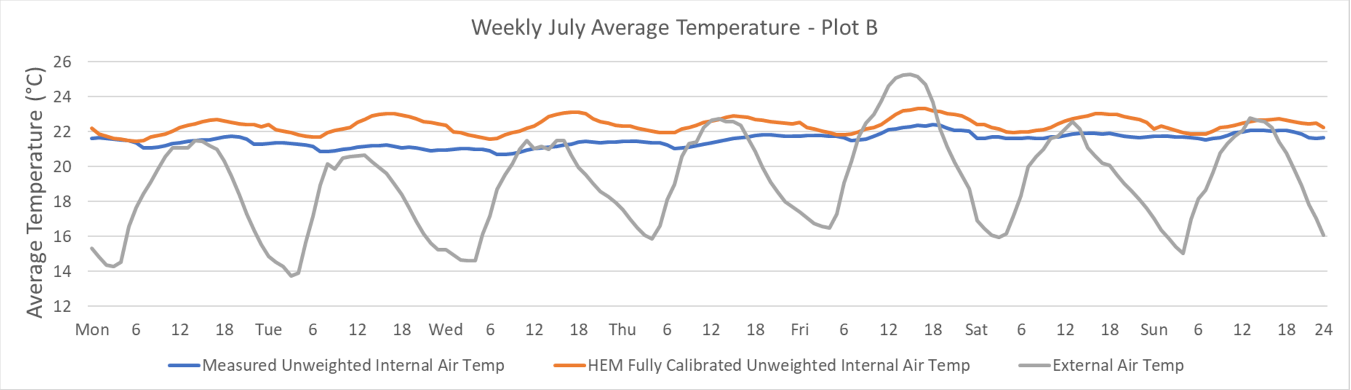
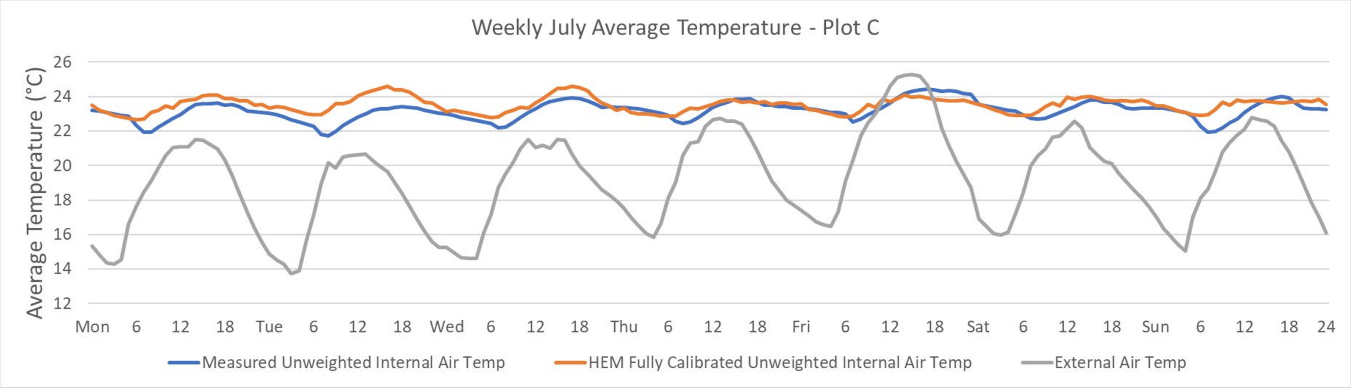


Figure 22: Weekly July 2020 unweighted average internal temperature Plot C



Summary and conclusions

DESNZ is comparing the Home Energy Model (HEM) with other modelled and measured data to gain confidence in the HEM model. This paper describes a comparison with measured data for three homes. The measured and modelled data had a range of significant limitations that makes it challenging to undertake a detailed model validation, this includes:

1. Data for one of the buildings was missing for a period.
2. The actual heat pump efficiency, its actual flow temperature, and split between hot water and space heating energy was not known.
3. The actual ventilation rate was unknown and the HEM did not have the functionality to model the MVHR system with summer bypass at the time of this validation.
4. Some of the monitoring occurred after the first March 2020 Covid-19 lockdown, a period of very significant behaviour change. However, the majority of heating season data is from prior to the Covid-19 pandemic.
5. The model assumes no interzonal heat flow.
6. Default values have been used in several areas, including thermal bridging, SFP, thermal mass, among others. This reduces the accuracy in these areas.
7. A model as complex as HEM has 100’s of inputs, all with uncertainties and value judgements about how a building should be modelled. Due to these uncertainties, and also interactions between inputs which might result in the cancelling out of uncertainties, validation accuracy is limited and can only demonstrate an approximate agreement between modelled and the measured data.

The Home Energy Model produced results that plausibly match the measured annual space heating electricity consumption data after measured internal and external temperature data and measured non-space heating electricity consumption was used. Significant differences existed between monthly and hourly electricity consumption and temperature even after calibration. As discussed in this report, the differences identified could potentially be explained by uncertainties in the case study or model limitations. A major uncertainty is the limited data available on the behaviour of the residents which may result in significant differences between the occupancy profiles modelled in the HEM and the actual occupancy behaviour; this is mitigated as far as possible through the calibrations described earlier. Other uncertainties include the accuracy of the input data entered into the model and the accuracy of the measured data. As a result, there will be error bars associated with both the HEM predicted results and the comparison measured values which could plausibly explain the differences identified.

Further work could be undertaken to both improve the modelling and better quantify the uncertainties. 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.

Potential Future Activities

Uncertainty analysis

This analysis would better quantify whether the differences between HEM results and measured data can potentially be explained by uncertainties associated with the HEM input data and the monitored data.

The HEM calculations to date are based on the best estimate of the HEM input values. There is no performance data available for those homes monitored to use as the input values e.g. no post-completion testing for those plots modelled. The HEM input values are based on the developer's SAP input data. This has been modified as appropriate based on a combination of observations of the development during construction and completion and measurements on other plots in the development.

Reasonable low and high estimates of key inputs have already been agreed. The impact of the uncertainty for each input on the HEM results can be tested both in isolation and in combination across all HEM inputs.

Additional modelling of the core HEM runs

Potential additional runs identified are as follows. This integrates points raised earlier in the report, plus some additional ones.

Better calibrate the heating regime

- Further review of the assumed zones and set-point temperatures for HEM and how well this fits the experimental set-up and likely occupancy in the homes.

Further consideration of solar gains

- Investigate overshading from fences, trees and neighbouring buildings.
- Investigate shading from use of blinds and curtains
- Investigate effect of dirt on glazing affecting solar gain

Better match variation in monthly space heating and domestic hot water electricity consumption

- HEM calibration for heating patterns and domestic hot water consumption to be each updated to separately calibrate for each month. In particular, this may better account for changes in behaviour associated with restrictions during Covid-19.

Better match variation of heat pump model

- A substitute Daikin heat pump inside unit with a slightly lower maximum heat output was used in HEM. The modelling might improve if a closer match was found. (See the Information used in the HEM models section for more details on the differences.)

Better match measured daily temperature profile

- Revise thermal mass assumptions. Details supplied by the timber-frame manufacturer mention load bearing internal walls manufactured with large panels, and the use of load bearing columns and beams (using cross-laminated timber). These may have greater thermal mass than assumed.
- Review the difference in profile between air and internal wall temperatures in HEM and whether the latter is a better fit with measured data. In addition to the inclusion of greater thermal mass as above, this may help explain the differences between HEM air temperature results and measured data.

Summer temperatures

- Revise assumptions for opening/closing of windows in the summer, and the use of internal shading (blinds or curtains), which may help better reconcile predicted and measured summer temperatures.
- Adjust effective window U-value with blinds or curtains using the formula in SAP 10.2 (Section 3.2 Window U-values). [Albeit relevant all year round]
- Implement MVHR summer bypass in HEM which should also help better reconcile temperatures.

General

- Any further HEM modelling highlighted by the uncertainty analysis.

SAP 10.2

- Review the assumptions (e.g. ventilation) for SAP 10.2 to ensure best comparison to HEM.

In addition, the work has highlighted potential additional analysis of the Building for 2050 dataset to investigate issues around the measured ventilation electricity consumption being higher than predicted by HEM. This could potentially include further HEM modelling to better calibrate for the MVHR air flow.

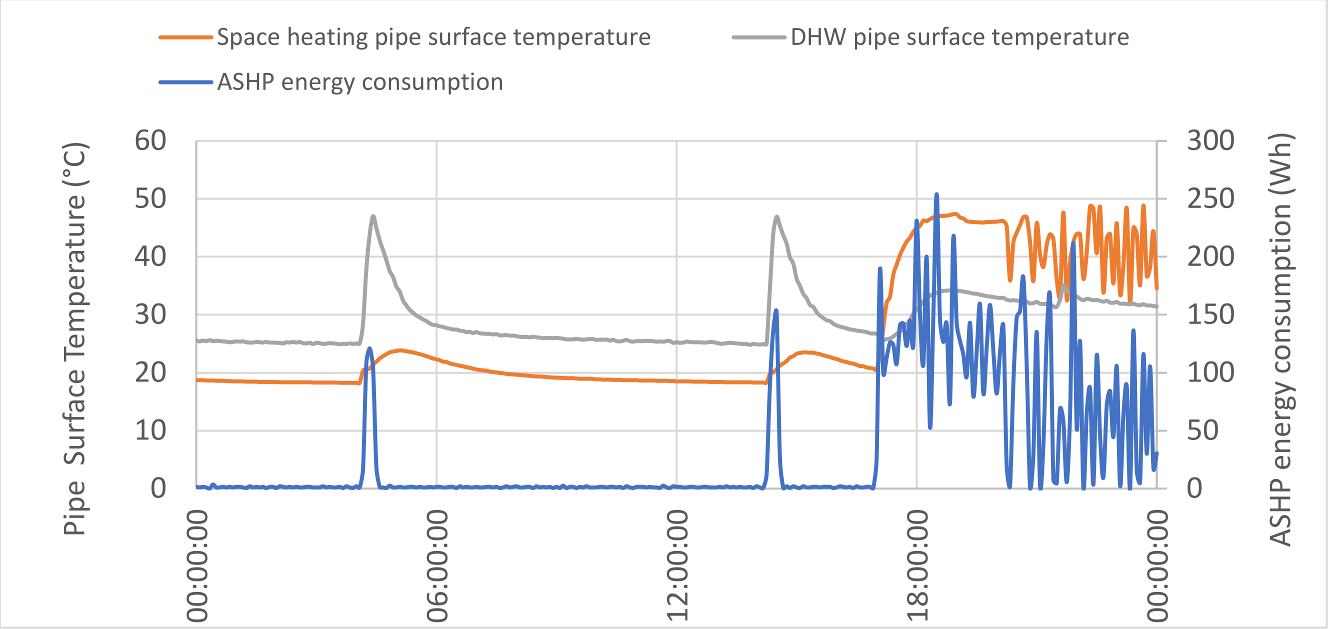
Appendix A – Approach to estimate the split in electricity use for space heating and domestic hot water; and sensitivity analysis

The Building for 2050 project metered the combined electricity consumption for space heating and hot water in each of the three plots. It used this data to estimate the split between the electricity use for space heating and hot water. This Appendix summarises the approach taken to estimate this split. Note that there were no heat meters installed on the heat pumps.

The split between the electricity consumed for space heating and hot water was estimated using surface temperature sensors which were installed on the distribution pipework serving the space heating and hot water circuits[14] downstream of the heat pump. This surface temperature data was matched with the electricity consumption time-profile to identify when the heating system served space heating or hot water. For Plot A, the surface temperature was only measured on the domestic hot water pipework for practical reasons.

The Building for 2050 project recorded electricity and surface temperature data at five minute time intervals. An example daily profile is as below in Figure 23. This commences with two distinct events when the domestic hot water was used followed by a long period of space heating use later in the day. All three plots showed peaks of a similar height when space heating or hot water was in use.

Figure 23: ASHP electricity consumption and pipework surface temperature example profile for 24 hours



---

[14] The domestic hot water sensors were installed to the pipe between the heat pumps and domestic hot water cylinders.

For Plots B and C, the approach to estimate whether the electricity use in a five-minute time-step is allocated to space heating or hot water is as follows. For the electricity in the time step to be allocated to domestic hot water, it needs to meet either of the following two criteria. If neither of these criteria are met, then the electricity in the time-step is allocated to space heating.

- Criterion 1: The surface temperature for the domestic hot water pipework is greater than 40°C, or
- Criterion 2: The surface temperature for the domestic hot water pipework is greater than that of the space heating pipework.

For Plot A, only the domestic hot water surface temperature data is available and hence the allocation between space heating and domestic hot water is expected to be less robust. The approach to estimate whether the electricity in the time-step is allocated to space heating or hot water is follows. For the electricity in the time-step to be allocated to domestic hot water, it needs to meet the following criterion. If this criterion is not met, then the electricity in the time-step is allocated to space heating.

- Criterion 1: The surface temperature for the domestic hot water pipework is greater than 40°C.

The threshold temperature of 40°C for domestic hot water pipework was selected by:

- reviewing the impact of differing threshold temperatures on representative samples of data and
- establishing the temperature which best apportioned space heating and domestic hot water electricity consumption to match clear data signals within the case study homes.

Sensitivity Analysis

Some sensitivity analysis was also undertaken for all three plots to assess the change in the estimated split in annual space heat heating and hot water electricity use if the above criteria are amended.

Two analyses were undertaken:

1. Criterion 1, for plots A, B and C was adjusted such that the surface temperature threshold for the domestic hot water pipework changed from “greater than 40°C”, to “greater than 35°C” or “greater than 45°C”.

    - Further figures of “greater than 30°C” or “greater than 50°C” were considered unrealistic and ruled out as poor matches to the observed sample profiles.

    Note that this sensitivity analysis is not intended to be exhaustive. Alternative variations for the criteria could be assessed at a future point.

2. Plots B and C results were re-run as per the Plot A method, using the surface temperature data for DHW only (i.e. no space heating data). This helps to assess the robustness of the Plot A results where only the domestic hot water surface temperature data is available.

Sensitivity analysis results

The sensitivity analysis results are summarised in Table 7 below. The total energy consumption from space heating and domestic hot water remained constant but the split between these two energy uses varies within the analyses.

Table 7: Sensitivity analysis results

Analysis	**Space Heating (SH) / Domestic Hot Water (DHW)**	**Plot A (17) (DHW data only)**	**Plot B (15) (SH and DHW data)**	**Plot C (26) (SH and DHW data)**
		Total (kWh)		
1. Modification of Criterion 1				
Baseline - Threshold Temperature 40°C	**SH**	855	563	802
	DHW	925	452	1595
Threshold Temperature 35°C	**SH**	652	513	778
	DHW	1137	502	1619
Threshold Temperature 45°C	**SH**	956	570	805
	DHW	818	445	1592
2. Comparison to indicate robustness of Plot A				
Using no SH pipe data method (Threshold 40°C)	**SH**	855	757	1048
	DHW	925	259	1349

Changing Criterion 1 had greatest impact on Plot B and C results when the threshold was reduced. It affected the split between space heating and hot water consumption, with space heating reducing by up to 9% and the hot water increasing by up to 11%. When the threshold for Plot B and C was increased, space heating increased by up to 1.5% and hot water reduced by up to 0.2%. This provides a measure of uncertainty in the annual consumption data.

Changing Criteria 1 had a greater impact for Plot A both when the threshold reduced and increased. The space heating consumption varying by up to 24% and hot water consumption varying by up to 23% from the baseline values.

When Plot B and C split estimates were re-run as per the Plot A method, using the surface temperature data for DHW only (i.e. no space heating data), the estimate of space heating consumption increases by approximately 30% and a corresponding reduction in domestic hot water consumption. This further suggests that the absence of space heating pipe data can have a significant impact on the results and lowers the confidence in the results for Plot A. Assuming reasonable to apply the findings from Plot B and Plot C to Plot A, it suggests that the space heating consumption should be reduced and the domestic hot water consumption increased. It is difficult to reliably quantify what these changes should be given data from only two plots.

Appendix B – Approach to calculate Heating Degree Days and estimate missing data for Plot A

For Plot A only, there was a period of incomplete total space heating and hot water electricity consumption data between March 2020 and July 2020 and data from corresponding months from 2019 was used. The estimated split of hot water consumption from the prior year was used directly, while the estimated split of space heating was adjusted by Heating Degree Days (HDDs) to reflect the differing external temperatures between 2019 and 2020. HDDs predict the relative change of space heating demand over time periods, accounting for the length of time and the difference between the external temperature and a reference external temperature at which point no heating is assumed to be required.

An external base temperature of 14.5°C was selected, to represent the external temperature at which the home is assumed to require no space heating. HDDs were calculated on an hourly basis, by subtracting the measured external temperature at the site from the base temperature. The HDDs were then summed for each month. The resultant HDDs are shown in Table 8 below.

Table 8: Heating Degree Days (HDDs) at Marmalade Lane, Cambridge, Jan 2019-July 2020

Month	2019 Heating Degree Days	2020 Heating Degree Days
January	174	206
February	175	183
March	216	207
April	149	105
May	68	60
June	110	19
July	1	3
August	8	
September	33	
October	97	
November	229	
December	229	

For Plot A, in order to fill missing data from March 2020 to July 2020, HDDs were used to adjust the estimate of space heating from corresponding months in 2019 to account for the differing weather. For instance, for April 2020, the estimated space heating electricity consumption for April 2019 of 80kWh was multiplied by the estimated 105 HDDs in April 2020 and divided by the estimated 149 HDDs in April 2019. Hence, the estimate of space heating electricity consumption for April 2020 is 57kWh.

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