Review of co-heating test methodologies

Primary research

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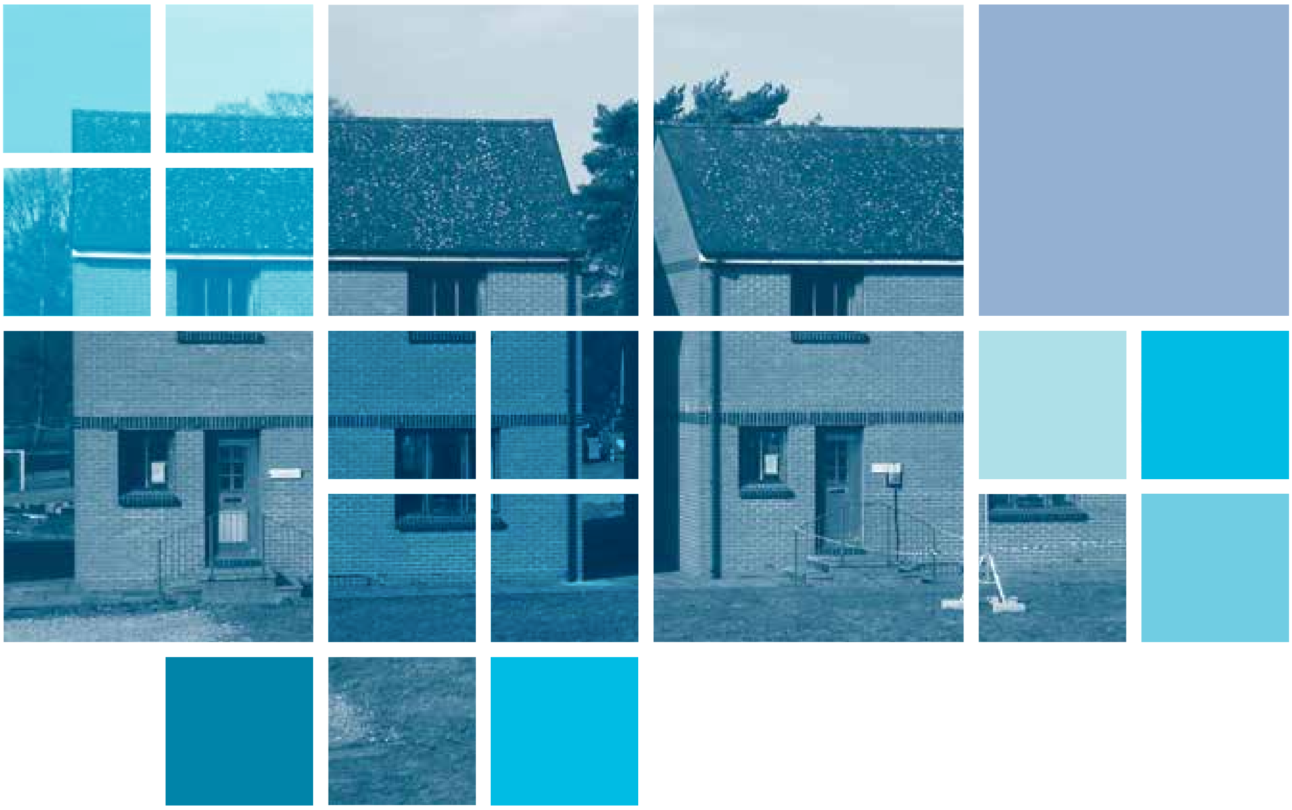

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About NHBC Foundation

NHBC Foundation was established in 2006 by NHBC in partnership with the BRE Trust. Its purpose is to deliver high-quality research and practical guidance to help the industry meet its considerable challenges.

Since its inception, NHBC Foundation's work has focused primarily on the sustainability agenda and the challenges of the Government's 2016 zero carbon homes target. Research has included a review of microgeneration and renewable energy technologies and the earlier investigation of what zero carbon means to homeowners and house builders.

NHBC Foundation is also involved in a programme of positive engagement with Government, development agencies, academics and other key stakeholders, focusing on current and pressing issues relevant to the industry.

Further details on the latest output from NHBC Foundation can be found at www.nhbcfoundation.org.

Contents

Glossary

GPRS	GPRS (general packet radio service) allows transmission of data including text messaging via the mobile phone network.
Heat loss coefficient (HLC)	HLC is the total heat loss from a building resulting from heat transfer through the envelope (walls, roof and floor) and from background ventilation per °C of temperature difference between inside and outside (expressed as W/K).
Infiltration rate	Infiltration is the unintentional or accidental introduction of outside air into a building, typically through cracks in the building envelope and around windows and doors. Infiltration rate is generally measured in m^3/h.
Infrared thermographic survey	Infrared thermographic surveys may be undertaken in buildings to provide digital images showing the variation in surface temperature of solid objects, such as walls and roofs, through the variation in an artificial colour scheme. It is an effective method of identifying small variations in surface temperature caused by air leakage, changes in insulation and thermal bridging.
Linear regression	Linear regression is a method of defining the relationship between two variables by fitting a linear equation or straight line to the observed data. One variable is considered to be an explanatory variable, and the other is considered to be a dependent variable. The linear equation defines a straight line and has the form $Y = a + bX$, where X is the explanatory variable and Y is the dependent variable. The slope of the line is b, and a is the intercept (the value of y when $x = 0$).
Pulse width modulator (PWM)	This is a method of digitally modulating electrical signals and electrical power. The signal or electrical power is switched on and off rapidly so that the percentage of full power is proportional to the percentage on time. The switching time for electric heaters is typically up to 60 times a second (60 hertz).
Pyranometer	A pyranometer is an instrument that measures broadband solar irradiance, or solar radiation flux density, on a flat surface. Pyranometers are designed to have a 180° field of view and generally provide a voltage output proportional to the incident solar radiation (W/m^2).

SAP	The Standard Assessment Procedure (SAP) is the methodology used by the Department of Energy & Climate Change (DECC) to assess and compare the energy and environmental performance of dwellings. SAP assesses how much energy a dwelling will consume and how much carbon dioxide (CO_2) will be emitted in delivering a defined level of comfort and service provision, based on standardised occupancy conditions. This enables a like-for-like comparison of dwelling performance.
Siviour method and Siviour plot analyses	The Siviour method is a graphical method of analysing a building's heat balance by plotting heat input (electric heaters) divided by the inside and outside air temperature difference against south-facing vertical solar irradiance also divided by the inside and outside air temperature. This graph is usually known as a Siviour plot. The whole house HLC and also the solar aperture can be directly inferred from the graph.
Solar aperture (solar heat coefficient)	Solar aperture (solar heat coefficient) is the equivalent surface area (m^2) of perfectly transparent south facing vertical surface, which lets in the same solar energy as the whole building.
Solar heat gain	This is the amount of incident solar radiation transmitted to the house interior in the form of heat energy (Watts).
Thermal mass	Thermal mass describes the heat storage effect of the building structure and its fabric. A high thermal mass building can absorb more heat than a low thermal mass building. Thermal mass delays the effect of solar heat gains and external temperature changes on the internal air temperature.
U-value	U-value is the thermal transmittance (W/m^2K) of a building element such as a wall, floor or roof and is equal to the reciprocal of the total thermal resistance. The heat transferred through an element is calculated by multiplying the U-value by the surface are (m^2) of the element and the temperature difference (K) across the element.

Foreword

As our understanding of the issues involved in delivering energy-efficient housing has developed, there has been growing concern about the performance gap between design expectations and in-use outcomes. Given the complexity of designing homes to achieve high standards of energy performance and the on-site challenges of building homes, it is perhaps not surprising that their as-built energy and carbon performance may fall short of the design intent. To address the challenge posed by this performance gap, it is essential that we can measure accurately how well our new homes are performing. The co-heating test, developed in its present form by Leeds Metropolitan University, provides a means by which the as-built performance can be measured.

The aim of this project was to understand the accuracy of the co-heating test and its wider application. This was done by carrying out a series of co-heating tests on the same house, each test being conducted by a different project partner. This was a potentially challenging process, so we were delighted by the willingness of our project partners to become involved and the spirit of cooperation that prevailed throughout.

The headline finding is that there was a reasonable spread of results, principally due to the differing methods of analysis used, as opposed to significant variations in the way different project partners conducted the test. This spread demonstrates the need for caution in the interpretation of results from individual co-heating tests. A key secondary finding highlighted by this research is that solar gain is the largest cause of the differences. Some recommendations on how this can be controlled are presented in this report.

As we get nearer to the target date for zero carbon new homes, it is essential that our understanding of the so-called 'performance gap' improves. This primary research from NHBC Foundation and BRE Trust helps to underpin that work. These findings are well-timed and will have relevance to the current government-sponsored project being led by the Zero Carbon Hub, with the title 'closing the gap between design and as-built performance'.

Rt. Hon. Nick Raynsford MP
Chairman, NHBC Foundation

Executive summary

The co-heating test is an experimental method of determining a building's 'as-built' heat loss coefficient (HLC), a parameter which is calculated by plotting the daily heat input against the daily difference in temperature between the inside and outside of the building. The test potentially allows deviations from the design performance to be identified by comparing the HLC, derived using the co-heating procedure, with the HLC determined through the Standard Assessment Procedure (SAP) using the building design parameter values.

In practice the reliability and practicality of the co-heating test method has been questioned due to the long test duration and uncertainty in the HLC. For example, a test duration is typically two weeks and during that time no access to the building interior is permitted. External weather parameters including temperature, wind and in particular solar radiation are major confounders. For these reasons it is recommended that the current approach to co-heating testing is at present unsuitable for large scale application across the construction industry.

This report describes co-heating tests undertaken by test teams from BRE and six project partners including BSRIA, Stroma Technology and four universities in one of BRE's test houses, with a second identical test house used as a control. In addition BRE also undertook some further co-heating tests with various forms of window solar shading.

The test teams based their co-heating tests on a methodology previously developed by Leeds Metropolitan University. Although that guidance did not cover analysis and derivation of the HLC, all of the test teams used a form of regression analysis including a Siviour plot which is a method of graphically analysing the house heat balance to determine the whole house HLC. The test teams also made measurements in order to derive the solar aperture.

It was clear from the tests carried out that the external weather conditions, particularly solar radiation, represented a major confounder and had a major impact on the accuracy and repeatability of the co-heating test by making it difficult to achieve true steady state. The maximum uncertainty in the results from the co-heating tests and the SAP equivalent HLC was 17%.

A major factor in determining repeatability and accuracy was the spread in external temperature and solar radiation during the co-heating tests. In order to derive the solar aperture accurately it was necessary to obtain a large spread or range in external temperature and solar radiation values. This means that shortening the test duration very likely reduces its accuracy. It also follows that a long spell of consistent weather conditions (temperature and sunshine) with a small range or variation may have the effect of reducing accuracy and repeatability.

Additional co-heating tests with window shading appear to have reduced the uncertainty such that the measured values were within -3.8% of the SAP HLC. However, with just three tests carried out (each one undertaken with a different type of shading) this result cannot be considered to be conclusive and should be tested with other types of building and at other times of year. However, if it is subsequently shown that physical window shading is effective elsewhere then it would make the co-heating test a more accurate and therefore useful method of determining the as-built HLC. It is therefore recommended that the effect of

external shading on reducing the uncertainties should be investigated further by trialling in other types of houses, other building types and under different weather conditions.

It has also been suggested that the analysis of co-heating test data for overnight hours only, might reduce the uncertainty caused by solar heat gains and might also reduce the test duration. The use of window shading may also contribute to the reduction in uncertainty from night data analysis by reducing the daytime solar heat gains stored in the building and therefore the effect on the night time thermal balance. More research and testing in buildings with a range of thermal mass would be necessary to prove the effectiveness of such measures, and also to determine the optimal day beginning and end times.

Section 1 of this report provides background information on co-heating tests in general and Section 2 introduces the objectives of the research project. Section 3 provides an initial review of the co-heating test as it is used currently in the UK. The testing, results and findings of the research project are presented in Sections 4 and 5. The final section of the report presents the main findings and conclusions drawn from the research project and provides recommendations for areas in which further research is required in the future.

1 Background

The co-heating test is an experimental method of determining a building's overall HLC due to conductive heat losses (through the wall, roof, floor and windows) and ventilation heat losses. The HLC is calculated by plotting the daily heat input against the daily difference in temperature between the inside and outside of the building. In most circumstances during the test the building is heated using metered electric heaters and air circulation fans to a constant air temperature, usually around 25°C. All windows, doors and ventilators are kept closed during the test and other heat sources should be prevented. Therefore the building has to be unoccupied. Special consideration also has to be made for houses that are semi-detached, terraced or are in a block of flats. Ideally adjacent buildings or rooms are heated to the same air temperature for the duration of the test.

The co-heating test duration is normally around two weeks in order to ensure that steady state is achieved and that a range of weather conditions is covered. An energy balance is undertaken between the electricity supplied to heat the building (plus estimates of solar heat gains) and the heat loss through the fabric, and due to air infiltration. The whole house heat coefficient (in Watts per Kelvin [W/K]) can then be determined from the gradient of a plot of mean heat input measured in Watts against the internal to external temperature difference (dT). Estimating the solar heat gains requires additional analysis, and prolonged high levels of solar heat gains and/or high wind speeds can considerably increase the uncertainty. Such factors may also require the test duration to be extended.

External air temperature, wind speed and solar irradiance local to the building should also be measured during the test. The location of each of the instruments used for this needs special consideration to avoid shading, influence of warm surfaces in sunny weather, and in some locations the risk of theft or vandalism.

Comparison of the empirical co-heating test derived whole house HLC against the whole house heat loss calculated through SAP can identify anomalies in the performance of the building fabric that may not be identifiable by any other method. The HLC is the rate of heat loss measured in Watts through the building fabric and is proportional to the inside to outside temperature difference. The co-heating test is a field measurement of the as-built building whereas SAP calculates the HLC using standard U-values and levels of airtightness. An infrared thermographic survey and airtightness test can assist in any subsequent analysis of data.

The usefulness of the co-heating test can be improved by simultaneously measuring the infiltration rate (the unintentional or accidental introduction of outside air into a building, typically through minor cracks in the building envelope and around windows and doors), usually using a tracer gas technique. This allows the infiltration heat loss to be estimated and therefore makes it possible to estimate the respective contributions to total heat loss by losses via fabric and infiltration. The addition of heat flux plates attached to representative fabric elements, such as the walls and top floor ceilings, allows individual fabric element U-values to be estimated.

Ideally co-heating tests should not be undertaken in hot weather although in some cases it may be possible to get around this by heating the building to a higher internal temperature (possibly as high as 35°C). However, there are practical and safety issues associated with this and it is not known what the impact on conduction and infiltration might be. The best time of year to undertake co-heating tests is winter as it is easier to maintain sufficient temperature difference and there are generally more cloudy days, which reduces the uncertainties caused by high solar heat gains.

Currently the co-heating test is expensive and time-consuming to conduct, and the sensitivity and accuracy of the test is not fully understood. The test has much merit as a diagnostic tool as part of the 'building performance toolkit'. There is an appetite for standardisation of the test, but the first step in such a process is to have a better understanding of the many variables inherent in the test and the presentation and use of results.

Better knowledge of the accuracy, sensitivity and limitations of the test as it is currently applied by practitioners would greatly benefit the construction industry and all of its stakeholders at a time when good thermal performance of buildings is of paramount importance with respect to the UK's drive for energy efficiency in buildings. More robust, better understood and more widely applied, the co-heating test could provide valuable information regarding the 'real-world' fabric and infiltration heat losses of buildings. The test could also identify 'gaps' in the real performance of fabric insulation – which could inform design and ensure optimum levels of energy efficiency and required levels of workmanship and quality. This is similar to the way in which mandatory airtightness testing has led to improvement in various aspects of construction. However, it might be argued that use of the co-heating test in its current format would probably be limited to use in development and type-testing of new designs and construction methods.

In principle the HLC determined by the co-heating test method is comparable to the whole house HLC determined by SAP. The principal difference is that the co-heating HLC is of the as-built building, while the SAP HLC is based on the design specification including standard or manufacturers' values for the thermal transmittance (U-value) of the various building elements. As-built factors include discrepancies between standard and as-built U-values for individual materials and the effect of workmanship on thermal bridging and the integrity of thermal insulation. A further discrepancy between co-heating and SAP HLCs may arise due to differences between design and achieved airtightness.

Both SAP and co-heating tests determine a 'steady state' HLC. This assumes that the building fabric is at steady state and is fully heat-soaked. In reality for the co-heating test this will not be strictly true because of the varying external air temperature and solar heat gains. However, under normal building operation the effects of heating controls and occupancy heat gains will add very significantly to the climate-induced variation in temperature difference across the fabric and stored heat. Therefore an HLC determined during occupancy, were this to be possible, may be significantly different to either SAP or co-heating test HLCs.

Throughout this report comparison is made between the HLC values determined from the co-heating test results and from SAP in order to evaluate the uncertainty in the test measurements. This approach must be treated with a high degree of caution and is not recommended for buildings in the field. The BRE test houses had factory-manufactured timber frames, were constructed very carefully under BRE supervision and the construction details were precisely determined and recorded.

2 Introduction

The objectives of the research project were as follows:

- Set up a small project steering group. This was to include commercial and academic project partners willing to conduct a co-heating test on a test house at BRE in Garston, as well as other interested parties.
- Provide a brief review of the co-heating test as it is carried out at present in the UK.
- Prepare a pair of identical detached test houses (House A and House B) at BRE in Garston, for use in the research project. The level of workmanship employed in the construction of these houses and their materials of construction have been well documented as a result of extensive research carried out on them by BRE over several decades.
- Undertake a co-heating test of House A continuously throughout the testing phase of the research project as an experimental control.
- Undertake a co-heating test on House B using the current BRE co-heating test methodology and protocols.
- Undertake infrared thermographic surveys on the houses during co-heating testing.
- BRE to liaise with six collaborating project partners to undertake co-heating tests on House B in series, using their own protocols, but according to a set of agreed minimum requirements with respect to the testing, results reporting and data evaluation.

- BRE to undertake a repeat of the co-heating test on House B after all other tests have been carried out, as well as further co-heating experiments as defined by the steering group regarding the effect of solar shading.
- Analyse the test data and report the HLC for House B by the project partners.
- As part of the comparison of results, BRE to undertake an analysis of the sensitivities of co-heating testing to factors including different levels of instrumentation, duration, types of weather and mean temperature.
- Develop the research project report, in agreement with the project partners, to include further requirements for research and follow-up investigations.

Following invitations from NHBC Foundation to around 10 organisations, six agreed to participate in the research project to undertake their own co-heating tests on one of the test houses based at BRE, Garston:

- BSRIA
- University College London (Energy Institute)
- Loughborough University (Low Carbon Energy Technology)
- Stroma Technology
- University of Nottingham (Sustainable Energy Technology)
- Cardiff University (Welsh School of Architecture).

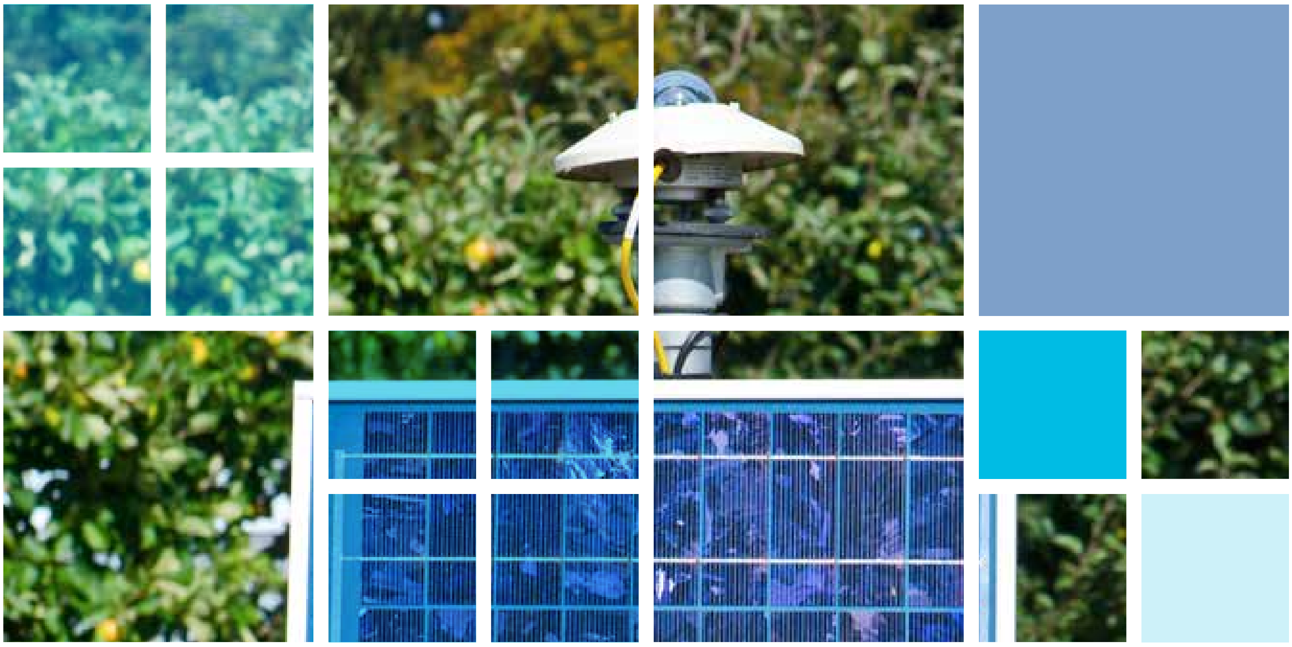
The following organisations agreed to participate as part of the project steering group:

- Good Homes Alliance
- Leeds Metropolitan University (Centre for the Built Environment)
- Richards Partington Architects
- Technology Strategy Board
- The Zero Carbon Hub.

During, and subsequent to, the initial meeting of the steering group in November 2011 the practical and logistical aspects of the research project were agreed and implemented. Crucially this included protocols for the minimum and common requirements for scope of testing and reporting of data in connection with the testing carried out by the project partners.

The initial BRE co-heating tests were carried out in the period December 2011 to January 2012, the six co-heating tests carried out by the project partners in the period January to May 2012, and additional BRE solar shading tests in the period June to September 2012.

3 What is a co-heating test?



3.1 General methodology

In the simplest terms a co-heating test involves heating the inside of a building to a constant elevated temperature, typically 25°C, using electrical resistance heaters over a period of one to three weeks. All other internal heat gains should be switched off or eliminated, which means that the building must be unoccupied during the test, and that all external windows, doors and ventilators should be kept closed. Any open appliance flues should also be temporarily sealed and drainage traps checked to ensure that they are filled with water, since air leakage through flues and traps as well as openable windows or ventilators are not unintentional air leakage paths. Practical guidance on testing procedures, but not analysis, has been published by Leeds Metropolitan University[1].

By measuring the electrical energy required to maintain the constant temperature, the daily heat input to the building can be determined. The HLC can then be determined by plotting the mean daily heat input (P [measured electrical power of the heaters], Watts [W]) against the mean daily inside to outside temperature difference (dT, K). The resulting slope of the curve plot gives the HLC (P/dT, W/K). In practice a dT of at least 10 K is required, which generally means that the best time to undertake a co-heating test is considered to be during the winter months.

Testing in winter also reduces the effect of solar radiation on the measured electrical heat input. During periods of sunny weather, solar heat gains to the building may be a significant proportion of the total daily heat input but are difficult to quantify accurately. The largest source of solar heat gains is usually through the windows but gains through the roof may be significant in summer and are very difficult to quantify.

3.2 Equipment

3.2.1 Heaters and fans

The heat input is normally provided by electric point heaters. These are generally used one or two per zone, with at least one air circulation fan deployed per zone, in order to ensure an even air temperature throughout the space (Figure 1) and to avoid stratification effects. Electric fan heaters and convector heaters are commonly used, although the disadvantage of fan heaters is that the heater element cannot normally be switched independently of the fan unless it is specially modified electrically. Either type of heater is acceptable so long as the air circulation is continuous and consistent. The positioning and speed of the fans is important to prevent direct impingement of high velocity air into walls, floors and ceilings as this would artificially increase the surface heat transfer coefficients. The number and size of fans should not be excessive, as otherwise the constant electrical heat could cause temperature control difficulties, especially in low heat loss buildings. It is important that all internal doors are fully open, especially those to storage cupboards.

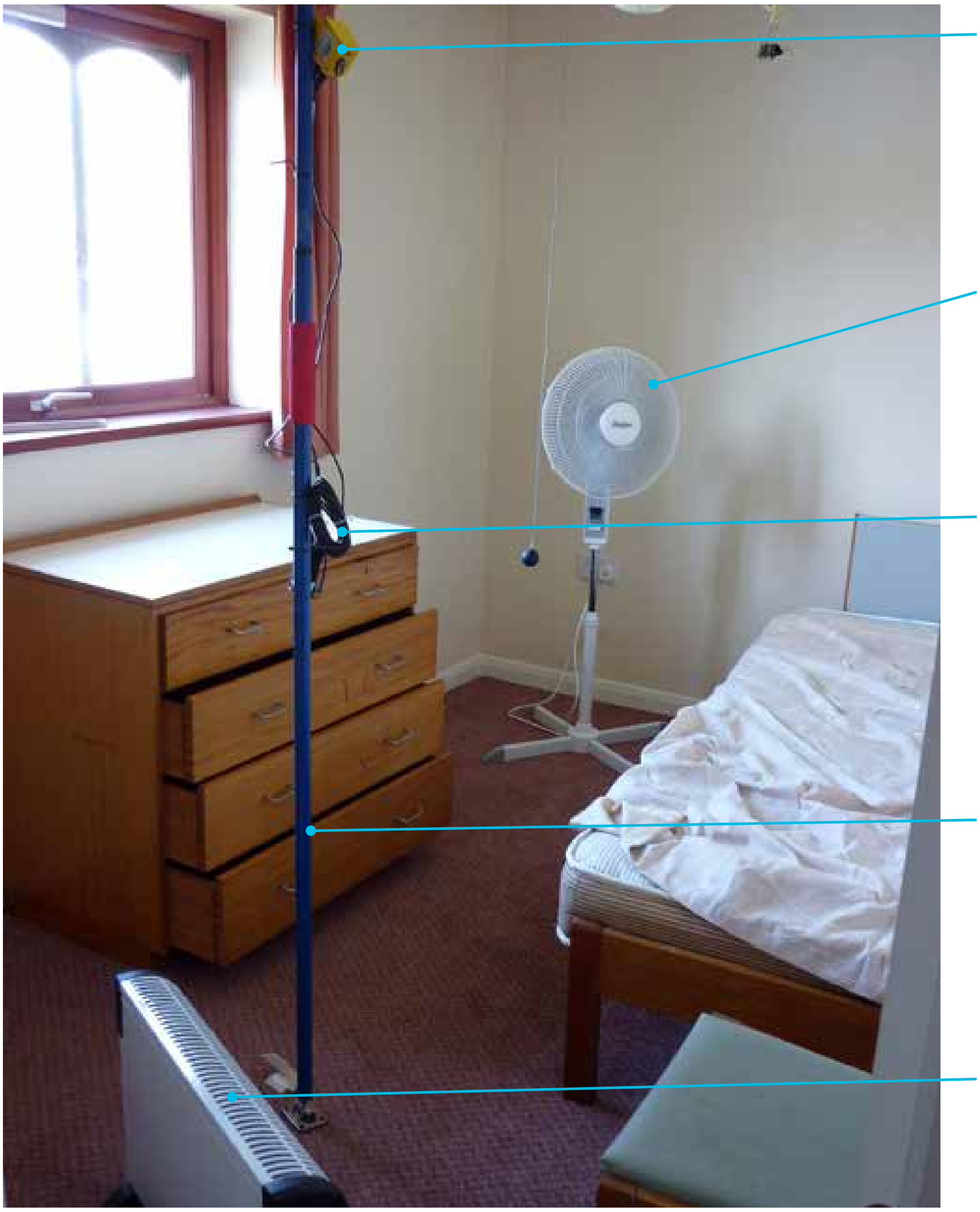


Figure 1 Co-heating zone set-up

Temperature control is important since the aim is to achieve a constant internal air temperature. Some research teams have used a simple on/off room thermostat in each zone, although experience shows that a digital proportion and integral temperature controller with a remote temperature sensor on a cable that can be positioned in the centre of the room is worth the extra cost, since it allows the sensor to be calibrated and matched to the controller. This avoids the need to return to the building to undertake fine adjustment of thermostat settings and makes it easier to achieve a uniform temperature across all of the control zones in the building. The digital temperature controller may control the heater via a pulse width modulated solid state relay or thyristor - which makes fine control of heat input possible.

The number of zones depends on the size, form and thermal characteristics of the building and the exposure to solar radiation. As a guide a typical two-storey dwelling would be divided into four zones, so that the rooms on the same elevation and floor are in the same zone. If a particular room or area of the building have significantly different thermal characteristics or level of glazing and solar heat gains then they should normally be considered as a separate zone. The proof of correct zoning will be seen through the uniformity of temperature levels achieved throughout the building.

An example of the level of temperature control that can be achieved with digital temperature controllers, even with widely varying solar irradiance and external air temperature, is shown in Figure 2. In this test the internal temperature was also subject to a stepped reduction to reduce the temperature differential when the weather turned colder. The data for three days following this step change was omitted from the co-heating analysis to allow the building fabric to adjust to the reduced internal temperature. Note that the temperature values were based on 15-minute interval data.

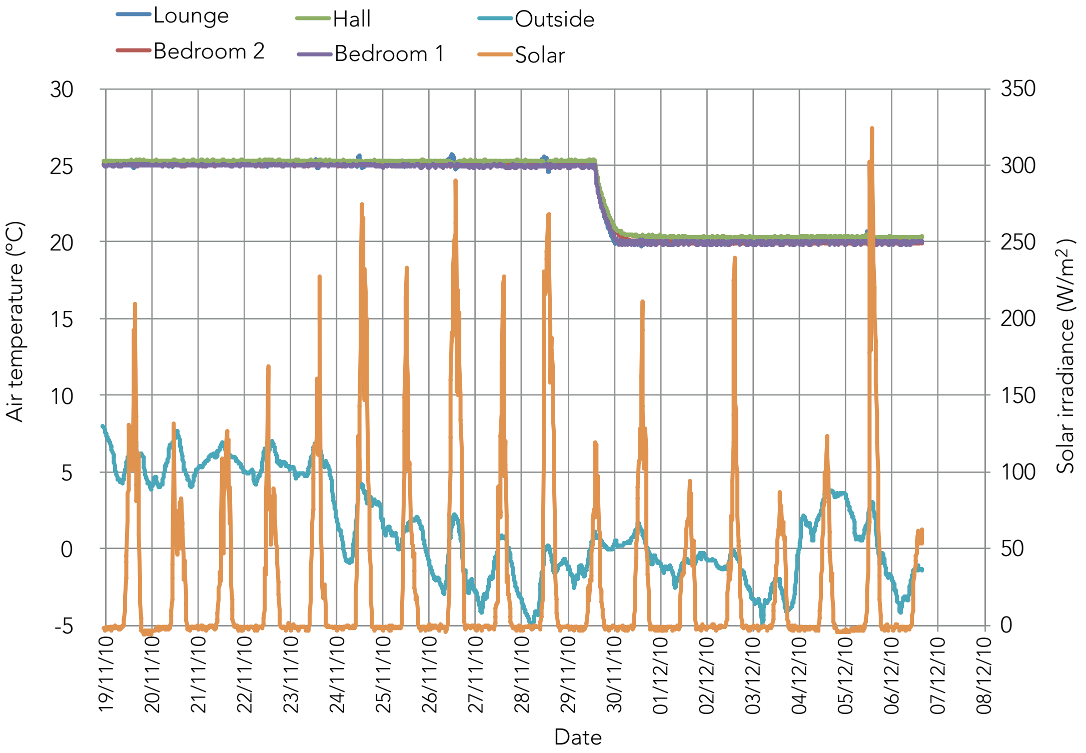


Figure 2 Example of mean house temperature during a co-heating test in an apartment, including a stepped change in temperature level (19 November 2010 to 6 December 2010)

Temperature sensors should be shielded from direct solar radiation through the windows. Care is needed when sun angles are very low at the beginning and end of the day, and especially in the winter. Effective shields for the instruments can be constructed from a small section of insulation board faced with aluminium foil, or alternatively the temperature sensor may be mounted inside a vented metal tube with shiny exterior surface.

3.2.2 Temperature and electrical energy monitoring

The electric energy meters should include capture of the electrical energy used by the heaters and the fans and any other equipment used. All other electrical loads in the building should ideally be off, or otherwise their electrical energy should be accounted for. The electrical energy should be metered at least on a daily basis. This can be done by using a pulse data logger and optical interface on the existing house electricity meter but relies on a compatible electricity meter. An alternative is to incorporate class one electricity meters with volt-free pulse outputs (1000 pulses per kWh) in the zone temperature controller boxes coupled to a pulse data logger (eg 'Tiny Tag'). The fans should also be supplied through these controller boxes, ensuring that all electricity consumption is accounted for.

Each control zone should have its own air temperature measurement data logger or channel if a multi-channel data logger or data acquisition unit is used. A 5 or 10 minute data recording interval has been found to be adequate. Experience has shown individual air temperature data loggers to be convenient for one-off co-heating tests in buildings. The use of wireless sensors and a base unit with a GPRS (general packet radio service) modem is more costly, and remote data download may be advantageous but is not vital.

3.2.3 External temperature, solar irradiance and wind speed

External air temperature and solar irradiance monitoring at the site is essential and measurement of wind speed and direction are desirable. External air temperature should be measured by a sensor, or combined sensor and data logger, inside a radiant shield. A standard Meteorological Office specification Stephenson screen is desirable but unlikely to be practical. More cost effective and practical alternatives are available from data logger suppliers, an example is shown in Figure 3. This should be located outside in free air away from heat sources such as flues or dark-coloured roof surfaces that will heat up in sunny weather. If it is attached to the building it should be on a north-facing elevation to minimise radiant heat pick-up from the walls of the building. Note that in direct sunlight standard brickwork can reach 50°C surface temperature.

Horizontal plane total solar irradiance should be measured at a location free from shading or building reflections. A typical instrument of appropriate cost and performance, which will provide direct linear output voltage proportional to incident solar radiation, is shown in Figure 4.

Figure 3 An external temperature sensor radiant shield

Figure 4 An instrument for measuring solar irradiance

3.2.4 Party walls

If the building to be tested has fabric elements shared with another building, such as in the case of semi-detached, terraced houses and apartments, then consideration has to be given to heat losses to these adjacent spaces. These may be heated living spaces or unheated communal areas. If sole access is available then the ideal solution is to heat these adjacent spaces to the same air temperature as the test building. It is not necessary to quantify the heat supplied, but the space temperatures should be monitored. Care is needed because heating these spaces to the same temperature may not be sufficient if there are any thermal bypasses in the party wall construction. For example this could be a vented wall cavity that communicated with an unheated roof space.

If access to the adjacent spaces and heating them to the same temperature is not possible then an alternative solution would be to install flux plates on the party wall (flux plates directly measure the heat flux at the surface of a wall or other component to which they are attached); this would still require the temperatures in the adjacent spaces to be measured. There is likely to be a high level of uncertainty with this approach, since there may be a variation in temperature across the adjacent space and the thermal characteristics of the party wall may vary - whereas flux plates are point measurement devices.

3.3 Analysis of co-heating test data and confounders

The HLC is determined by plotting the mean daily heat input (P [W]) against the mean daily inside to outside temperature difference (dT [K]). Performing a regression analysis of the data gives the equation of a straight line of best fit through the data. The slope of this line gives the HLC (P/dT with units W/K). An example of such a curve for a detached house tested in June 2009 is shown in Figure 5. A major source of uncertainty is in determination of the best fit line and its gradient. Standard simple linear regression techniques are usually based on the least squares method and are very sensitive to data scatter and especially outlier data points (data points that are a long distance from the best fit line). Depending on the weather during the co-heating test the range in dT may also be small (if the outside air temperature does not vary much) and can cause large errors in the gradient. The best fit line must not be forced through the graph origin (the bottom left-hand point of the graph where both heat input and dT equal zero) since the measured heat input is for the electric heaters only and excludes any heat input from solar radiation (or any other source). Total heat input cannot be measured directly and is usually determined by adding an estimate of the solar heat gains to the measured electric heater electricity consumption. A best fit line for total heat input may be forced through the origin of the graph since it is assumed that total heat input equals zero when dT is zero (when the room air temperature equals the outside air temperature it is assumed that the house requires no heating).

The solar heat input to the house cannot be directly measured. In some co-heating tests BRE has estimated the solar heat gains through the windows using a simple window solar transmission model and by estimating the solar irradiance on the vertical elevations from the measured horizontal solar irradiance data. This technique becomes more complicated and difficult if the building is partially shaded by trees or other buildings. Solar heat gains on each elevation of a house may be estimated from measured horizontal solar irradiance using factors derived from hourly CIBSE cooling load data (*CIBSE Guide A*, Table 5.19 Solar cooling loads)[2]. An example of total heat input (electric heaters and fans plus solar heat gains) determined by this method for the example house are shown in Figure 6. In this case the gradient of the two plots are in reasonably close agreement, suggesting that the whole house HLC is 191 W/K (the gradient of the best fit curves).

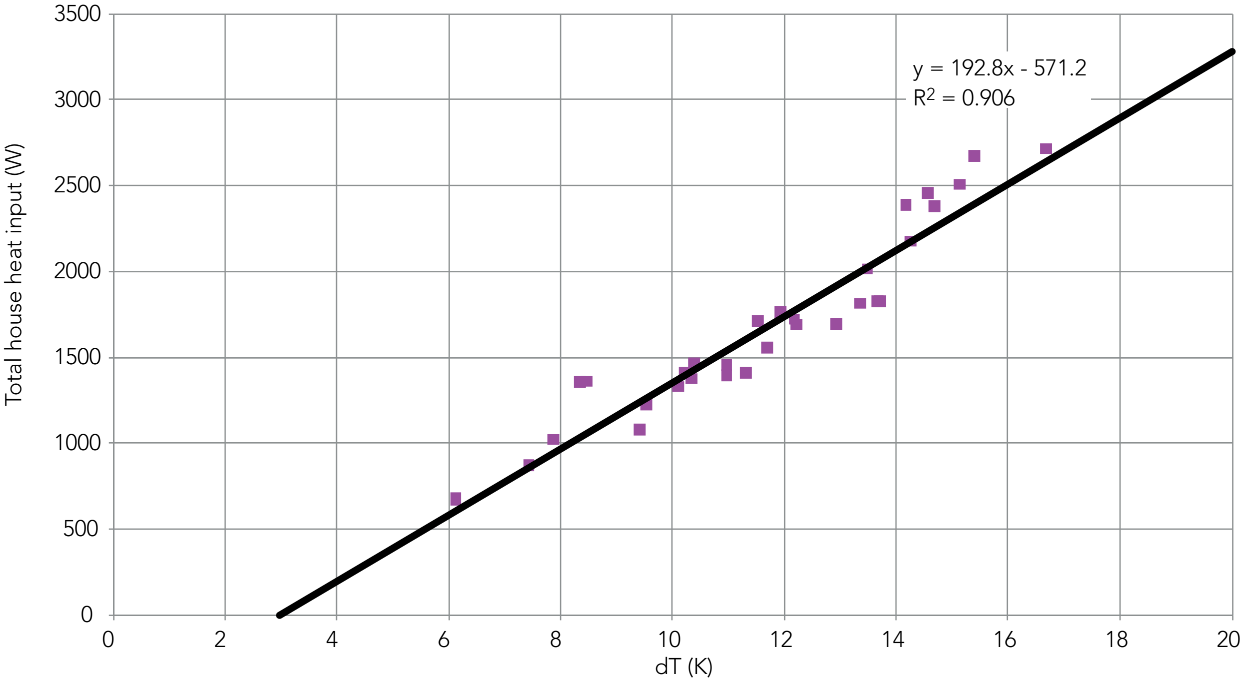


Figure 5 Example plot of electrical heat input (heaters plus fans) plotted against inside to outside temperature difference (dT)

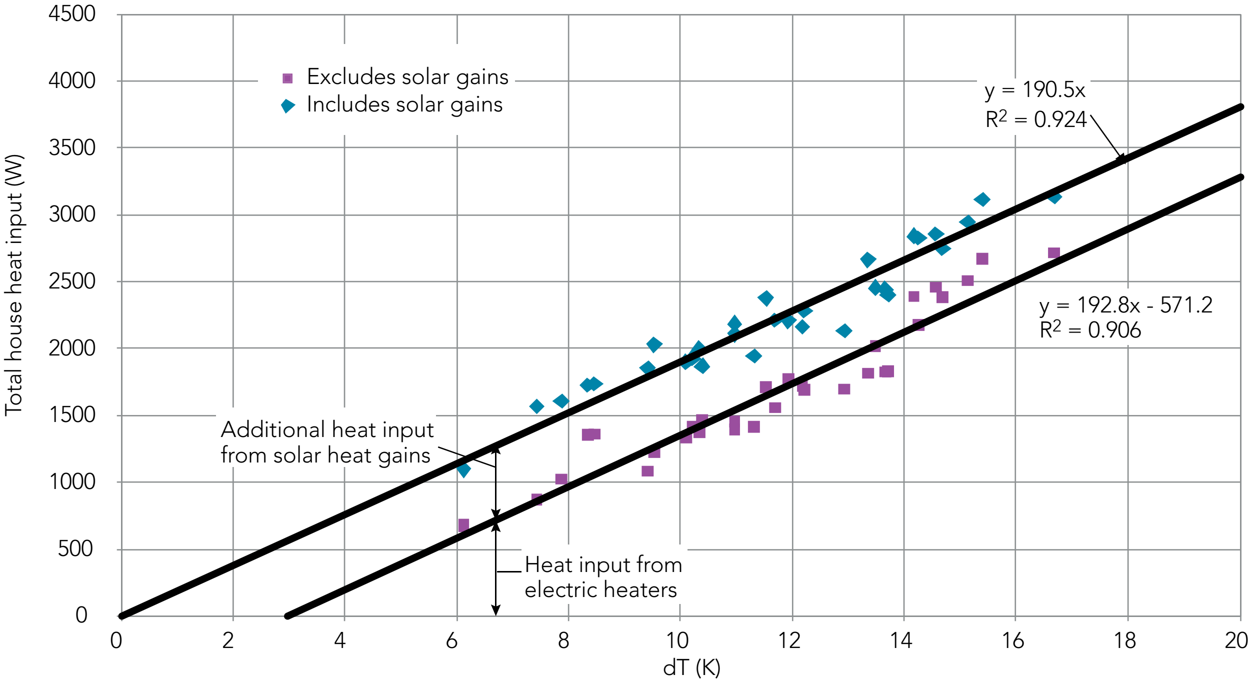


Figure 6 Plot of electrical heat input plus estimated solar heat gains plotted against inside to outside temperature difference (dT)

3.3.1 Effect of wind

The effect of wind on the whole house HLC is mainly through its influence on ventilation heat loss, although it also affects the rate of heat loss through the walls and roof since increasing wind speed increases convective heat losses from the outside surfaces (convective heat transfer coefficient). All windows, doors and ventilators (including trickle vents, hit and miss vents, mechanical and passive ventilation systems and open combustion flues) are shut or sealed for a co-heating test, so the ventilation heat loss is only due to the background infiltration through the building fabric. This obviously varies with the airtightness of the building fabric, and therefore its overall effect can vary significantly.

An example of the influence of wind on co-heating test data is shown in Figure 7 for a test undertaken in winter on a building relatively well shaded from winter solar radiation. On two consecutive days, out of a total test duration of 17 days, the mean wind speed exceeded 7.5 m/s. In this example the effect of these two days on the co-heating analysis was relatively small – an increase in the HLC from 60.6 W/K to 63.7 W/K. However, a longer period of windy weather could cause a significant increase in the HLC, which is why local measurement of wind speed, and ideally direction, during the period of testing is desirable.

The simplest approach for dealing with the effect of wind is to undertake a co-heating test under low wind speed conditions or to omit data for windy days. However, depending on the prevailing weather and also the location of the test building this may be impractical. The effect of wind can also be assessed by plotting W/K (the ratio of total heat input to dT) against mean wind speed. The gradient can be used to correct for the increased heat loss due to wind. An example plot is shown in Figure 8. There is a relatively large degree of data scatter, which makes the linear regression plot gradient sensitive to outlier data points. In general the standard error from such a regression is likely to be quite large and therefore this method of correcting for wind speed may have a high level of uncertainty.

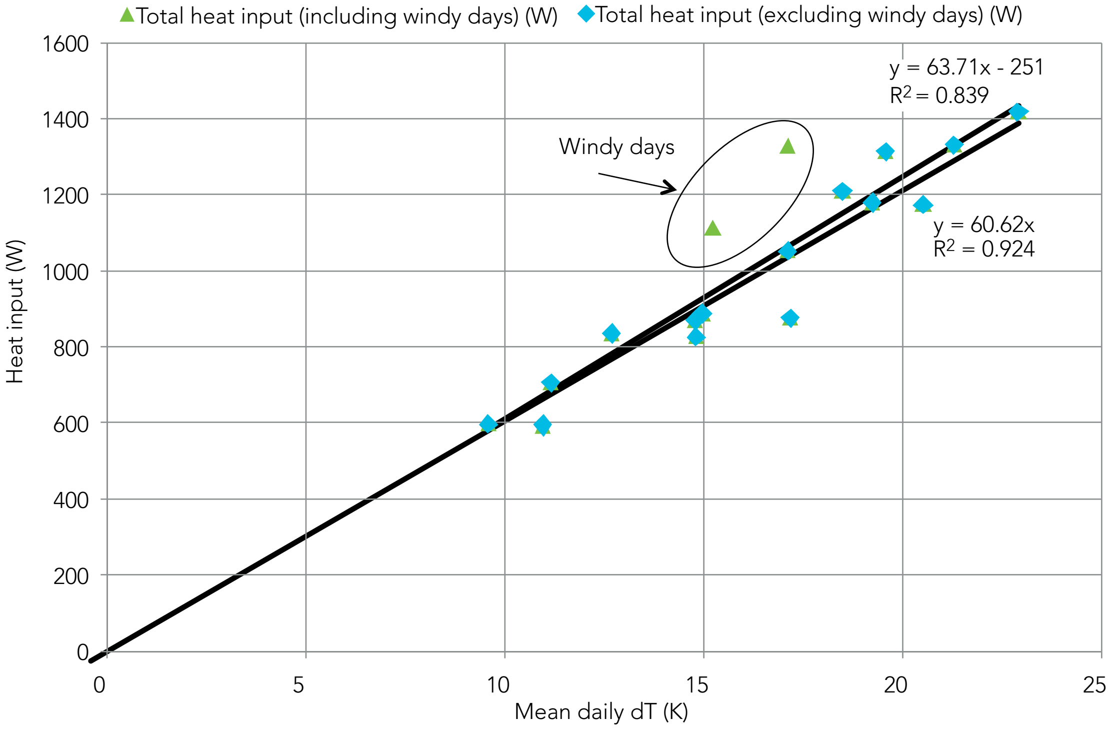


Figure 7 Effect of windy day outliers on a co-heating test

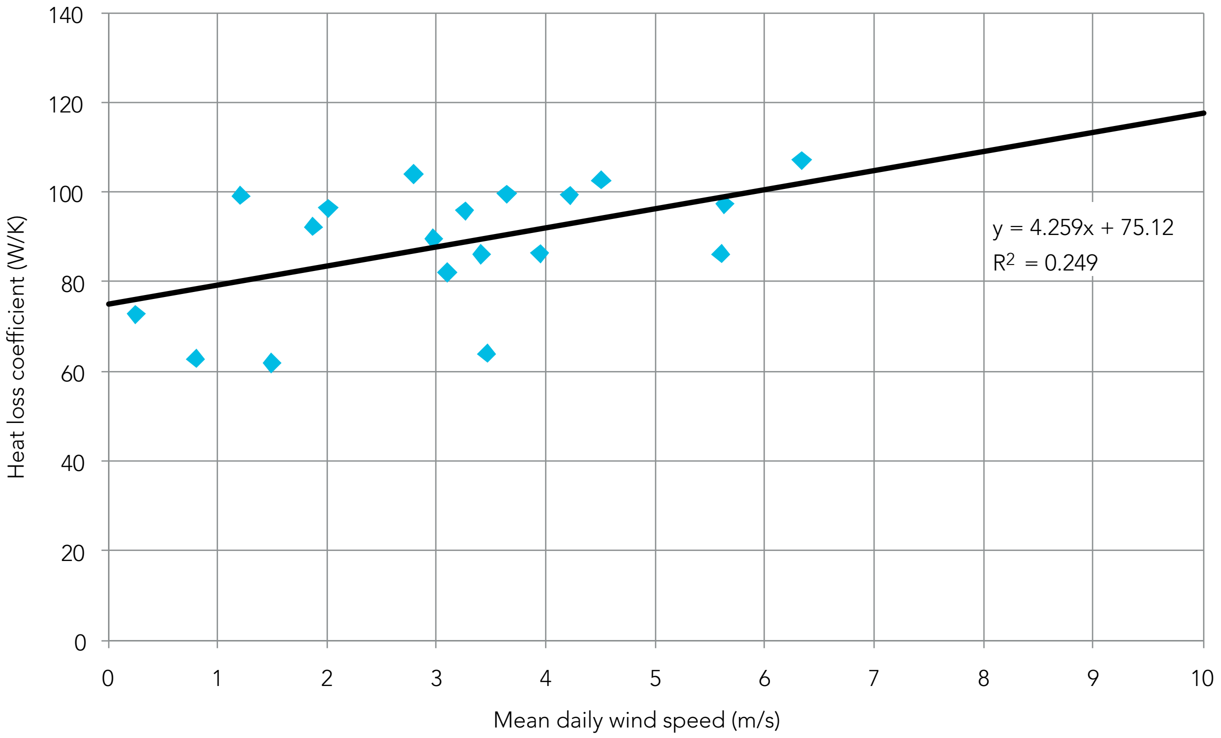


Figure 8 Regression to determine the effect of wind (W/K [excluding solar] versus mean wind speed)

3.3.2 The Siviour method

The Siviour method is a graphical method of analysing a house heat balance which was used extensively in the 1980s by the Open University in the Pennyland and Linford projects involving extensive monitoring and analysis of the energy consumption of low energy houses[3]. This method was also reported in a publication by DECC[4] and was used by most of the test teams in the project partners' co-heating tests. The Siviour method has also been reported by the Welsh School of Architecture[5] in the analysis of co-heating tests for Passivhaus buildings.

The Siviour method considers a steady state heat balance in the form:

$$Q + K = \sum(UA + Cv)\,\Delta T - Sa\ VSol$$

Where:

Q = total daily heating energy input (W)
K = free heat gains (W)
U = U-value of element (W/m^{2}K)
A = area of the element (m^2)
Cv = ventilation/infiltration heat losses (W)
ΔT = inside to outside temperature difference (K)
Sa = solar aperture (m^2)
$VSol$ = vertical south solar radiation (W/m^{2}K).

The term K represents free heat gains from cooling, lights etc., which for a co-heating test are zero since the house is unoccupied.

The ∑(UA + Cv) term is the HLC of the whole building. The equation can be rearranged as follows:

$$(Q + K) / \Delta T = HLC - (Sa\ VSol) / \Delta T$$

Q + K, VSol and ΔT are known (VSol can be estimated from the measured horizontal solar irradiance for example by using the *CIBSE Guide A* solar cooling load tables[2]). By regressing Q / ΔT against Vsol / ΔT the HLC and the solar aperture can be determined. The slope of the plot is the effective solar aperture and the HLC is the y axis intercept.

The solar aperture is the equivalent surface area (m^2) of perfectly transparent south facing vertical surface, which lets in the same solar energy as the whole building. Therefore the solar aperture may be considered to be a solar radiation coefficient and allows the total house solar heat gains to be directly determined from the incident solar irradiance. The incident solar irradiance should be measured on a vertical south facing surface although it is possible to determine it by calculation from the more usual measurement of horizontal solar irradiance.

Data for the co-heating test example (Figure 7) has been subjected to analysis using the Siviour method. The Siviour plot is shown in Figure 9, based on the measured horizontal solar irradiance corrected to vertical. The term P is the measured electrical power of the heaters and is equivalent to Q + K in the heat balance equation shown above. The solar aperture is 1.4 m^2 (gradient) and the HLC is 176.6 W/K (y axis intercept). This compares with the higher value of 191 W/K obtained from the plot of heat input against dT (Figure 6).

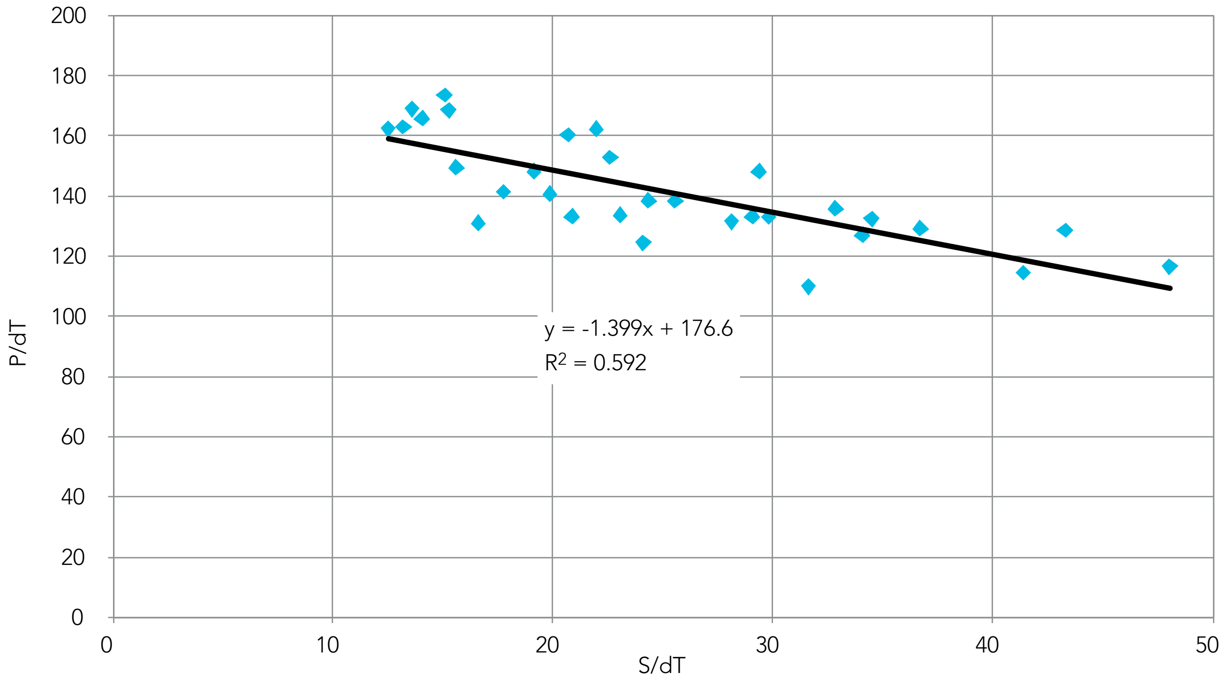


Figure 9 Siviour plot for a semi-detached house (based on measured south vertical solar irradiance) [where P/dt is (Q + K) / ΔT and S/dT is (VSol / ΔT]

3.3.3 Infiltration measurement

The usefulness of the co-heating test can be improved by simultaneously measuring the infiltration rate, usually using a tracer gas technique. For example this could be undertaken using multiple PFT (perfluorocarbon tracer) sources and air pumped gas adsorption tubes. If the tubes are changed and analysed daily the daily average infiltration rate can be determined. Alternatively continuous CO_2 gas dosing and gas concentration measurement may be used in order to automate the process. This might be considered an unacceptable method on safety grounds, whereas the use of small PFT sources has been shown to be very safe.

The infiltration heat loss may be calculated from the infiltration rate using the measured inside and outside air temperatures. It is important to note that infiltration is driven by wind pressure as well as by temperature difference.

It is unlikely that the results from a standard fan pressurisation airtightness test could be used to determine the infiltration rate during a co-heating test, because such a test imposes a uniform pressure difference across the building fabric. Under normal building operation, infiltration is a function of dT and wind speed and direction which cannot be predicted accurately from the fabric airtightness alone.

3.3.4 Accuracy of results

The overall uncertainty of the co-heating test methodology is based on the uncertainty of the respective measurement instruments as well as the fact that the building is in a continuous non-steady thermal balance due to constantly varying outside air temperature, wind and solar radiation. Measurement uncertainty can be accounted for relatively easily, but the non-steady thermal balance is dependent on uncontrollable external weather and is therefore more difficult to account for. The way that these factors interact with the building fabric will depend on various factors including the fabric mass, building orientation, building size and orientation of the glazing and the roof. Therefore it is not possible to readily determine a value for the overall accuracy or level of uncertainty.

3.4 The purpose and costs of conducting co-heating tests

There are several common purposes for undertaking co-heating tests:

- For a new house to determine the as-built whole house HLC and allow comparison with the SAP whole house HLC. This may be used as part of a quality assurance process or building investigation to research the reasons for poor thermal performance. It may be in response to higher than expected heating fuel bills or apparent under-sizing of the space heating system. This may be especially apparent when certain types of renewable heat, such as heat pumps, are in use.
- As a powerful building diagnostic and research tool, especially when used in conjunction with other techniques such as infrared thermal imaging, heat flux surveys and airtightness testing. For example, co-heating testing formed the basis of the research that identified the issue of party wall heat loss caused by the wall cavity being open to an unheated roof space.
- Before and after major refurbishment of a building to qualify and demonstrate any improvement in the thermal performance and airtightness of the building fabric. Often such tests are undertaken by a third party organisation in order to provide an independent assessment free of bias, and also independent of occupation effects. Occupation effects often include improvements in thermal comfort through higher room temperatures after refurbishment, which reduces the energy savings and reductions in fuel bills, and makes evaluation of any fabric thermal improvements difficult to quantify.

The main direct costs of undertaking co-heating tests are connected with staff time, since a minimum of two site visits are required to set up and remove test equipment and data loggers. This includes external meteorological instruments, so one half day for each visit for a single building is not unrealistic. The cost of instrument hire or depreciation should also be added. In addition to this the cost of electrically heating the building needs to be covered and the responsibility for this cost agreed. An additional component is the cost of data analysis required following the period of testing. Since the basis of the co-heating test is that the building is unoccupied and that access is closed off, ideally for a minimum of two weeks, this may result in a significant cost in lost rental income, cost of alternative accommodation, or delay in sale of a new or refurbished building.

4 The co-heating tests

The co-heating tests centred around a matched pair of test houses at BRE (Figure 10), designated House A (the experimental control house) and House B. The houses are identical Swedish timber-framed detached houses, supplied by Nordic Homes Ltd and erected around 1990. The houses had a SAP whole house HLC of 68.4 W/K (65.9 W/K for the fabric and 2.5 W/K by infiltration). This was achieved through heavily insulated and draught-proofed fabric, and triple-glazed timber windows. A summary of construction details and floor plans are shown in Appendix A.

Figure 10 The test houses at BRE, Garston. House A, the experimental control house (left) and House B (right)

4.1 BRE co-heating tests

BRE undertook co-heating tests in both houses at the start and end of the research project in December 2011 to January 2012 and again in June 2012. Additional testing to investigate the effect of external shading was also undertaken by BRE from June to September 2012. The co-heating tests were carried out in both houses and House A was used as an experimental control.

During the BRE co-heating tests, heat input was provided by electric convector heaters, generally one per room, and an oscillating room fan (Figure 11). The fans operated continuously and the heaters were controlled by proportion and integral controllers with solid state relays. This provided fine control of temperature and the controllers enabled correction offsets to be programmed, so that the controller plus temperature sensor, could be calibrated. This made the process of obtaining consistent temperatures throughout each house easier.

Each zone temperature controller was mounted in a box with a standard kWh meter with pulse output (1 pulse per Wh) and connected to a Tiny Tag pulse data logger. The electrical supplies to the fans were also provided through the control boxes. The room temperature control and temperature measuring sensors, and pulse data loggers were attached to tele-props in the centre of each room.

External air temperature, wind direction and speed, solar irradiance and other meteorological data was measured by a weather station adjacent to the test houses. Electricity consumption, room air temperatures, external air temperature and solar irradiance were continuously measured and recorded with an interval of 15 minutes.

Figure 11 Typical room configuration for the BRE co-heating tests

4.2 Project partners' co-heating tests

The tests were undertaken in House B by each of the following project partners: BSRIA; University College London (Energy Institute); Loughborough University (Low Carbon Energy Technology); Stroma Technology; University of Nottingham (Sustainable Energy Technology); and Cardiff University (Welsh School of Architecture).

The successive co-heating tests took place between 27 January and 8 May 2012. Each project partner was independently responsible for instrumentation and test method, including data analysis.

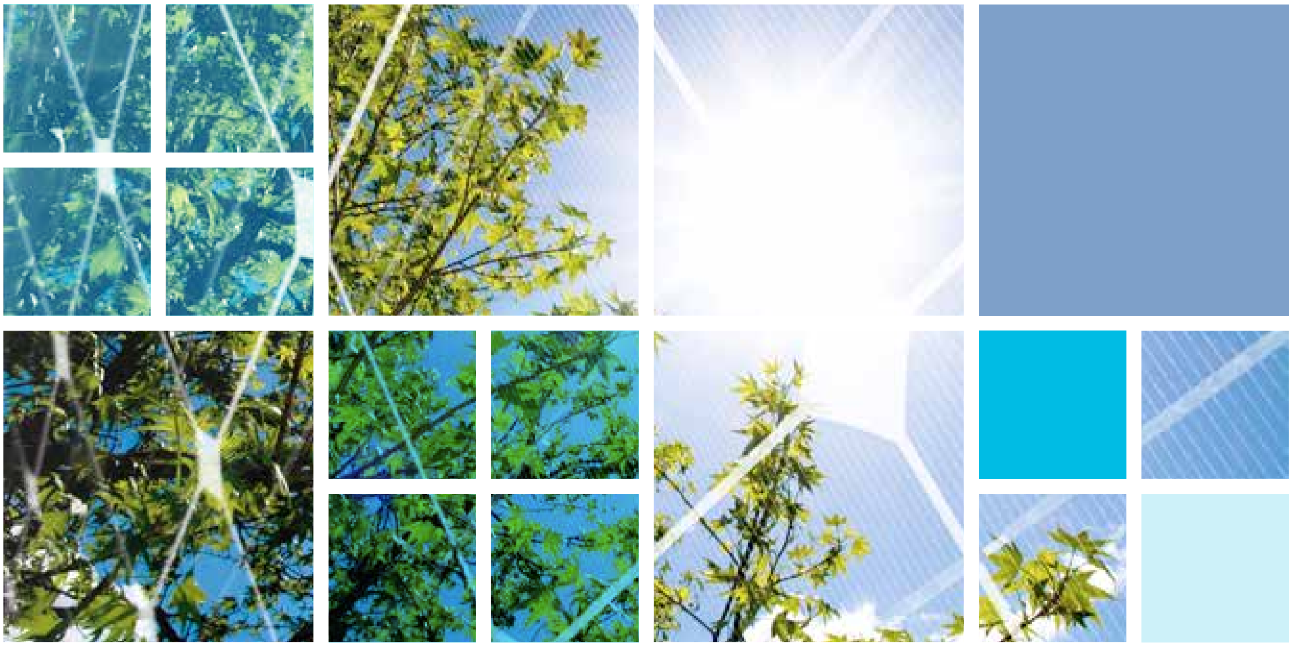
4.3 Solar shading experiments

The project partners reported that the greatest difficulty they experienced in undertaking their respective data analysis was in the treatment of solar heat gains. Therefore BRE undertook additional testing of House B in order to investigate the effect of directly shading the windows from solar heat gains between 4 June and 28 August 2012. The window shading tests were undertaken with a house room air temperature of 31°C.

Three individual solar shading tests were undertaken:

- aluminium foil attached directly to the glass on the inside of the window
- aluminium foil attached directly to the glass on the outside of the window
- heavyweight cotton fabric attached to the external wooden window frames, approximately 100 mm between the glass and the fabric.

5 Research project findings



5.1 BRE co-heating test results

BRE undertook two periods of co-heating testing in both of the test houses: one at the start of the project (December 2011 to January 2012) and another on completion of the project partners' tests (in June 2012). A further period of testing was also undertaken (June to August 2012) in House B to investigate the effect of solar shading following observations by the project partners' test teams during the co-heating tests in June 2012.

Figure 12 shows house and weather conditions and hourly HLC (W/K) for the initial winter period for House A and House B. The results show a period of unseasonably mild weather with a small variation in external temperature and wind speed, and also low solar heat gains apart from the last day of the test period (2 January 2012). The first day shown in Figure 12 (22 December 2011) is excluded from the analysis as it was part of the pre-conditioning period required to obtain steady state. Figure 13 shows measured heat input (heaters plus fans) plotted against house and outside temperature difference (dT). The effect of the high solar heat gains on 2 January is clearly discernible. Figure 13 has also been re-plotted with the data for 2 January omitted, as shown in Figure 14. Without the effect of large solar heat gains, regression lines forced through the origin show a relatively good fit with the data (r^2 values > 0.8). The curve gradients show HLCs of 67.6 W/K for House A and 67.1 W/K for House B. These values are very close to the SAP equivalent whole house HLC of 68.4 W/K.

Siviour analyses were also undertaken for the two periods (with and without the high solar gain day of 2 January) and are shown in Figures 15 and 16. This shows that the degree of 'data skew' resulting from one day of high solar heat gains is a change in the predicted HLC from approximately 69 W/K to 76 W/K (+10%) for both houses. This skew has also produced a large difference in solar aperture values, between 0.3 m^2 and 2.98 m^2. The higher values of solar aperture (based on the test period including 2 January) have been used to correct the total house heat input to account for solar heat gains. The resulting heat input values have been plotted against dT in Figure 17. This shows an HLC of 75.73 W/K for both houses. This is higher than the values obtained from the low solar gain period (22 December to 1 January) and also the SAP value of 68.4 W/K. It is clear that solar heat gains can have a significant effect on the results of co-heating test analysis.

Quiet spells of weather, particularly where there are low solar heat gains, may provide an opportunity to assess mean instantaneous HLC. This is shown in Figure 18 for 27 December. This period has very low solar irradiance and very little variation in external temperature and wind speed. The HLC for both houses was nearly constant. The mean values for 27 December were 65.5 W/K for House A and 64.03 W/K for House B, which are reasonably close to the SAP value (68.4 W/K). Unfortunately such periods of quiet weather cannot be expected very often, and therefore this cannot be seen as a reliable co-heating analysis method.

Another area of interest is a comparison between the two test houses, House A and House B. Figure 19 shows daily electric heat input for each house plotted against each other. The calculated correlation coefficient is 0.995, which indicates a statistically very close fit between the individual data points and the line of best fit and proves that the two houses are very similar in terms of heat loss.

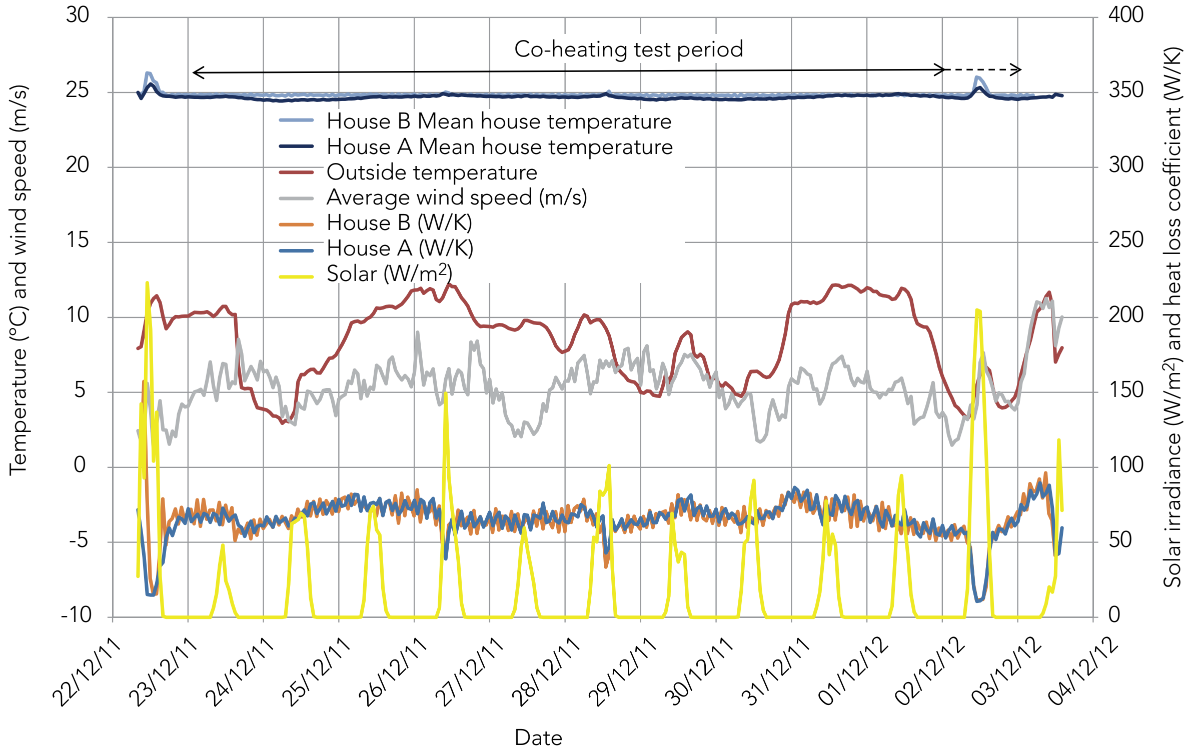


Figure 12 Co-heating test hourly data for House A and House B (23 December 2011 to 4 January 2012)

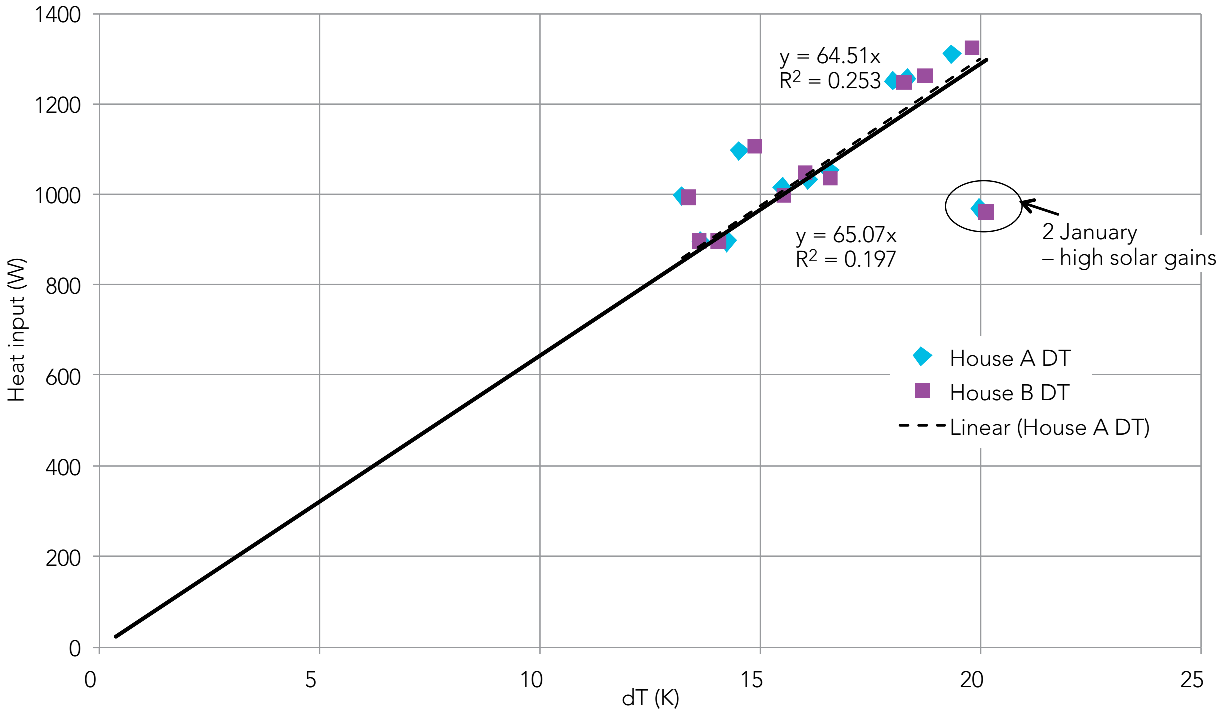


Figure 13 Heat input plotted against inside to outside temperature difference (dT) for House A and House B. The whole test period including one high solar gain day (23 December 2011 to 2 January 2012)

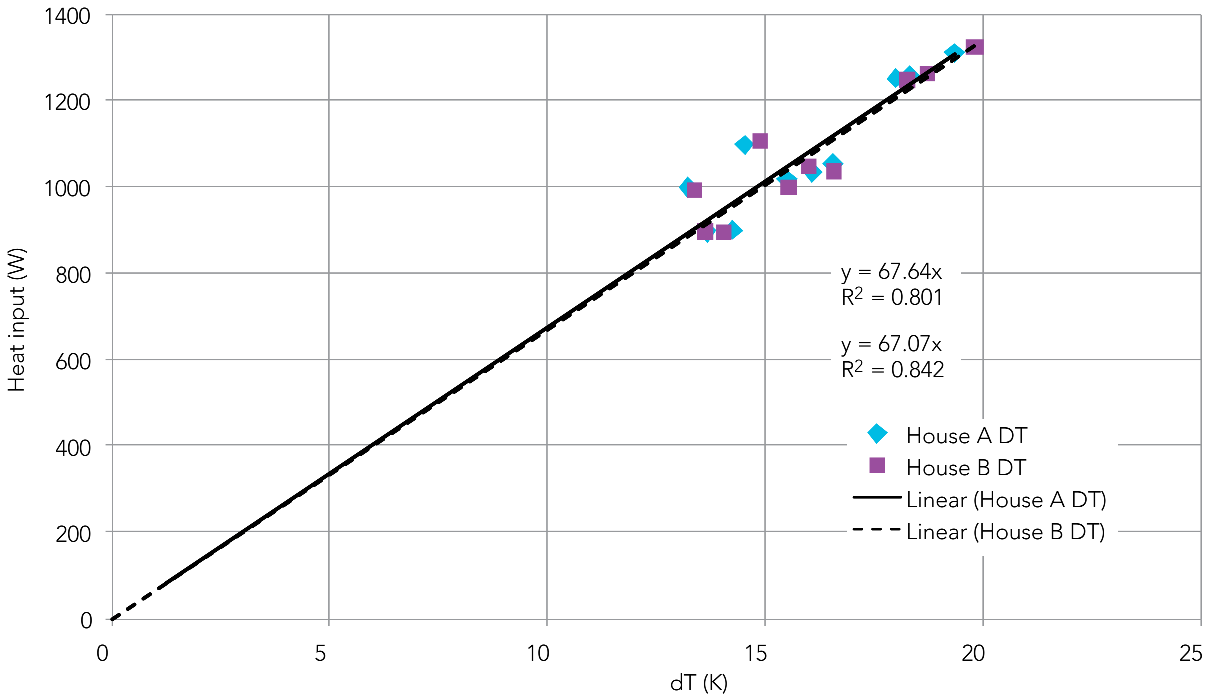


Figure 14 Heat input (uncorrected) plotted against inside to outside temperature difference (dT). The whole test period excluding high solar gain day (23 December 2011 to 1 January 2012)

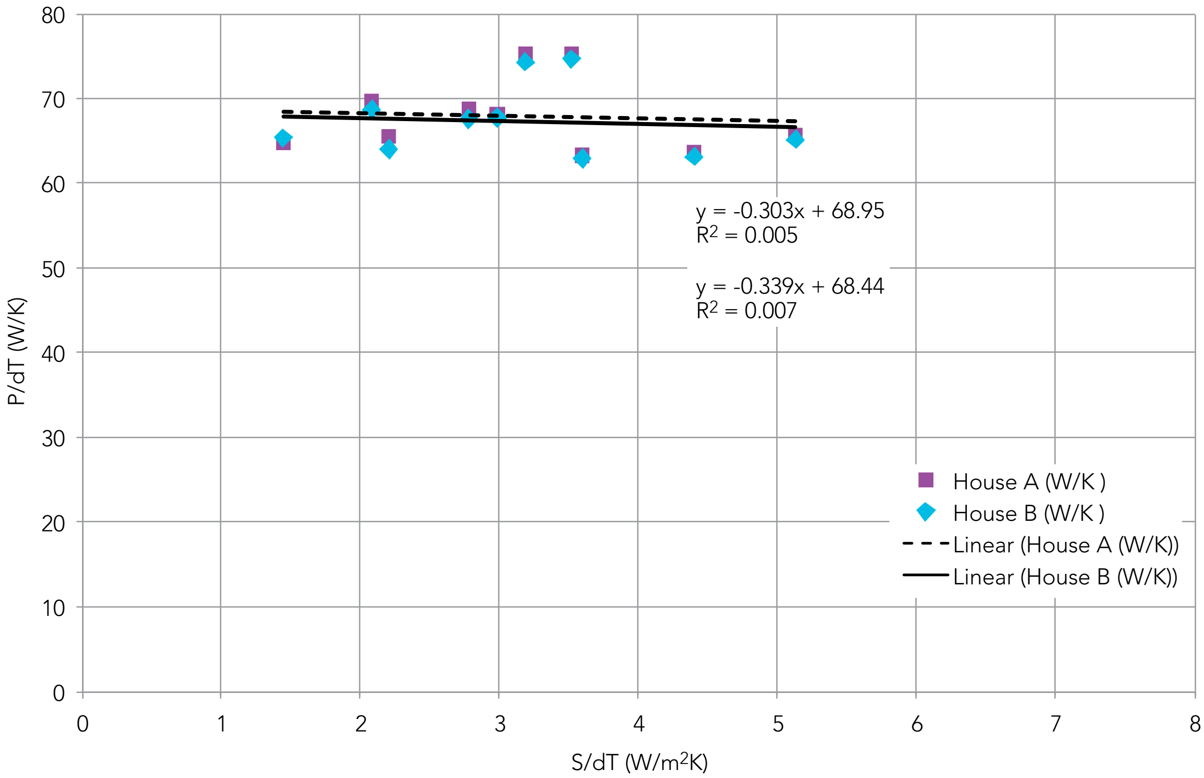


Figure 15 Siviour plot excluding one high solar gain day (23 December 2011 to 1 January 2012) [where P/dt is (Q + K) / ΔT and S/dT is (VSol / ΔT]

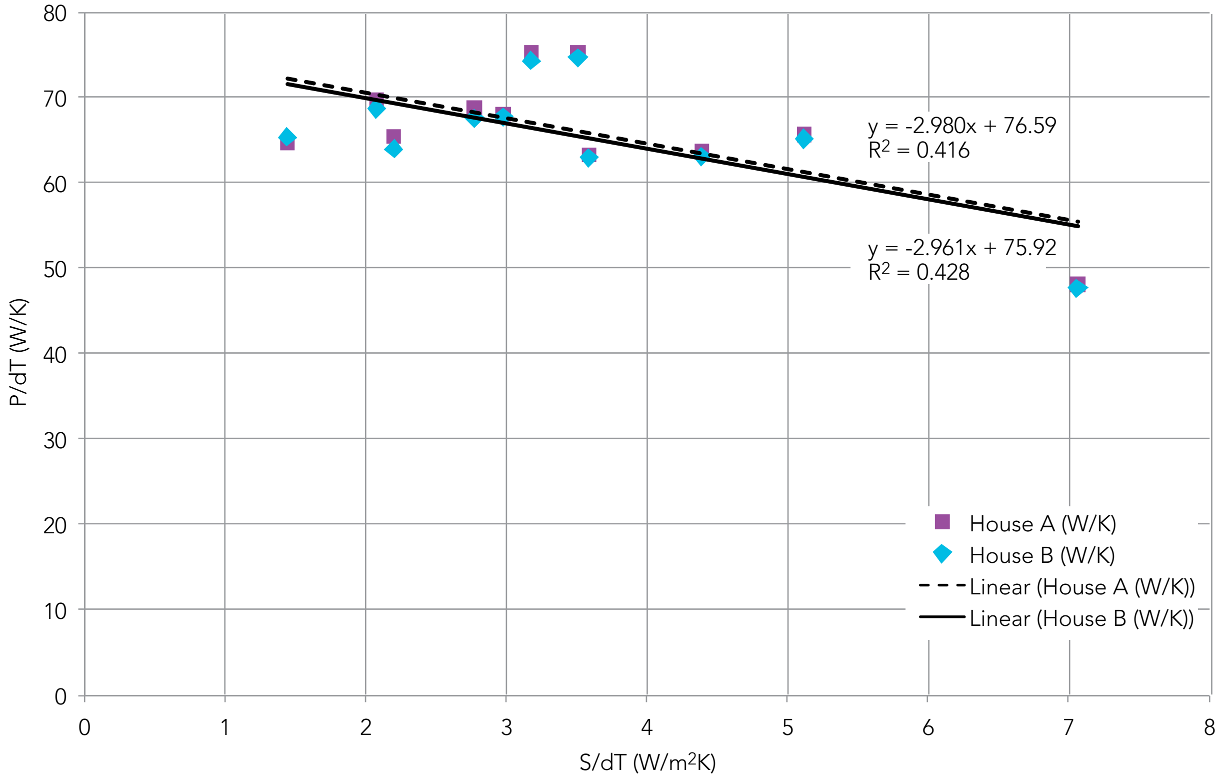


Figure 16 Siviour plot including high solar gain day (23 December 2011 to 2 January 2012) [where P/dt is (Q + K) / ΔT and S/dT is (VSol / ΔT]

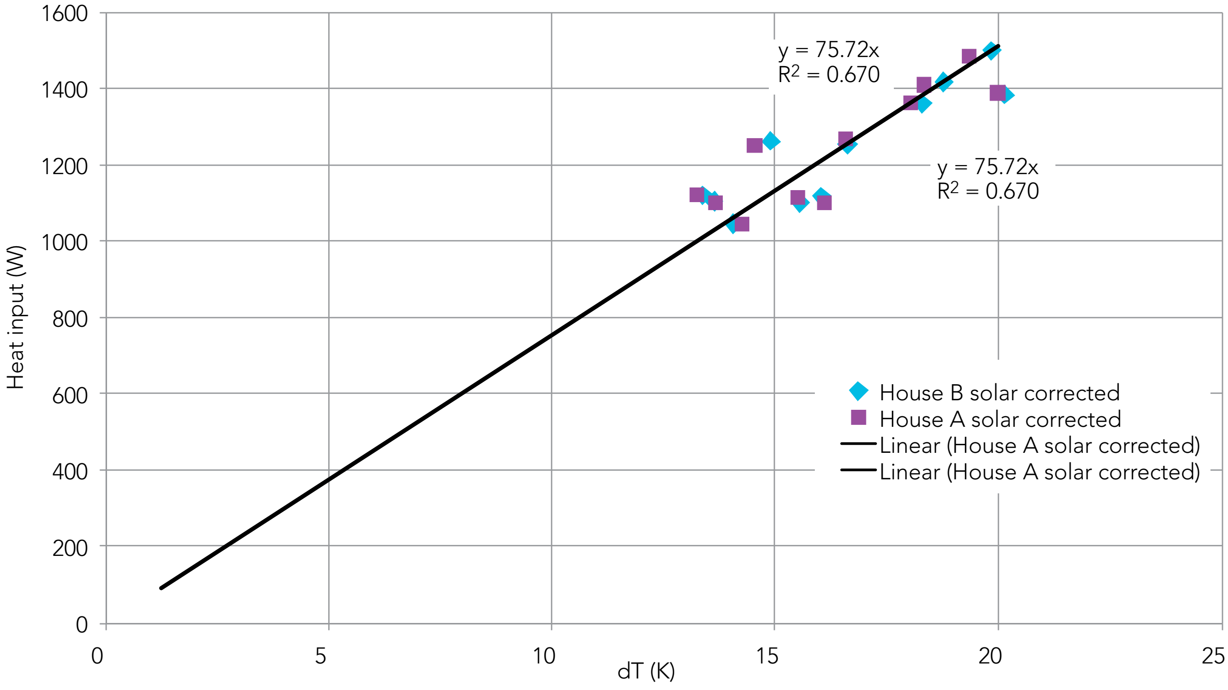


Figure 17 Solar corrected heat input for House A and House B (23 December 2011 to 2 January 2012) plotted against inside to outside temperature difference (dT)

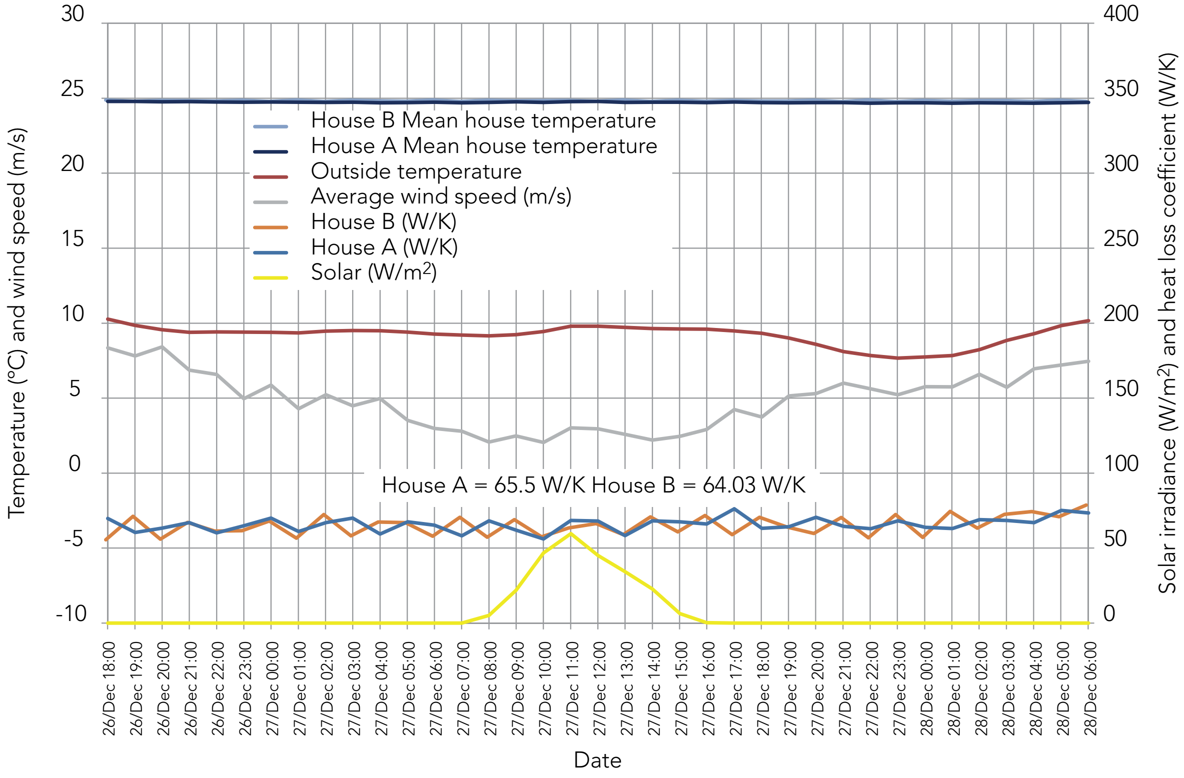


Figure 18 Co-heating test for House A and House B with low solar gain and stable outside air temperature and wind speed (26 to 28 December 2012)

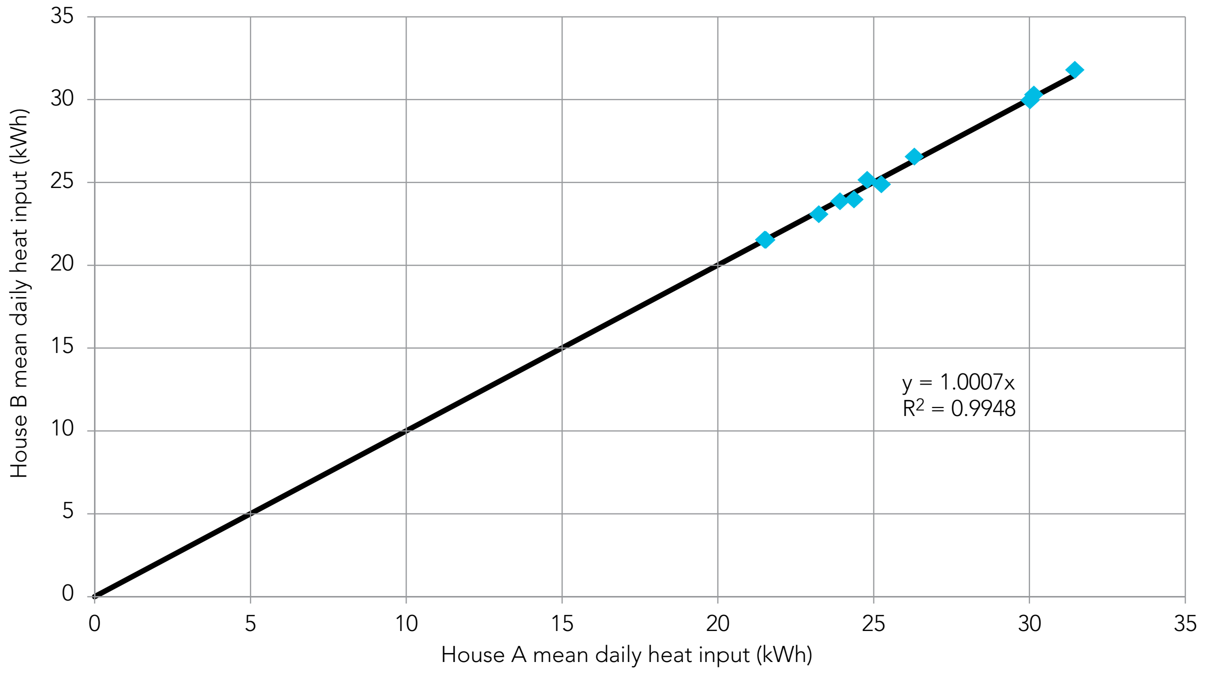


Figure 19 Daily electrical heat input for House A and House B (23 December 2011 to 2 January 2012)

BRE also undertook a second period of co-heating in both houses in June 2012 following the end of the project partners' co-heating tests. The Siviour plot is shown in Figure 20. The HLCs and solar apertures derived from the best-fit curve gradients and intercepts were:

- House A HLC = 60.72 W/K
- House B HLC = 63.49 W/K
- House A solar aperture = 1.97 m^2
- House B solar aperture = 2.25 m^2.

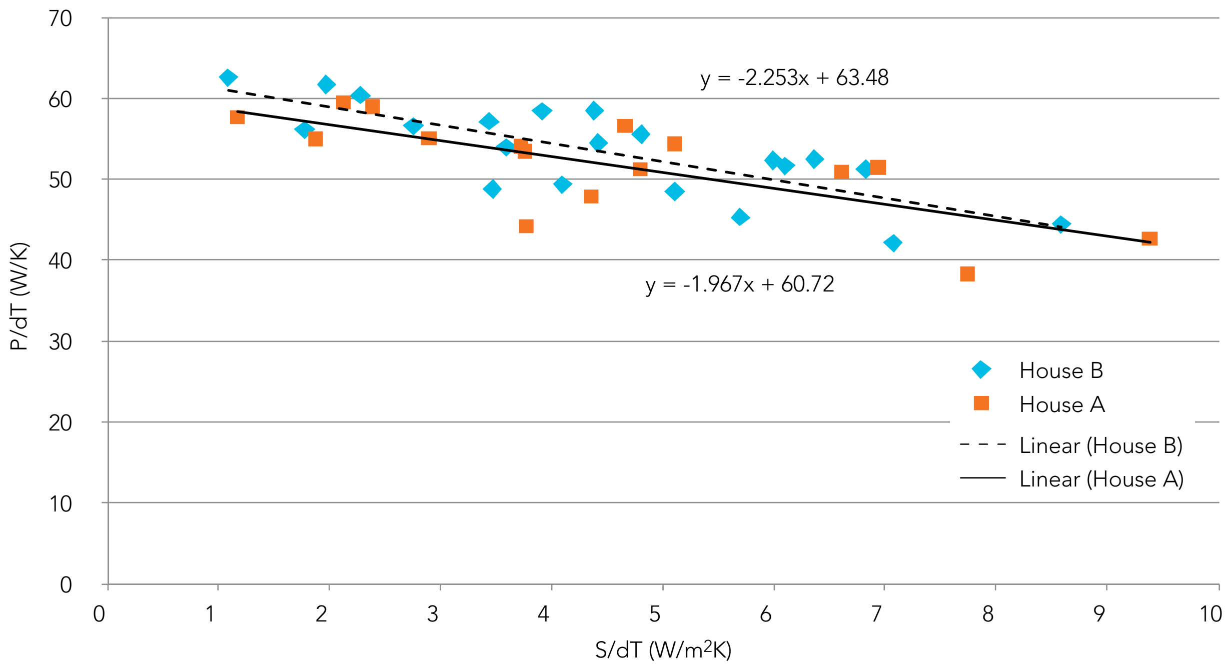


Figure 20 Siviour plots for House A and House B (4 to 24 June 2012 [where P/dt is (Q + K) / ΔT and S/dT is (VSol / ΔT]

The solar aperture values were also used to provide a solar heat correction to the measured electrical input. The solar corrected heat input plotted against dT is shown in Figure 21. The HLCs were 63.56 W/K for House B and 60.95 W/K for House A, which are close to the values derived directly from the Siviour plots.

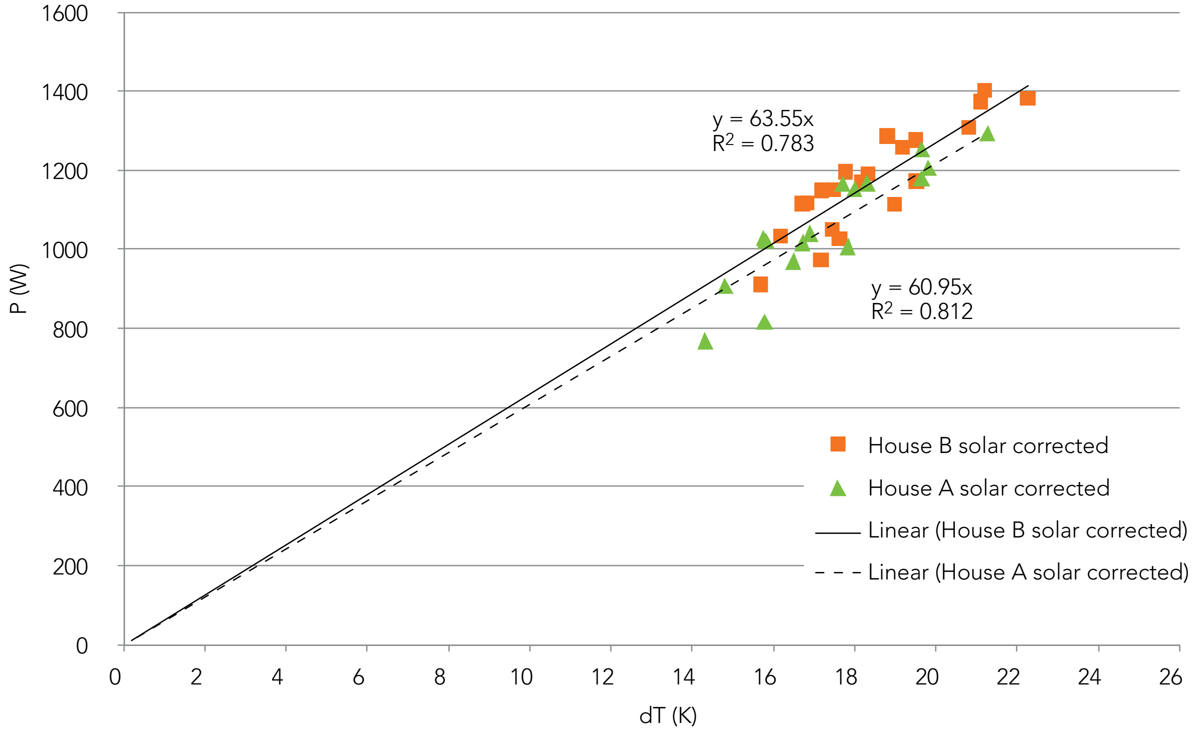


Figure 21 Solar corrected heat inputs for House A and House B (4 to 24 June) plotted against inside and outside temperature difference (dT)

5.2 Project partners' co-heating test results

The results from the co-heating tests undertaken in House B between December 2011 and May 2012 by BRE and the project partners are compared in Figure 22 and show a range of HLC test results between 56.7 W/K and 77.1 W/K. All reported values were corrected for solar heat gains except where noted (first value only).

The calculated steady state heat loss based on as-built dimensions and specified (not measured) fabric element U-values and infiltration was 68.4 W/K. Compared to this value the experimental co-heating test values were within the range -17% to +11%.

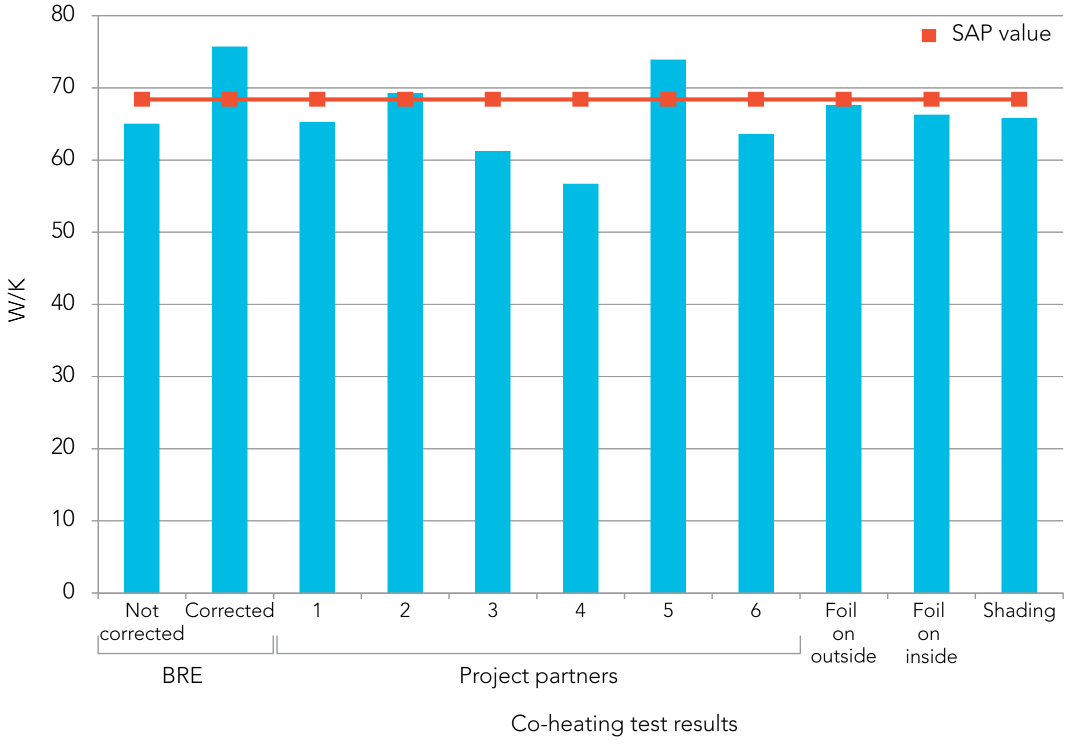


Figure 22 Results from the co-heating tests in House B

5.3 Data analysis comparisons

The majority of the project partners who participated in the co-heating tests reported that they generally followed the Leeds Metropolitan Protocol[1] for the practical aspects of the test. Separate thermostatic controllers were mostly used for the heaters in each control zone. This meant that the set point on each controller required manual fine tuning to reduce calibration errors, which required return visits. Despite this it was apparent that some test teams were unable to achieve uniform temperature levels between the different zones in the house and had to derive a weighted average internal temperature for the house.

Solar heat gains were generally corrected by using the solar aperture derived from a Siviour analysis to correct the measured electrical heat input to the house. The solar aperture was derived from the gradient of the Siviour plot. The solar aperture or solar radiation coefficient was then used to determine the solar heat gains from the measured solar irradiance and added to the measured electrical heat input.

Some deviations from the normal analysis method were reported by three project partners. These concerned the definition of the start and end of each test day in relation to an argument that one day's data should contain only the solar heat gains from that day. On this basis one test team defined the day as the hours from 9 am to 9 am. However, another test team used 6 pm to 6 pm, and another 6 am to 6 am. There was therefore no consensus on this.

A summary of the HLC, solar aperture (solar heat coefficient) and day start and end hour for each test is provided in Table 1. A comparison of HLC values is also shown in Figure 22. The solar aperture appears to vary with season, being higher in winter than in summer. This might be explained by lower sun angles in winter making the solar radiation more incident to the window surface. However, with such a small data set it is difficult to draw any definite conclusion from this. The effect of redefining the beginning and end of a day appears to show no consistent effect on the HLC.

Table 1 Summary of individual test results (House B)

Test period	HLC (W/K)	Solar aperture (solar heat coefficient, m$^{2)}$	Definition of a test day
23 December 2011 to 2 January 2012, solar corrected	75.0	2.96	Midnight to midnight
23 December 2011 to 2 January 2012, not solar corrected	67.6	n/a	Midnight to midnight
28 February to 15 March 2012	65.2	2.60	9 am to 9 am
3 to 17 April 2012	56.7	n/a	6 pm to 6 pm
23 April to 8 May 2012	78.0	n/a	Midnight to midnight
10 to 24 February 2012	70.1	2.38	6 am to 6 am
27 January to 5 February 2012	65.3	n/a	Midnight to midnight
19 March to 2 April 2012	61.2	n/a	Midnight to midnight
June 2012	63.6	2.25	Midnight to midnight

Although not apparent in the information presented here, it was remarked upon by several test teams that a wide spread in external temperature and solar radiation was critical to obtaining a strong correlation and in deriving solar aperture accurately. This is demonstrated by comparing the Siviour analyses in Figures 15 and 16 where the exclusion of just one day of high solar heat gains results in an apparently erroneous solar aperture value. This leads to a conclusion that shortening the test duration is likely to reduce accuracy. It also follows that a long spell of consistent weather conditions (temperature and sunshine) is also likely to reduce accuracy.

5.4 Solar shading test results

A consistent remark from the test teams carrying out the tests was that the major confounder during the tests was high solar heat gains. Since the weather cannot be controlled it was suggested that physical shading of the windows from direct solar radiation may be beneficial. The three types of shading tested where chosen on the basis of what may be considered to be practical to implement in the field.

The three types of window shading tested on House B are shown in Figures 23 to 25. Two tests were conducted using aluminium foil, a heavyweight commercial catering grade, attached directly to the glass on the inside and outside of the window with the shiny side facing outwards using aluminium tape (Figures 23 and 24), which proved both durable and easily removable. For the third (solar shading) test, heavyweight cotton fabric was attached to the external wooden window frames with staples, approximately 100 mm between the glass and the fabric (Figure 25).

Figure 23 House B with aluminium foil directly attached to the glass on the inside of the window

Figure 24 House B with aluminium foil attached directly to the glass on the outside of the window

Figure 25 House B with heavyweight cotton fabric attached to the external wooden window frames (approximately 100 mm off the glass)

A summary of the key weather and house parameters during the solar shading tests is shown in Figure 26. Note that during late May the house temperature level was raised from 26°C to 31°C in response to warmer weather, in order to maintain a sufficient temperature difference between the internal air temperature in the house and the outside air temperature.

The standard and solar corrected co-heating data are shown in Figures 27 to 29 and the HLC and solar aperture values are summarised in Table 2. Inspection of Figures 27 to 29 shows that the uncorrected heat input (from the electric heaters and fans), shown by the lower curve in each graph, is highest for the test with the aluminium foil attached directly to the glass on the outside of the window and lowest for that with the aluminium foil attached directly to the glass on the inside of the window. This shows that the aluminium foil attached to the glass on the outside of the window followed by the heavyweight cotton fabric attached to the external wooden window frames are the most effective forms of solar shading, and that the aluminium foil attached to the glass on the inside of the window is least effective. This is also shown by the solar aperture value being lowest for the aluminium foil attached to the glass on the outside of the window and highest for the aluminium foil attached to the glass on the inside of the window (Table 2).

The corrected HLCs for the tests with window shading were within 3.8% of the SAP value of 68.4 W/K.

Table 2 Summary of co-heating test results for solar shading tests

Test period	HLC (W/K)	Solar heat coefficient (solar aperture, m^2)
4 to 24 June 2012	63.6	2.25
26 June to 7 August 2012, aluminium foil attached directly to the glass on the outside of the window	67.6	0.73
28 August to 12 September 2012, aluminium foil attached directly to the glass on the inside of the window	66.3	1.13
7 to 28 August 2012, heavyweight cotton fabric attached to the external wooden window frames	65.8	0.84

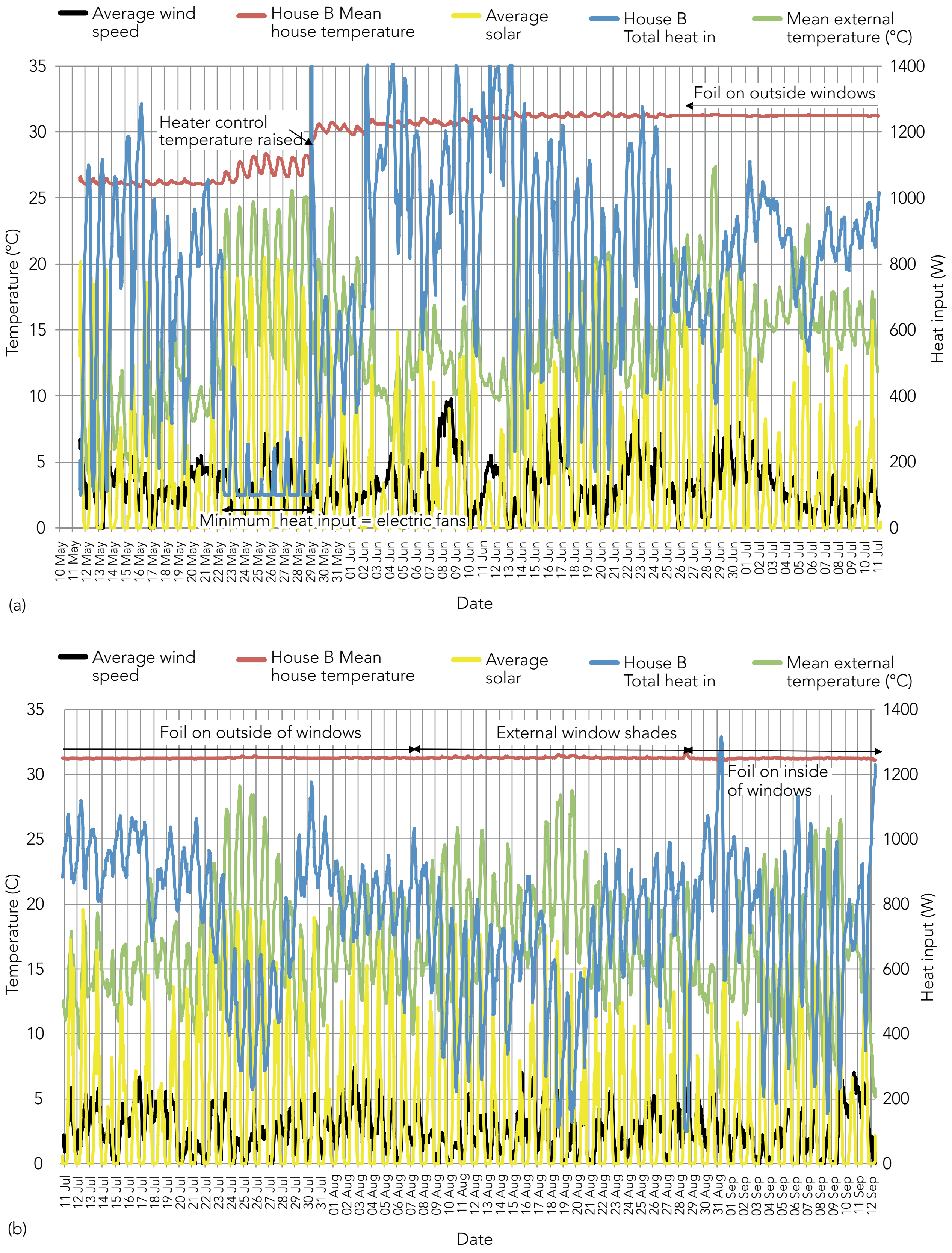


Figure 26 Summary of key weather and house parameters during solar shading tests: (a) 10 May 2012 to 11 July 2012 and (b) 11 July to 12 September 2012

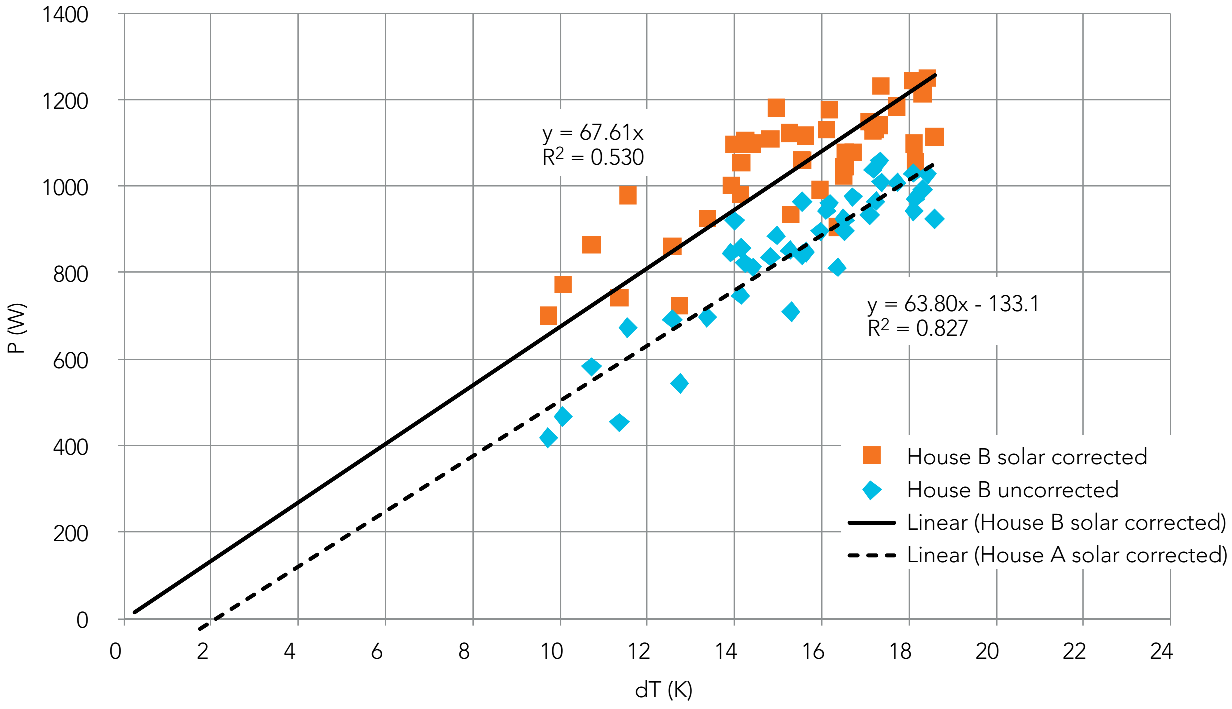


Figure 27 Heat input for House B with aluminium foil attached directly to the outside of the glass, solar corrected, plotted against inside and outside temperature difference (dT)

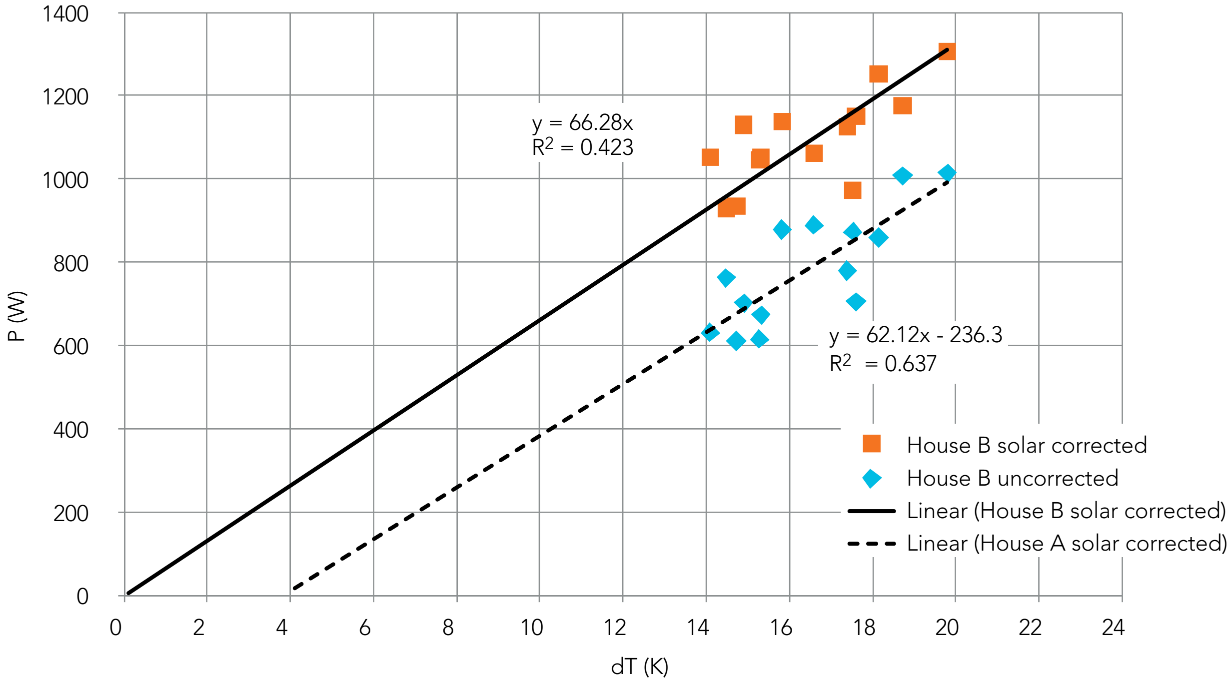


Figure 28 Heat input for House B with aluminium foil attached directly to the inside of the glass, plotted against inside and outside temperature difference (dT)

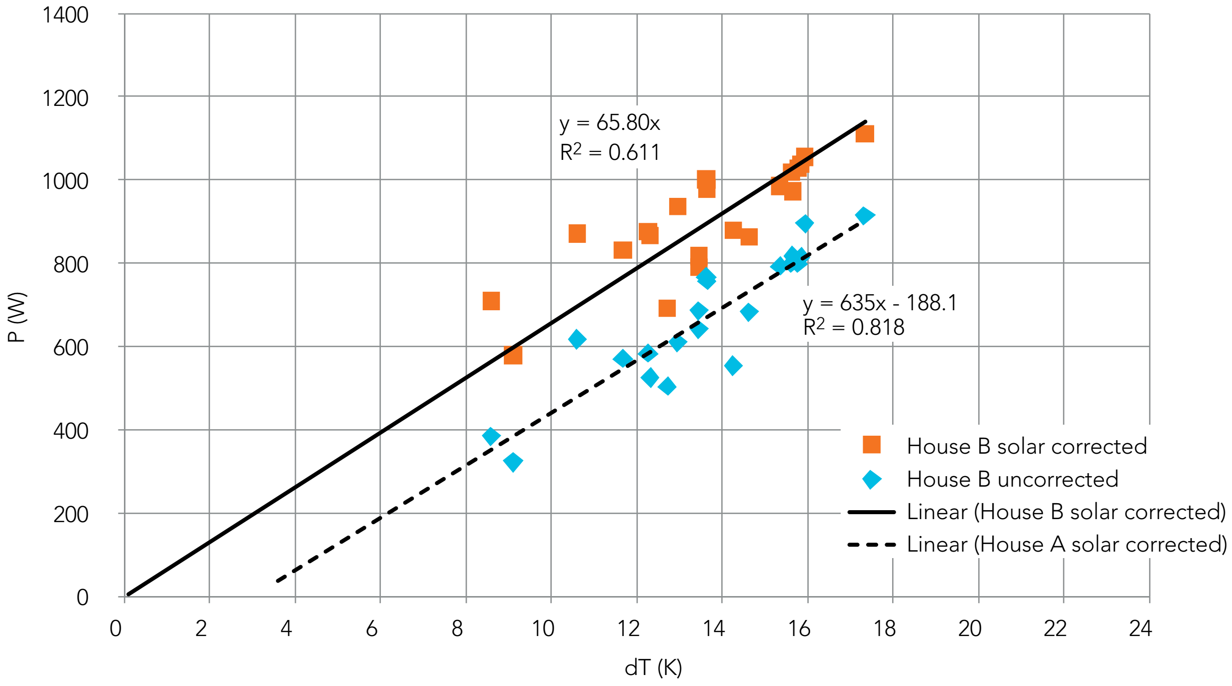


Figure 29 Heat input for House B with heavyweight cotton fabric attached to the external wooden window frames, plotted against inside and outside temperature difference (dT)

6 Conclusions and recommendations

6.1 Practicalities, repeatability and reliability

All of the test teams based their co-heating test methods on the methodology published by Leeds Metropolitan University[1]. However, this test methodology currently does not provide any guidance or information on analysis of the results obtained from the practical test measurements.

At a practical level most of the test teams used standard room thermostats to control the temperature in each building zone via electric fan heaters and air circulation fans. This type of thermostat has a relatively coarse and imprecise setting, and in practice this often made it difficult to achieve a uniform temperature across all control zones. It was also sometimes necessary to make return visits to the house to make fine adjustments to individual thermostats and to refine heater positions. BRE employed a different approach to temperature control based on industrial digital temperature controllers with external PT100 sensors. Although the equipment cost was slightly higher, the zone temperature control improved and became more reliable and resulted in time savings as return visits to adjust thermostat settings were not necessary.

It was very clear that the external weather conditions, particularly solar radiation, were a major confounder and had a major impact on the accuracy and repeatability of the co-heating test by making it difficult to achieve true steady state. In the course of this research project, wind appeared to have a second order effect although this is thought to be partly due to the low wind speed prevalent during the test period and also the relatively high airtightness of the test houses (air permeability at 50 Pa = 2.2 m^3/hm^2).

A major factor in determining repeatability and accuracy was the spread in external temperature and solar radiation during a co-heating test. A large spread or range in external temperature and solar radiation was found to be critical to obtaining a strong correlation and in deriving the solar aperture accurately. The solar aperture is essentially the solar radiation coefficient and is used by most co-heating analysis methods to correct for solar heat gains to the building. This means that shortening the test duration is very likely to reduce accuracy. It also follows that a long spell of consistent weather conditions (temperature and sunshine) with a small range or variation is also likely to reduce accuracy and repeatability.

It is clear that a major disadvantage of the co-heating test in the field is uncertainty regarding accuracy and repeatability. Where repeatability is important, and where there is a need to investigate a wide range of test scenarios in specific standard building types, construction of either a whole building or a representative section in an environmental chamber should be considered. While this is not a low cost option it would allow a wide range of repeatable steady state and dynamic tests to be undertaken.

Additional factors not analysed in this co-heating test project which may act as additional confounders include ground floor heat losses and fabric shrinkage. It is assumed that the external envelope of the building is in contact with outside air at a uniform temperature. Ground floors present a complication since the ground temperature is not the same as the outside air temperature, and also some ground floors are raised and have a ventilated void below them. The temperature of the air in the void will also be influenced by the ground temperature. The process of undertaking a co-heating test usually involves elevating the internal air temperature of the building above normal occupation temperature levels. When this is coupled with the absence of occupation-related moisture gains, the abnormally dry and hot conditions may lead to significant shrinkage of joinery and other parts of the envelope. A progressive deterioration in airtightness during the co-heating test may then occur. This will result in a gradual increase in HLC during the test.

6.2 Data analysis and calculation

Although the co-heating test method developed by Leeds Metropolitan University does not include data analysis and calculation of the HLC, various papers published by Leeds Metropolitan University and other organisations detail a calculation method. The calculation method is based on a Siviour method analysis and use of the solar aperture or solar radiation coefficient to correct the metered electrical heat input to include solar heat gains. Most of the test teams appear to have used this method or something very similar.

The derivation of solar aperture and HLC is dependent on obtaining a reasonable spread of data. A small spread of data can lead to large errors in the coefficients derived from linear regressions on the data. Linear regression is also vulnerable to skew caused by a relatively small number of data outliers.

Variation in solar radiation and solar heat gains to a building is a major source of inaccuracy and poor repeatability. Therefore it has been suggested that the analysis and determination of HLC should be based on night time data only. However, this could still be vulnerable to the uncertainty caused by large daytime solar heat gains remaining stored in the building fabric for a lot more than a few hours. More research and testing in buildings with a range of thermal mass would be necessary to prove the effectiveness of this approach, and also to determine the optimal day beginning and end times. If the analysis were based on night time data only, it might be possible to dispense with the requirement for a pyranometer to measure solar irradiance.

6.3 When and where co-heating tests should be used, and comparisons with SAP

The BRE test houses used in this research were based on very high quality Swedish timber frame constructions, originally erected under the supervision of BRE staff. Therefore it is reasonable to expect that the design details of the house and the calculated SAP HLCs were reasonably accurate. This is unlikely to be the case for houses in the field. Comparison of the co-heating test HLCs with the SAP value shows that the largest difference was approximately 17%. However, the effect of solar shading on the windows appears to have reduced the uncertainty such that the measured values were within -3.8% of the SAP value. With just three tests carried out, each one being undertaken with a different type of shading, this result cannot be taken as conclusive and such measures should be tested with other types of building and at other times of the year. The possible effect of different types of shading on the thermal performance of the building should also be considered since the shading is likely to have some effect on the thermal transmittance of the windows. However, if it is subsequently shown that physical window shading is effective elsewhere then it would make the co-heating test a more accurate, and therefore useful, method of determining the as-built HLC. The test's possible use in demonstrating compliance with building regulations could then be considered, and its role as an investigative and diagnostics tool made much more informative.

6.4 Further research

It is clear that the co-heating test is highly sensitive to external weather conditions, in particular solar heat gains. Therefore the current approach to co-heating testing is unlikely to be suitable for large scale application across the construction industry due to a relatively long test duration, appreciable costs and uncertainty in the results. However, the research described in this report suggests that the uncertainty may be reduced through relatively simple and low cost shading of the windows. It is therefore recommended that the effect of external shading on reducing the uncertainties associated with solar heat gains in co-heating tests should be investigated further by trialling in other types of houses, other building types and under different weather conditions. This investigation should also consider the effect of heat gains through unheated roof spaces when subject to high levels of solar radiation. The effect of shading on the thermal performance of the windows should also be considered.

It has also been suggested that the analysis of co-heating test data, for overnight hours only, might reduce the uncertainty caused by solar heat gains and also reduce the test duration. The use of window shading might also contribute to the reduction in uncertainty from night data analysis, by reducing the effect of daytime solar heat gains stored in the house on the night time thermal balance. The splitting of HLC into the component parts for infiltration heat loss and fabric heat loss has not been fully investigated here and should also be addressed in further research.

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Appendix A
Construction details for the BRE test houses

Wall construction

- 103 mm facing bricks
- 50 mm air gap
- 13 mm bitumen impregnated fibreboard
- 170 mm Rockwool insulation
- Vapour barrier
- 9 mm plywood
- 45 mm Rockwool insulated service cavity
- 13 mm plasterboard.

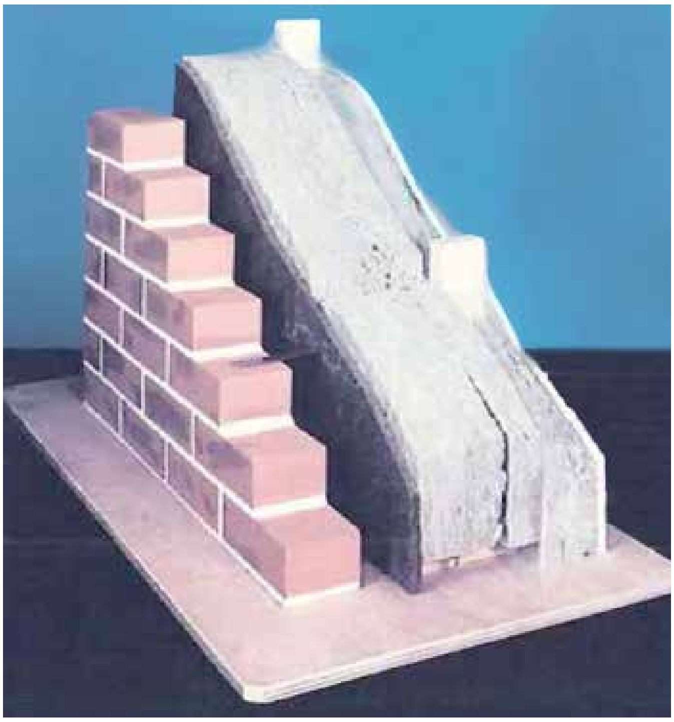


Figure A1 Model of the BRE test house wall construction

Roof construction

- 13 mm plasterboard and vapour barrier
- 240 mm Rockwool insulation between 250 mm joists at 600 mm centres
- 35° pitch roof with tiles on cross batten and felt and 9 mm plywood below.

Floor construction

- Carpet over 22 mm chipboard
- 22 mm Rockwool insulation laid between 220 mm joists at 555 mm centres.

Windows

- Timber framed with triple glazing.

Principal U-values:

- External wall: 0.21 W/m^2 K
- Floor: 0.21 W/m^2 K
- Roof: 0.16 W/m^2 K
- Triple glazing: 1.85 W/m^2 K
- External doors: 1.0 W/m^2 K.

Air permeability

- 2.20 m^3/hm^2 (measured at the end of the second BRE co-heating test period).

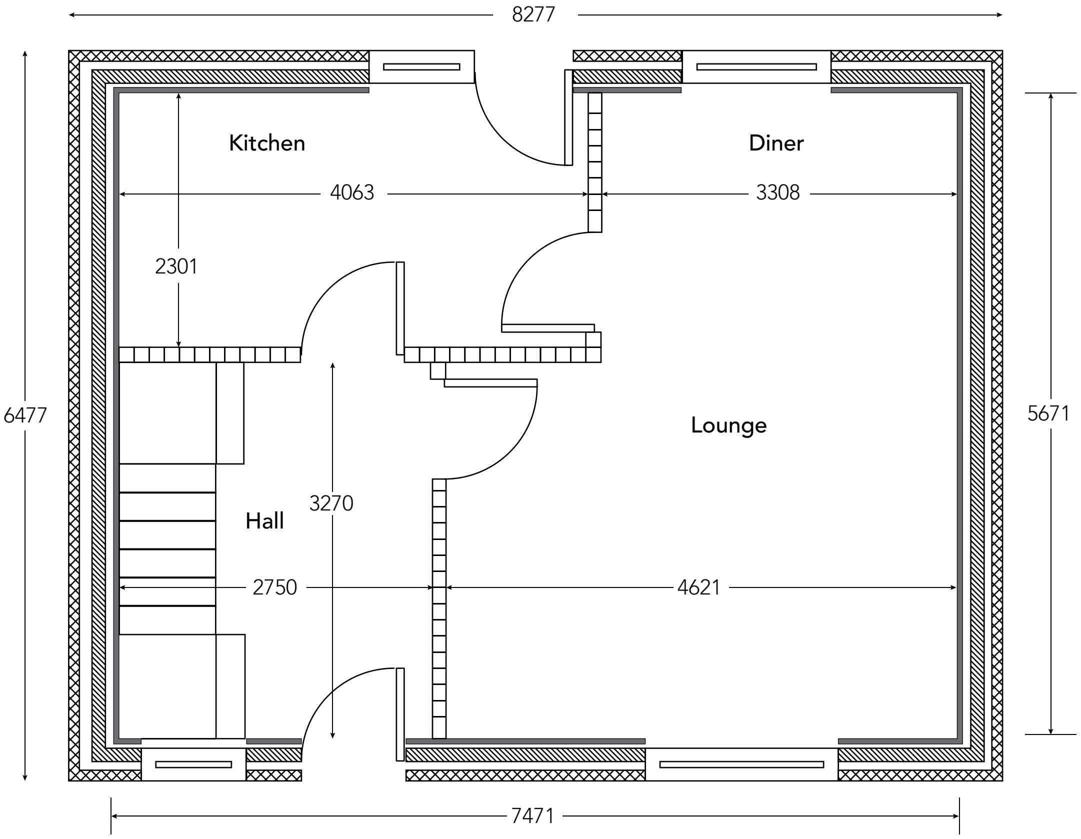


Figure A2 Ground floor plan for the BRE test houses (dimensions measured in millimetres)

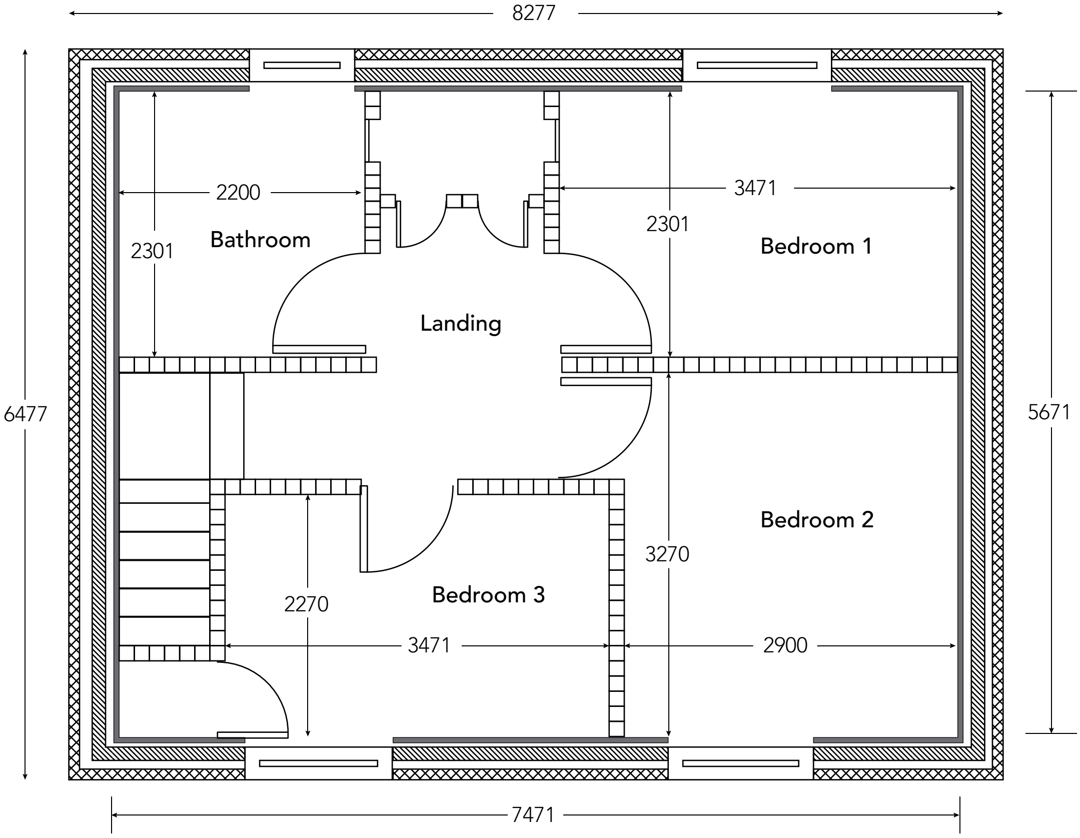


Figure A3 First floor plan for the BRE test houses (dimensions measured in millimetres)

NHBC Foundation recent publications

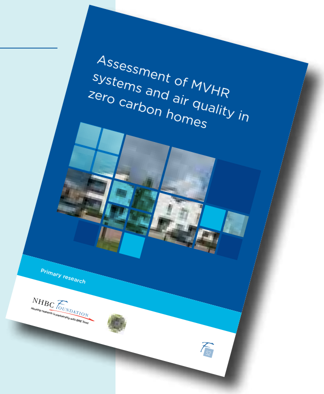
Low- and zero-carbon technologies in new homes


Low- and zero-carbon technologies in new homes
Learning from the experiences of consumers and on-site sales teams
Primary research

The polarisation between the developer and the consumer forms the starting point for this research, which focuses on low- and zero-carbon (LZC) technologies because it is known that these have a significant (perhaps disproportionate) impact on occupants' perceptions of their homes. The work gives new insights on the actual consumer experiences of LZC technologies in their homes. Second, carefully building upon the consumer findings, the actual knowledge and practices of on-site sales teams in promoting (or hindering) consumers' awareness of the benefits of LZC technologies and their use are explored.

The report provides new real-world insights into the detailed, day-to-day marketing and use of homes with LZC technologies. Further, these insights inform the development and demonstration of a continuous improvement marketing approach for house builders.
NF 53 November 2013

Assessment of MVHR systems and air quality in zero carbon homes


Assessment of MVHR systems and air quality in zero carbon homes
Primary research

This report is based on the experience of MVHR systems in 10 homes built by Scottish and Southern Energy at Greenwatt Way, Chalvey. Built to Code for Sustainable Homes Level 6, these homes provided a perfect test bed for the detailed evaluation of MVHR systems in practice. As well as looking at design, specification, installation, and commissioning issues, the research also gauged the use of these systems by some typical home occupants. ***NF 52*** August 2013

Fires in cavities in residential buildings


Fires in cavities in residential buildings
The performance of cavity barriers in external walls with combustible materials
Primary research

As a follow-up to the 2011 publication *Fire performance of new residential buildings*, this report focuses specifically on fire spread within external walls where the cavity between the external façade and the structural frame is incorporated either as a lining material or as a form of insulation (or both).

In support of the project, a programme of 21 fire experiments on walls containing various options for sheathing and cavity barriers was undertaken. ***NF 51*** April 2013

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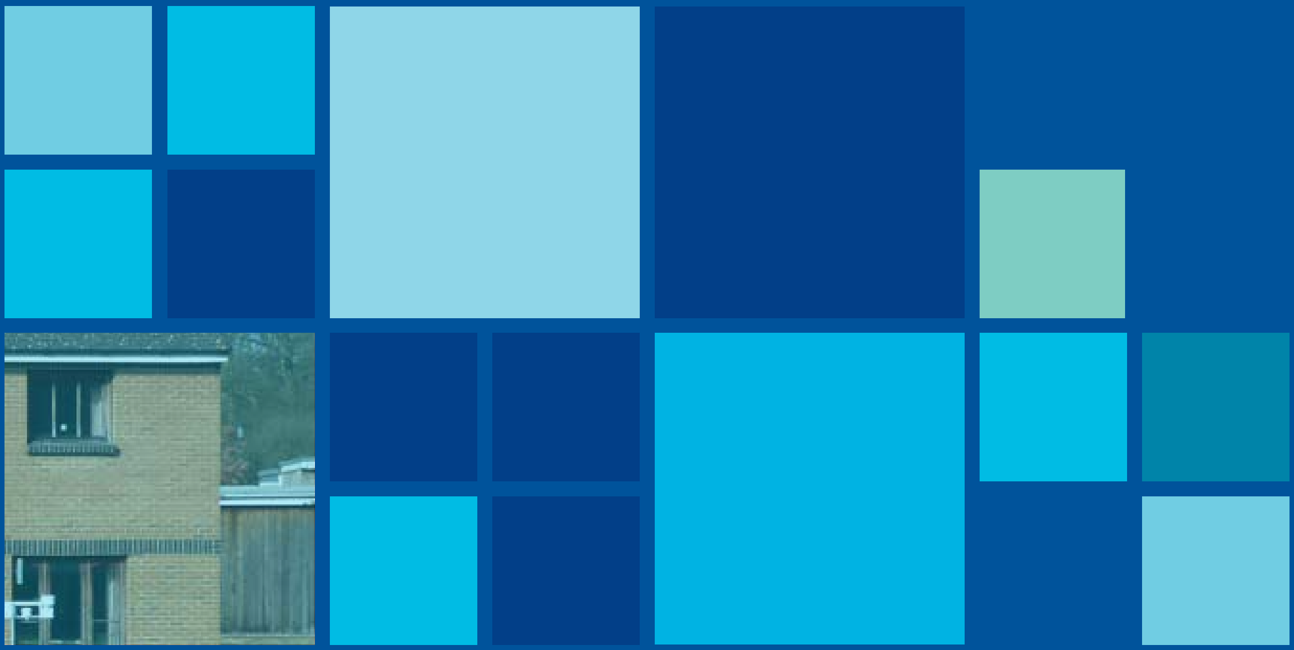
Review of co-heating test methodologies

As our understanding of the issues involved in delivering energy-efficient housing has developed, there has been growing concern about the performance gap between design expectations and in-use outcomes. The co-heating test, developed in its present form by Leeds Metropolitan University, provides a means by which the as-built performance can be measured. In practice, the reliability and practicality of co-heating tests for large scale application across the construction industry has been questioned due to the long test duration and uncertainty in the heat loss coefficient.

This report describes a series of co-heating tests undertaken by test teams from BRE and six project partners (commercial and academic) in one of BRE's test houses, with a second identical test house used as a control.

The project assessed the approaches taken by investigators undertaking the co-heating test, with particular regard to test protocols, data analysis and treatment of uncertainties.



NHBC Foundation has been established to facilitate research and development, technology and knowledge sharing, and the capture of industry best practice. NHBC Foundation promotes best practice to help builders, developers and the industry as it responds to the UK's wider housing needs. NHBC Foundation carries out practical, high quality research where it is needed most, particularly in areas such as building standards and processes. It also supports house builders in developing strong relationships with their customers.

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