CO-HEATING TEST OF CAMDEN PASSIVHAUS

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Executive Summary

Camden Passivhaus is part of the Technology Strategy Board's Building Performance and Evaluation programme. Part of this programme includes a series of post-construction tests to evaluate the 'as-built' thermal performance of the dwelling. These tests are designed to evaluate any variation between design intent and as-built performance and to identify the causes of any such discrepancies. This report focuses on the results of two co-heating tests at Camden passivhaus. Co-heating tests experimentally determine the heat loss coefficient, a measure of the total heat loss across the entire building envelope. This quantitative measurement across the entire fabric separates it from other post-construction tools such as in situ u-values, which measure heat loss only at discrete points, and thermal imagery, which only provides a visual indication of heat loss. The measured heat loss coefficient from co-heating can carefully be compared to design predictions. When the measured and design heat loss coefficient show significant disagreement this can be an indication of issues with buildabilty/workmanship, design assumptions or real world material performance. When this is the case a variety of forensic tools can be used to attempt to determine the causes of such a disagreement.

To this purpose, at the end of March 2011 an initial co-heating test was undertaken at the Camden Passivhaus. There are two important points to note about this test. Firstly, the Camden Passivhaus has a low overall designed heat loss and a high glazing fraction, making it far more sensitive to uncertainties from the external environment than many other buildings. Secondly, the co-heating test, performed at the end of March, experianced high amounts of solar radiation. These two issues combined to cause difficulties in preserving the co-heating method and energy balance upon which the energy balance is based. Specifically due to large amounts of solar gains the house overheated beyond the co-heating set point of 25°C. This caused a large amount of uncertainty in the co-heating result.

It was therefore determined that, if possible, a second co-heating test under more favourable conditions should be pursued. As the dwelling was fully occupied arranging this second co-heating period was difficult and depended on the cooperation and holiday arrangements of the occupants. As only a short amount of time was likely to be available it was important to avoid any of the problems of the first test. An evaluation of when the second test should be performed was carried out using simulated co-heating tests and is included in this report. The results of this showed that the test was more likely to be successful in December or January but this still depended on having dull weather conditions.

The second co-heating test at the Camden Passivhaus was therefore performed between the 21st and 30th December 2012. This test period coincided with a dull

spell of weather, reducing any risks of overheating. The second result could then be stated with far less uncertainty than the first.

Co-heating Result from first (2011) test:
Heat loss coefficient (HLC) = 35 ± 15[1] W/K

Co-heating Result from second (2012) test:
Heat loss coefficient (HLC) = 56 ± 5 W/K

The two results are significantly different. It is therefore important to understand the uncertainties in each measurement such that we can understand the true building performance. As fully discussed later in this report the first co-heating result is severely influenced by solar generated overheating in the test house. This overheating, which pushed internal temperatures above the co-heating set-point meant that the steady-state assumptions of the co-heating method were affected by dynamic thermal mass effects. In comparison the second co-heating test was performed under almost ideal test conditions for the Camden Passivhaus, being largely dull and overcast. This means the second test was far more successful and its result far more reliable.

The indication is that with a measured value of 56 W/K the Camden Pasivhaus is performing within its PHPP design heat loss value of 66 W/K. Previous air tightness, in situ u-value and thermography results support this conclusion. The indication is that the Camden Passivhaus is one of only a few co-heating tested dwellings that meets its design intent. This is a positive reflection on the design and build quality of the house and is especially encouraging considering the low heat loss that was targeted here.

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[1] The error here is the standard deviation of the HLC calculated across each day in the test.

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1. Introduction

This report will document the second co-heating test in detail (section 2) and also briefly summarise the original test in order to draw comparisons between the two (section 3). This section will describe Camden Passivhaus and the process used in which to schedule the second co-heating test.

1.1 The Test House

The Camden passivhaus is regarded as the first house in London to be accredited to Passivhaus standards. Situated on a residential street in north London, the two-story house has an entirely open plan 1st floor with bedrooms and bathrooms located on the ground floor. Both floors have large amounts of glazing (37.8m^2 in total), almost exclusively on the south façade.

Figure 1: Ranulf Road Passivhaus, south elevation

The building fabric can be divided up into several different elements. The timber frame walls are highly insulated and feature exterior cladding. The ground floor walls have an additional concrete retaining element as the ground floor is partially excavated. There is also an insulated concrete floor slab and a green roof with both a flat and a sloping element to the rear.

Full details of the construction can be found elsewhere but there are several features of note in regards to the success of the co-heating method.

- **A large south-facing glazing area:** There are two implications here. The first is the high potential for overheating above the co-heating 25°C setpoint. Secondly, potentially a large proportion of the heating input will come from solar gains, such that accurately determining the gains becomes increasingly important.
- **Low heat loss:** Designed to passivhaus standards Camden passivhaus is well insulated and has a low overall design heat loss coefficient. This low value means the measurement is more sensitive to some of the uncertainties in co-heating and the building is more susceptible to overheating.
- **Open Plan:** The 1st floor is an open plan living space. This facilitates good mixing under the co-heating method. The ground floor is more partitioned, particularly with a number of small WC's and cupboards.
- **Partially excavated:** Camden passivhaus is on a partially excavated site and therefore has a large proportion of its envelope in contact with the ground, rather than the air. The ground floor slab accounts for 15% of the total envelope and when incorporating the excavated external wall this increases to 35%.

1.2 Scheduling co-heating test

Work of the author involves investigating the uncertainty in co-heating through simulated tests. This allowed an Energy Plus model of Camden Passivhaus to be created and then a vast number of simulated co-heating tests to be performed. In particular these were used to determine the likelihood of achieving an accurate result and determining what weather conditions would achieve this. Continuous co-heating tests were simulated across a typical year, figure 2.

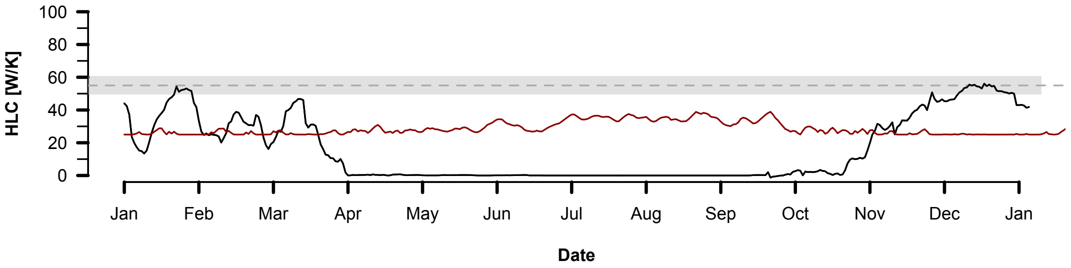

Figure 2: Results of simulated co-heating tests on Camden Passivhaus. The derived heat loss coefficient (black line) is shown throughout atypical year. The grey band represents a region ± 10% around the true HLC. The internal temperature (red) is also shown to identify overheating.

What is seen in figure 2 is that any significant overheating results in the co-heating method failing to achieve a result. Outside the typical co-heating test season of October-March there is no chance of achieving a result. In fact, there are only brief periods throughout the whole year when results were achieved to within 10% of the expected heat loss coefficient. These occur in December and January and represent periods with little solar radiation and no overheating. Furthermore, it is desirable that as high a proportion of heating input comes from electrical power, rather than solar gains. These two signals across the same simulated year are shown in figure 3. It is clear then that dull conditions are required and should be sought for the second co-heating test. Testing of the Camden Passivhaus is however very sensitive to the external weather conditions so any test carries with it an element of risk. Figure 2 really shows that performing a co-heating measurement in a house such as the Camden Passivhaus is extremely challenging and even at the best times of year there is a great risk the measurement will incorporate a large amount of uncertainty. This is in short the story that is told by the two co-heating tests documented here. Performing initial investigations such as this therefore seem increasingly prudent in sensitive test houses, where a little more foresight could avoid wasted tests.

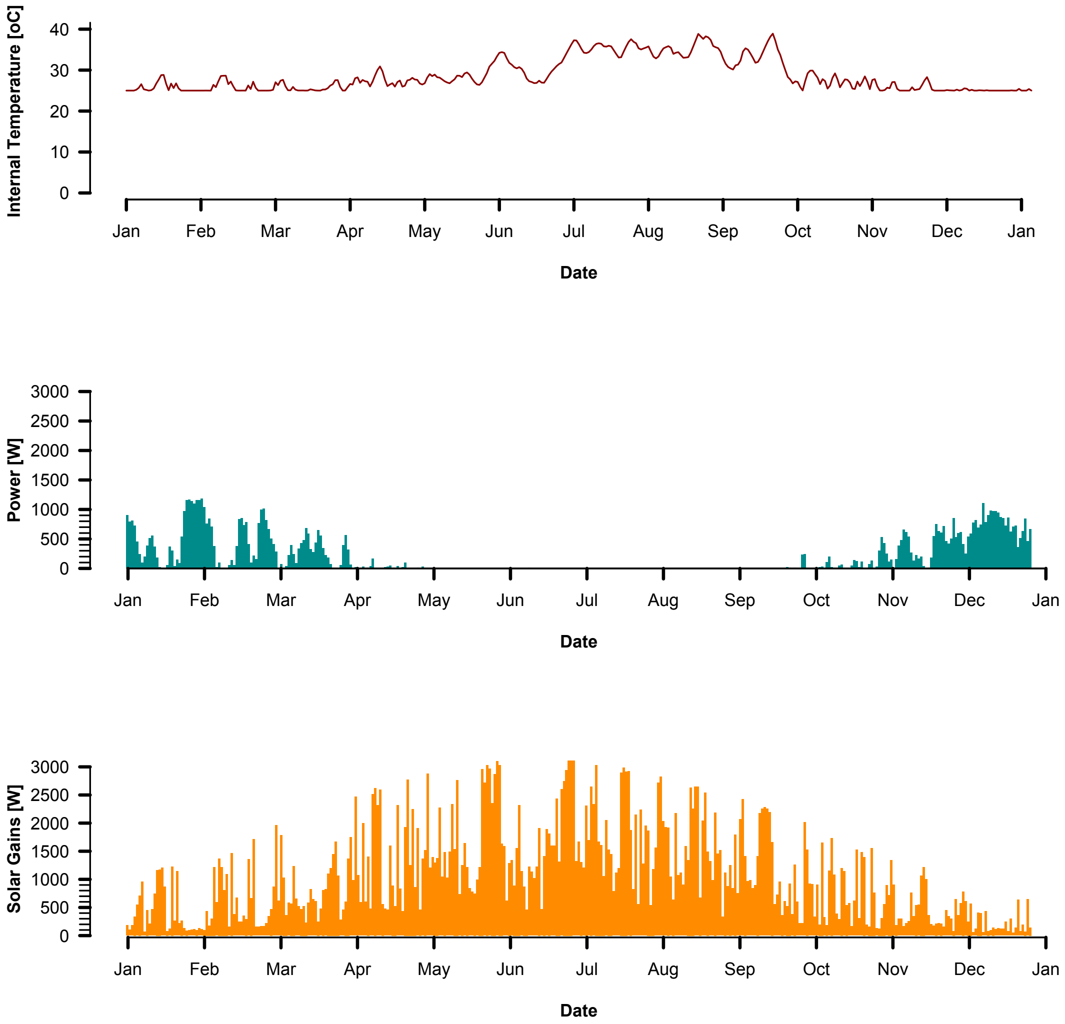

Figure 3: Simulated internal temperature, electrical heating power and solar gains across typical year.

2. 2012 Co-heating of Camden Passivhaus

2.1 Co-heating Principal

The co-heating method dates back to work in the US in the 1980's on the PStar and STEM methods (Subbarao et al., 1988) and to the work by Siviour & Everett in the UK (Everett, 1988; Siviour, 1981). This was then developed into the current set of experimental guidelines (Wingfield et al., 2010). The two co-heating tests described in this report are based on these guidelines.

The co-heating method is based on an energy balance at an approximated steady state. The test building is held at a constant internal temperature, typically 25°C, through the use of electric fan heaters and mixing fans, figure 6. This constant internal temperature minimises dynamic behaviour in the dwelling and means that, under co-heating approximations, the heat input equals the heat loss of the building across daily averaged measurements.

Heat input, Q [W], to all electrical equipment is recorded through the use of kilowatt-hour meters and pulse counters. There is additional heat input, from solar gains, that also need to be accounted for. Solar radiation, S [W/m^2], is measured externally by a pyranometer. This is then converted into the effective heating contribution [W] from solar gains by a solar aperture, R [m^2]. The solar aperture can itself be derived experimentally from the co-heating test or alternatively from the glazing characteristics of the dwelling.

Figure 4: Co-heating principal and analysis method. The energy balance the co-heating method uses is shown along side an example of data used in linear regression. Typically an additional independent variable and axis for solar radiation is included as part of a multiple linear regression.

$$Q + R.S = (\Sigma U.A + \tfrac{1}{3}nV)\Delta T \quad \text{(Equation 1.)}$$

Here, Q is the heat input from electric heaters or other heating device [W]
$R.S$ is the Solar Gains [W], where S is the solar radiation [W/m^2] and R is the solar aperture [m^{-2}]
ΔT is the temperature difference [K] between the internal and external conditions
$\Sigma A.U$ [W/K] is the sum of the U-values [W/m^2] and respective areas of the thermal envelope [m^2]
$\frac{1}{3}nV$ is the infiltration heat loss [W/K] comprising of n the air change rate [h^{-1}] and the volume, V.

By taking long enough averaging periods, 24 hours, the dynamic effects inside the test dwelling are assumed to be averaged out such that the energy balance equation 1 is satisfied. This allows the daily heat input (from electrical heating and solar gains) to be plotted against the daily averaged internal-external temperature difference, ΔT, (figure 4). The slope of the line of best fit, which goes through these points, gives the buildings measured heat loss coefficient, [W/K]. This regression of power against ΔT can be performed as a simple linear regression with solar corrections as explained here or through a 'Siviour' or multiple linear regression, both of which separate out the electrical power and solar radiation. All three are demonstrated in section 2.3.

2.2 Camden Passivhaus Set Up

In total four sets of kW-hour meter, fan, heater and thermostat combinations were positioned in the house, figures 5 & 6. This is to provide sufficient heating power and control to maintain an internal temperature of 25^{o}C. Additional temperature and relative humidity sensors were placed in all zones in the house to establish a representative internal temperature for use in analysis and to ensure a uniform temperature was achieved throughout the dwelling. Additionally, heat flux sensors were placed in pairs on sections of the lower and upper external wall as well as on the ground floor. As the house is occupied and it was not possible to affix the heat flux sensors with thermal paste these were not used to measure in situ u-values but more to understand heat flows throughout the co-heating test.

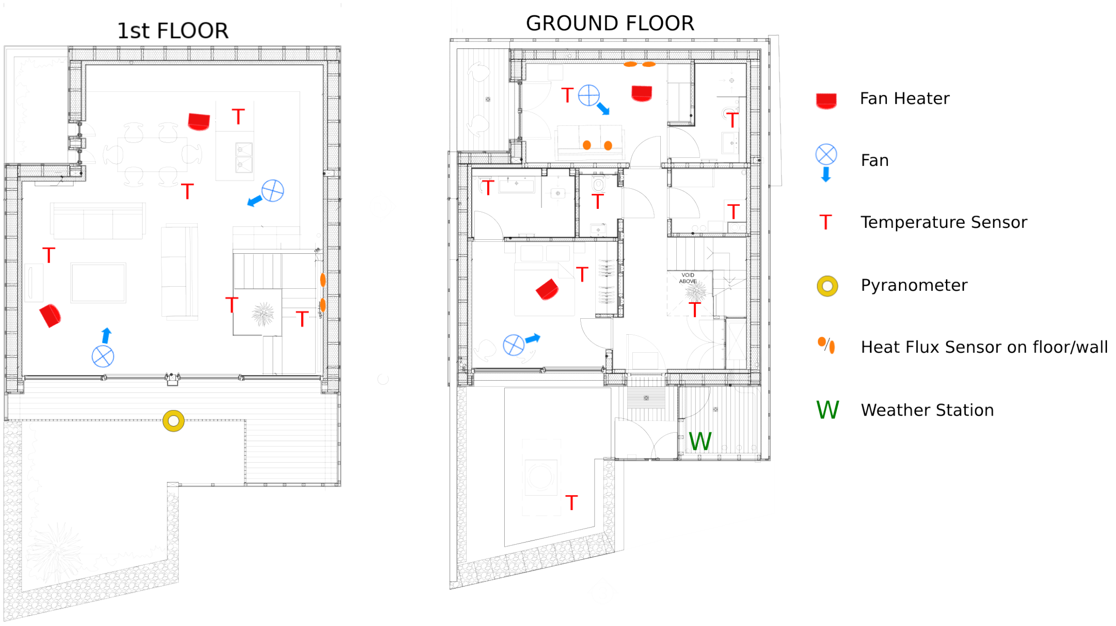

Figure 5: Equipment Layout for second (2012) co-heating test.

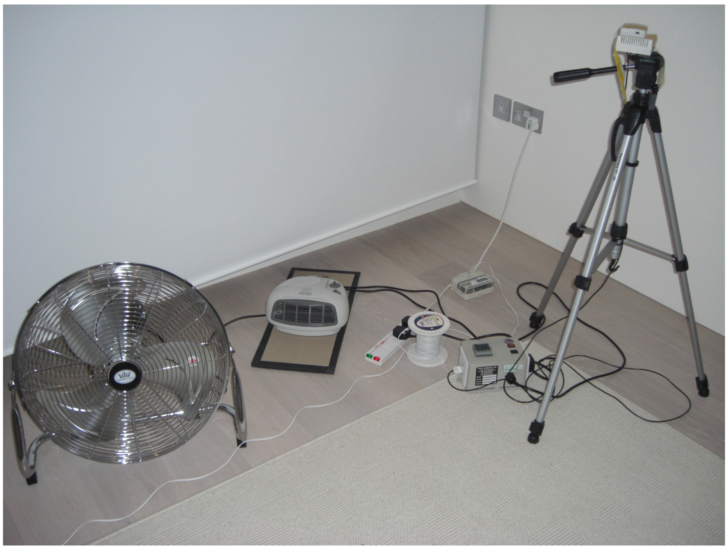

Figure 6: Co-heating zone equipment

The external environment needs to be monitored throughout the co-heating test, not only to record the external temperature required to establish a ΔT, but also to record other external variables which can be sources of uncertainty in the co-heating method. These external environment sensors included:

- An **external**, shielded, **temperature sensor:** located on a tripod stand in the front garden. (Note: this represents one of the few significant changes in equipment between the two tests. The original test did not include such a sophisticated external temperature sensor, this is discussed in the comparison section)
- **Local Weather Station**: Located on the 1st floor balcony. This included external temperature, relative humidity, wind speed & direction. Data from a second weather station, installed as part of the long term TSB monitoring programme located on the green roof was also available.
- **Pyranometer:** Vertical and in the plane of the south facing building façade. Measures solar radiation [W/m^2]

Figure 7:

Equipment used to monitor external environment. Clockwise from top left: Stevenson screen external temperature sensor, vertical facing pyranometer on balustrade, weather station, south façade showing weather station and pyranometer on balcony level.

2.3 Result of 2012 Co-heating Test

Camden passivhaus was unoccupied for a total of 10 days, of which 6 days are used in the full co-heating analysis. Including a day each end of the test for setting up and taking down equipment this left 8 days at test conditions. A further day at the beginning of testing was removed from analysis as the building's mass was still being heating to the set point temperature and was therefore a source of bias. Finally, a day was used to perform a cool down – warm up cycle, following that of the PStar method. This will be used later to evaluate the thermal mass of the dwelling but is not used in the co-heating data or included in this report.

The six days of co-heating data are analysed in four different ways:

1) Global Average

A simple average of total power input and average temperature difference across the test period can be calculated. This is often useful as a check on the regression process itself, particularly when there is not a wide spread in data points.

Global Average HLC = 56 ± 5[2] W/K

2) Simple Linear Regression

More traditionally co-heating data is analysed through regression. The simple linear regression model plots the heating power against ΔT. This is shown in a raw and solar corrected form in figure 8.

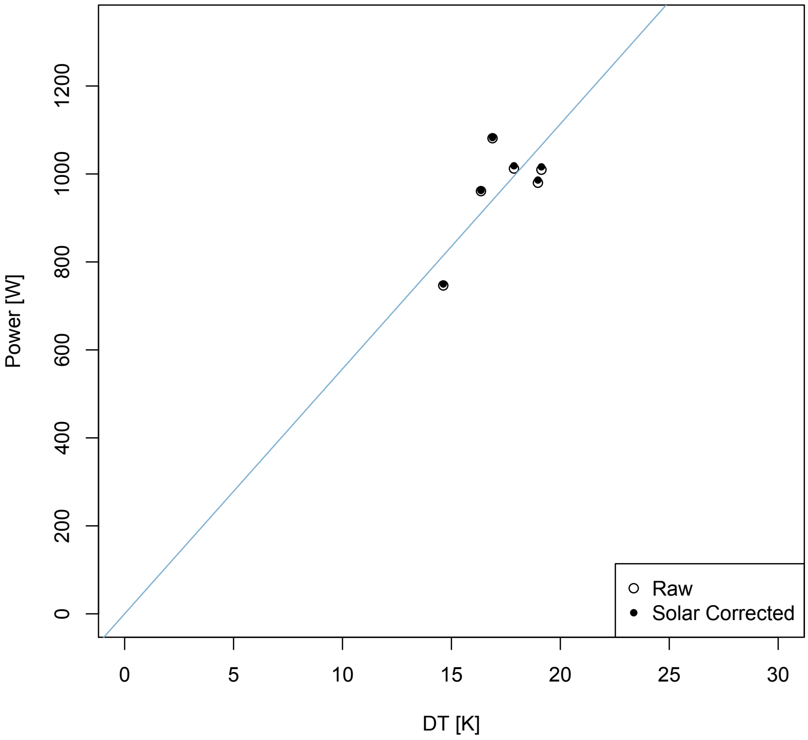

Figure 8: Simple Linear Regression co-heating analysis

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[2] The error here is the standard deviation from each days data.

The results from the simple linear regression show:

Simple Linear Regression HLC = 56 ± 5 W/K

The solar correction seen in figure 8 is very small. This is a result of such a low level of solar radiation being experienced across the test period. In fact only about 1% of the total heating power is calculated to come from solar gains, the rest from electrical heating. This is in stark contrast to the first test, discussed in section 3.

3) 'Siviour Analysis'

Another form of regression analysis often used is 'Siviour' analysis. This rearranges the energy balance equation into the form seen in equation 2. Here the heat loss coefficient is the y-intercept of figure 9. An advantage of this method is that the solar aperture can also be derived from regression, forming the slope of the line of best fit in this case.

$$\frac{\boldsymbol{Q}}{\Delta \boldsymbol{T}} = -\boldsymbol{R}.\frac{\boldsymbol{S}}{\Delta \boldsymbol{T}} + \left((\boldsymbol{\Sigma A}.\boldsymbol{U}) + \frac{1}{3}\boldsymbol{nV}\right) \qquad \text{(Equation 2)}$$

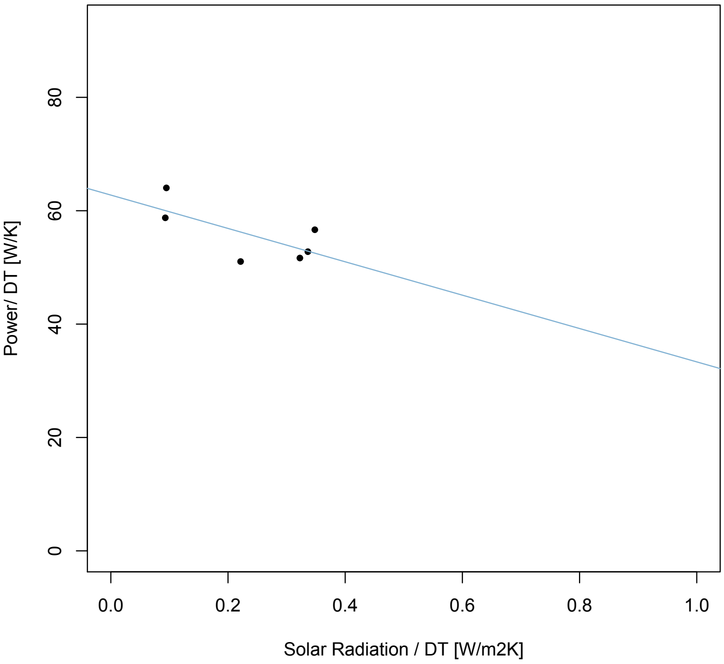


Figure 9: Siviour Co-heating Analysis

HLC = 63 ± 10 W/K
Solar Aperture = -29 ± 15 $\mathbf{m^{-2}}$

It is important to note here that the derived solar aperture has a significant amount of error associated with it. This is in part because all days data featured very low levels of solar radiation. A small range in data such as this results in a higher degree of uncertainty. The solar aperture can also be derived from the glazing properties, equation 3 (SAP 2009, pg 21).

$$G_{solar} = 0.9 \times A \times S \times g \times FF \times z \qquad \text{(Equation 3)}$$

Where:

0.9 is a factor representing the average transmittance to that at normal incidence
A is the glazed area [m^2]
S is the solar flux [W/m^2]
g total solar energy transmittance factor at normal incidence
FF is the frame factor, the fraction of the opening that is glazed
z is a solar access factor or shading factor

The solar apertures derived from regression in both the Siviour analysis and multiple linear regression differ from the calculated value here of 6.2 m^{-2}. This is not particularly significant in performing solar corrections in this second test as the amount of solar radiation was so small. It is however far more significant under high levels of solar radiation, as in the first co-heating test where is creates a significant uncertainty.

4) Multiple Linear Regression

Finally, and perhaps more commonly, multiple linear regression can be carried out between Power, ΔT and solar radiation. Again this extracts the heat loss coefficient and solar aperture through regression. The results are as follows:

HLC = 63 ± 10
Solar Aperture = -30 ± 14 m^{-2}

2.4 Discussion of results

The four methods of analysing the result here show a small variation between each other ranging from 55 – 63 W. Generally multiple linear regression can offer the more reliable results but can be biased by poor data in the regression variables. The poor range, and subsequent large error in solar radiation means its use as a regression variable is less reliable. As there was such a little amount of solar radiation and therefore the scale of any correction is very small the simple linear regression result offers a more reasonable result. Therefore the quoted value from this second co-heating test is to be taken as:

Simple Linear Regession HLC = 56 ± 5 W/K

2.5 External Conditions

The external environment is a key driver for sources of uncertainty in the co-heating result. High variation external temperature, solar radiation or wind speed can cause errors in the co-heating results. However, in this second test there was relatively little variation in wind speed and external temperature. There was also a very small amount of solar radiation across the test period.

Another point to note is that a large part of the building envelope is in contact with the ground, rather than the ambient air assumed in co-heating. This de-coupling of the two temperatures can cause an offset in the co-heating result and could be significant in the case of the Camden passivhaus. However, the ground temperature, measured at site, remains fairly steady across the test period. It also has an average value of 8°C which is close to the average air temperature of 7.6°C. It is therefore assumed no significant offset exists.

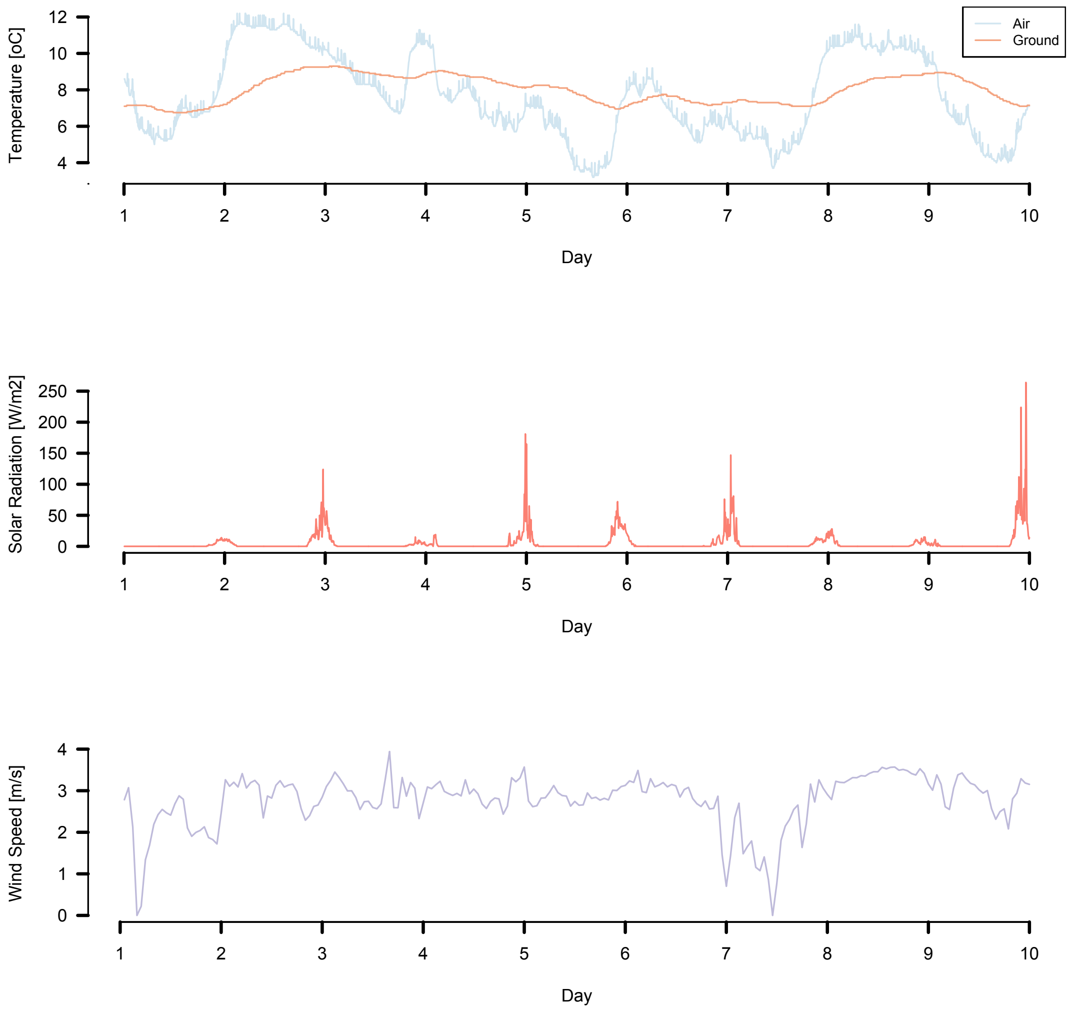


Figure 10: External Environment throughout the test period

2.6 Internal Conditions

The co-heating analysis is based on the assumption of a constant and uniform internal temperature. When the condition of constant temperature is broken thermal mass effects come into play, which can create lags and distort the energy balance. The initial Camden Passivhaus test is a prime example of this.

The second condition, of a uniform temperature can also create bias. If a particular area of the house experiences higher or lower temperatures than the average internal temperature then the heat loss through the associated building elements will equally be higher or lower respectively. If such an area has a substantially different heat loss this can significantly bias the results.

It is obviously impossible for a perfectly uniform and isotropic internal temperature to be maintained throughout testing. It is therefore important to assess the limitations to this assumption by viewing the internal temperatures throughout the test period.

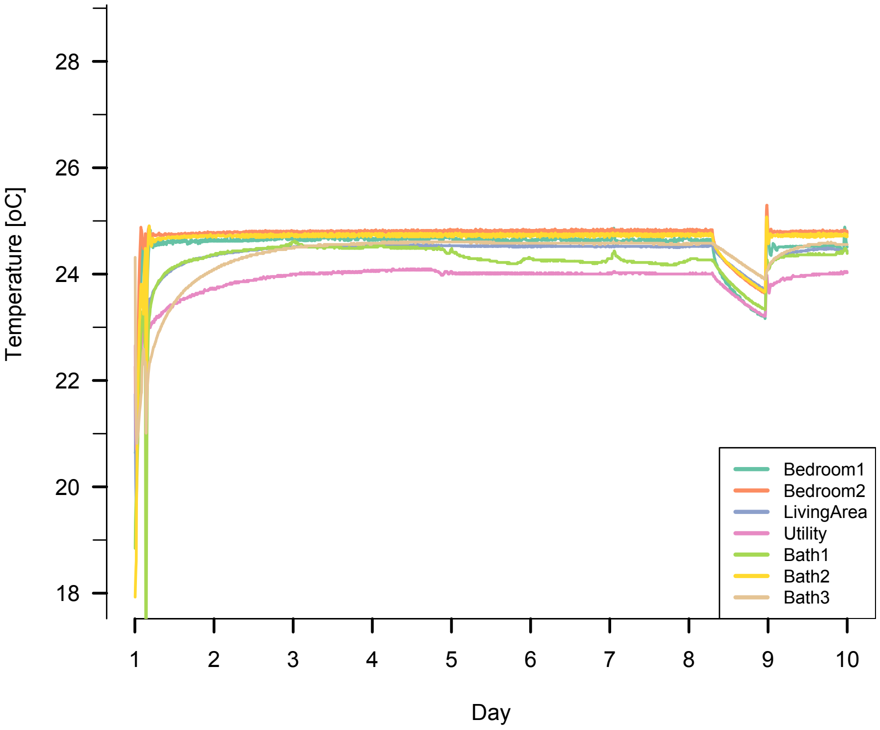


Figure 11: Internal temperature profiles throughout second co-heating test

Figure 11 shows most temperatures were maintained within a tight range, under half a degree. Some zones did take a longer period to heat up to the 25°C set point, either because they were not themselves directly heated (Bath1, Utility) or they incorporated a large volume in which to fully heat (Living Area).

The utility room, not being directly heated and being an enclosed space, did not reach a temperature as high as the internal mean. This, as mentioned, can cause a bias. A way of examining this problem and potentially correcting it is to take either volume weighted or heat loss weighted average internal temperatures – as opposed to a simple arithmetic mean. These were both examined but as the utility is only a degree different in temperature and represents a small proportion of the internal volume and external envelope this does not significantly alter the representative internal temperature.

Figure 11 shows a good degree of control in the internal temperature. This can often be upset by highs in midday solar radiation causing brief periods of overheating. If this persists at high levels then long term overheating can be seen, see section 3.3. This breaks down the assumption of a steady state thermal mass and can cause large amounts of error in the co-heating result, a steady state model that cannot handle this dynamic behaviour. The absence of any overheating in the second co-heating test affords us confidence that this assumption does still hold.

3. 2010 Co-heating of Camden Passivhaus

3.1 Introduction

The original co-heating test is documented in a previous report but some elements are again reported here to allow a comparison with the second test.

In general and as previously mentioned the timing of this second was far from ideal and featured high amounts of solar gains. This in turn led to overheating and undermined the accuracy of the derived heat loss coefficient. The stated result of 35 ± 15 W/K seemed to indicate the Camden Passivhaus was performing well but there was a large amount of uncertainty in this result. Further details can be found in the original report but relevant details are discussed in this section to provide a comparison to the second test.

3.2 Test Method

The same basic test method was followed for the first test as in the second. Again the house was occupied so scheduling a test was difficult. To allow for more co-heating data a pre-heating phase was used. This included heating the building to the 25°C set point temperature whilst still occupied. This was to reduce any loss of data to the building and its mass warming up. In total the pre-heating period lasted five days with a further 12 days of data used in the co-heating analysis.

Equipment used in both tests was largely the same although there were a couple of differences. The first test did not feature such a sophisticated external temperature sensor. This had meant external temperature measurements were more susceptible to the influence of solar radiation. To limit any inaccuracies these were also compared to an external local weather stations data. A dedicated on-site weather station was also not used in the first test. However, this is not too significant as there is little variation in heat loss with wind speed seen in the second test or similarly in the simulated co-heating tests.

The equipment layout can be seen in figure 12.

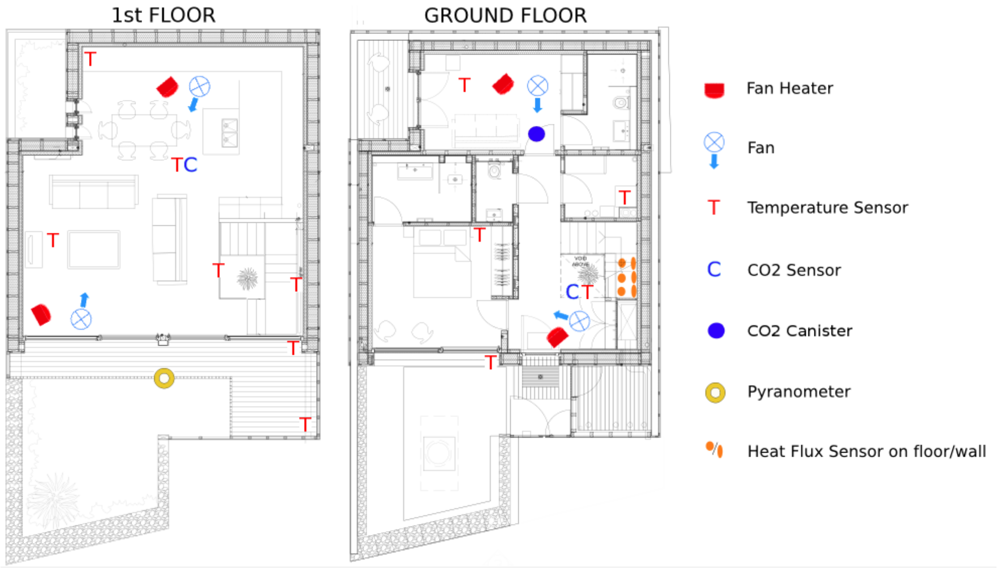


Figure 12: First Floor & Ground floor plans, with location of sensors and equipment for the first co-heating test.

3.3 Internal Conditions

The internal conditions and overheating in the first co-heating test of the Camden passivhaus need to be understood to put the result in context. The internal and external temperatures are shown in figure 13.

Significantly, after the overheating was observed the internal and external blinds were lowered. This was to see if further over heating could be avoided. Unfortunately, due to the low heat loss and thermal mass of the building it took a significant amount of time to cool down to 25°C again. This meant for an extended period the energy balance and steady-state co-heating assumptions broke down.

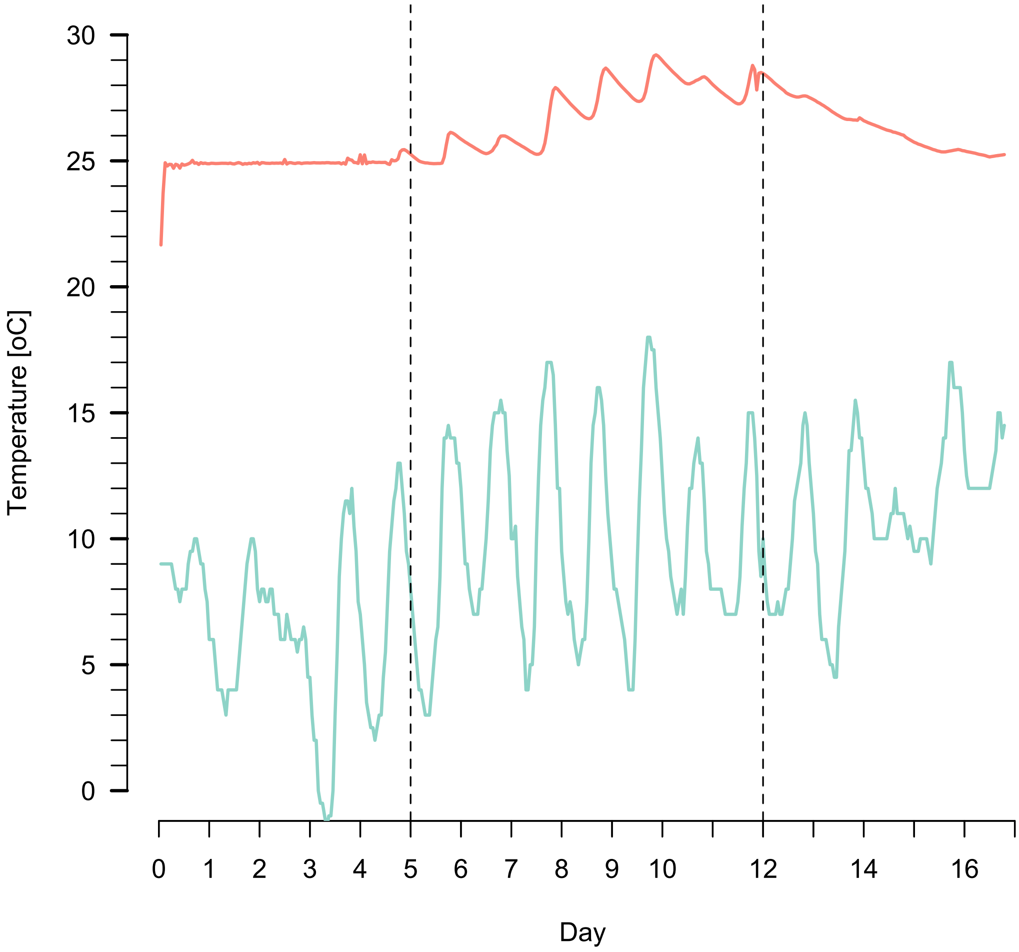


Figure 13: Internal Temperature profile from test 1. The first dashed line represents the end of the pre-heating phase and the second indicates when the blinds were shut.

As figure 13 shows the overheating started shortly after the beginning of the co-heating test proper on day 5. The overheating quickly meant that the internal temperature was rising and rising until day 12 when the blinds were shut. For the subsequent five days the building was still cooling down to the set point temperature. This all means that the steady state assumptions the co-heating test are based upon were not met and this significantly impacted the result.

3.4 Main Co-heating Result

The co-heating results from solar corrected linear regression, as originally reported, are shown in the two figures below. The data from days with the blinds shut is initially removed as during these days the highest heat input was not electrical power or even solar gains but in fact the thermal mass of the building itself. In the second plot a rudimentary correction to these days has been applied.

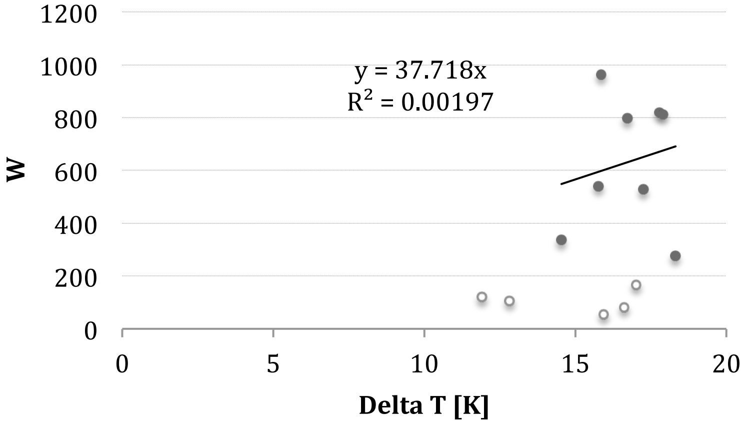
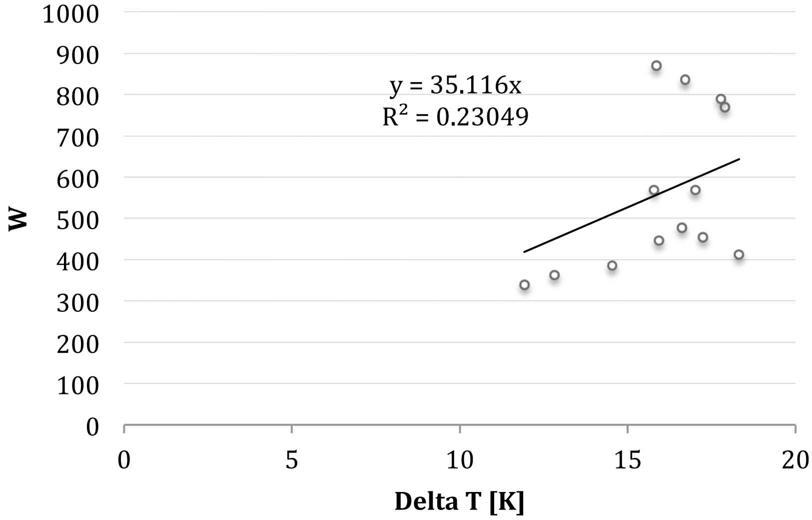


Figure 14: Plot to determine thermal heat loss coefficient. Solid data points represent the days 5-13 and the hollow points show the discarded points in the days 14-18 in which the blinds were shut.



- **Figure 15: Result with corrections for thermal mass contributions**

This rudimentary correction involved the use of heat flux data. The change in heat flux seen during the cooling down of the building was associated with the thermal mass contribution to internal heating. This was then extrapolated and used to correct those five data points. This does rely on some heavy assumptions and carries with it a large amount of uncertainty. The result from this first test was therefore stated to be:

$$35 \pm 15 \text{ W/K}$$

Another large source of uncertainty is the extent of the solar corrections derived from the solar aperture. As previously mentioned the solar aperture can be experimentally calculated or calculated from the glazing characteristics of the dwelling. The data in both co-heating tests did not allow for this to be done experimentally so it has been calculated from glazing characteristics in the PHPP file. As with the heat loss coefficient there is likely to be a difference between the design and as-built solar aperture value. In this first test as such a high proportion of the heating came from solar gains any inaccuracy in the solar aperture can have a significant influence of the stated heat loss coefficient. This makes any test that features high proportions of solar gains inherently less accurate than a dull one, in which the solar aperture has far less influence. This is one of the main reasons the second co-heating result can be stated with far more confidence than the first.

3.5 External Conditions

To compare with the external conditions of the second test in figure 10 the external conditions of the first test are shown below. It is important to note the lower ΔT, related to higher external temperatures, and a larger variation in external temperature, which will lead to more thermal mass effects. Most significantly solar radiation regularly reaches values four times higher than the maximum seen in the second test.

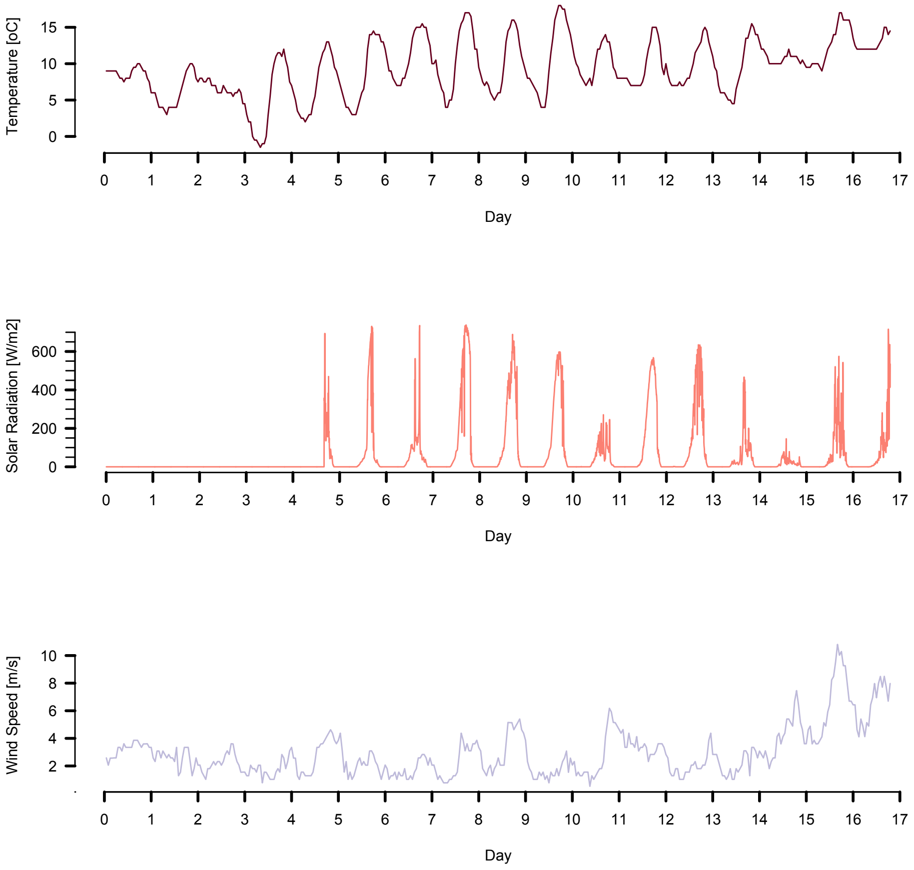


Figure 16: External weather conditions of the first co-heating test

4. Conclusions & Recommendations

Two co-heating tests were performed on Camden passivhaus, the first in March 2010 and the second December 2012. The result of the first test was 35 ± 15 W/K, indicating the building performed well in comparison to its design intent. However, this first test had a large amount of uncertainty due to high solar gains and overheating.

Therefore a second test was performed in December 2012. Simulated co-heating tests had show this was the most likely time to achieve an accurate result, although this depended on having dull conditions. Fortunately this second period was extremely dull and allowed a second result of 56 ± 5 W/K to be recorded with far less uncertainty.

This indicates that the Camden passivhaus is performing well in comparison to its PHPP design intent of 66 W/K. This is a good reflection on the design and build quality of Camden passivhaus and lessons from this process could be taken forward to ensure more buildings had as-built performances closer to design.

Co-heating is one of few post construction tools we have that are capable of evaluating actual performance in situ. The test method is fairly demanding in terms of test duration and requirements over the incumbent weather. The demands on modern energy efficient houses, particularly in passivhaus style designs, are even greater and the sensitivity to uncertainty higher. From simulation work in section 2 as well as both the co-heating tests it is clear that overheating above the co-heating set point temperature has massive implications on the co-heating result. The steady state co-heating model cannot handle the dynamic thermal mass effects induced when this overheating occurs. The solution, if the co-heating method is going to be used in dwellings similar to Camden passivhaus is that overheating needs to be avoided. This may mean lowering blinds throughout testing and accepting the limitations this causes. Or it may require a higher internal set point temperature and the repercussions to the building fabric cracking and drying out accepted. Performing simulated co-heating tests as in section 1.2 can allow the researchers greater understanding of both the uncertainty in the co-heating measurement and the likelihood of achieving an accurate result.

Even after avoiding overheating there still remain large amounts of uncertainty in the co-heating result from accurately determining solar gains and the solar aperture. The solar aperture itself may have more uses beyond the co-heating method, such as assessing the probability of summer time overheating. Therefore more research is needed into this type of building parameter measurement.

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