Using simulated co-heating tests to understand weather driven sources of uncertainty within the co-heating test method

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Abstract
The so-called performance gap between designed and as-built building performance threatens to undermine carbon reduction strategies in the built environment. Field measurements to date have indicated that the measured as-built fabric heat loss of tested UK buildings is consistently higher than design values, often considerably so. Currently, our lack of knowledge over the extent of this gap, and the processes that cause it, is compounded by a lack of robust post-construction evaluation tools. Much of this post-construction evaluation work is based, in part, on the use of co-heating tests: a method utilising an energy balance to determine the heat loss across the entire building envelope, defined by the heat loss coefficient (W/K). However, the errors associated with co-heating are not well understood or typically addressed in the literature. Furthermore, the test procedure requires a building to be unoccupied for two to three weeks and is therefore often cited as costly and unsuitable both for developers and as a policy tool. In order to improve the application of this test method it is crucial firstly to understand the sources of uncertainty in co-heating tests and the 'steady-state' energy balance they are based upon. However, with a small database of tests performed to date it is difficult to discern these sources of error. This paper presents the results of a method using simulated co-heating tests to show how key weather variables influence the co-heating result and generate uncertainty and bias. In particular the effects of short-wave solar and long-wave sky radiation are presented. Improvements to the co-heating method can be derived from this; in particular the need to consider when dwellings should be tested to avoid large solar-generated errors and the importance of a accurately calculated solar aperture. Recommendations also include the local measurement of sky radiation to avoid outlying data points, bias in the measurement and discrepancies when comparing design and as-built heat loss.

Introduction
The domestic sector of the built environment accounts for a quarter of final UK energy consumption with 60 % of this having long been associated with space heating (DUKES, 2011). To reach binding emission targets the UK government has targeted all new houses to be 'Zero Carbon' by 2016 (ZCH, 2010) and has implemented the Green Deal in an effort to address the challenge of retrofitting the existing stock. It has been estimated that reductions in the order of 80 % can be made in this sector through existing or emerging technologies (Lowe, 2007a) coupled with supply side transformation. However, understanding building performance in practice is crucial to informing strategy and controlling quality to ensure emissions targets are met in reality.

Understanding space heating energy use is complex. Occupants' behaviour, heating system efficiencies and fabric efficiency all drive energy use but their interactions are complex and notoriously difficult to disentangle. As a result, sets of 'post-construction' monitoring and evaluation tools have been developed to examine fabric performance in isolation. Whilst pressurisation and tracer gas tests have led to improved understanding and quality assurance in airtightness, heat loss, as a whole, is harder to measure. Infrared thermography has become a valuable diagnostic tool but its output is limited by its qualitative nature and difficult interpretation. Heat flux sensors now allow in situ u-values to be determined for various building elements through fairly unobtrusive methods (EN ISO 9896, 1994). However, this measurement is limited by the small sensor measurement area, which can effectively ignore the variation across the fabric and areas of complex thermal heat transfer. These more complex heat loss mechanisms and the variation in the fabric due to the 'buildability' of the structure are of key importance so also need to be captured. The heat loss across the whole building envelope can be measured by effectively holding the test dwelling at a constant internal temperature, measuring all heat inputs and hence inferring heat loss. This method, using approximated steady state conditions to solve a simplified energy balance equation is known as co-heating.

Despite having been in existence since the 80s, these post construction evaluation tools are in their relative infancy. However, their use to date has reinforced the importance of evaluating actual building performance. Of 34 co-heating tests conducted by Leeds Metropolitan University under the co-heating method, over 60 % have had measured heat losses more than 20 % higher than design with nearly half over 50 % worse (Stafford et al., 2012). Amongst further examples, in situ u-value measurements have reported the average measured cavity wall u-value to be 30 % higher than predicted (Doran, 2001).

The UK government has in part recognised the role the performance gap poses on reduction targets, recommending that 95 % of new buildings are performing equal to, or better than, design by 2020 (ZCH, 2011). For this target to be realised, robust and appropriate tools are needed to provide quality assurance and provide feedback on designs, materials and construction methods.

The Co-Heating Method

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 guidelines experimental guidelines (Wingfield et al., 2010).

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. Heat input to electrical equipment is recorded by kilowatt-hour meters but heat input from solar radiation also needs to be accounted for. Typically this is through the use of a pyranometer, measuring solar radiation, which is then converted into effective solar gains by a solar aperture, derived from regression of experimental data or from the buildings glazing characteristics. A form of regression, with heating power and ΔT, or multiple regressions, which also includes solar radiation, is used to evaluate the building heat loss coefficient and solar aperture.

$$Q + R.S = (\Sigma U.A + C_v)\Delta T \qquad \text{(Equation 1)}$$

With,

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
$\Sigma U.A$ [W/K]	is the sum of the U-values [W/m^2] and respective areas of the thermal envelope [m^2]
C_v	is the infiltration heat loss [W/K]
V	is the internal volume [m^3]

Despite having been developed over 30 years ago, the method has seen little application to date. In addition to the lack of interest on the part of funding bodies since the mid-1980s in empirical research on building performance, this is because there are a number of limitations concerning the suitability of the test method:

- For this energy balance to work the test dwelling needs to remain sealed and unoccupied.

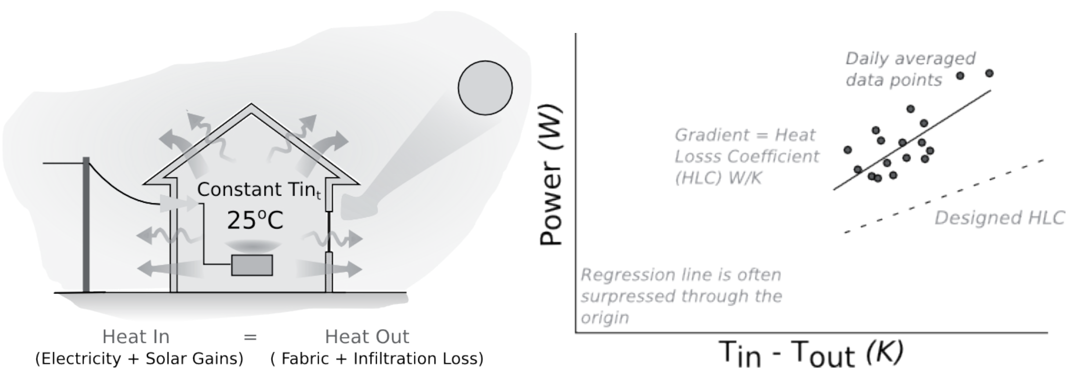

Figure 1. Co-heating principal and analysis method. The energy balance the co-heating method uses is shown along side an example of data used in linear regression. Typically an additional independent variable and axis for solar radiation is included as part of a multiple linear regression.

Table 1. Weather Files.

Weather File	*External Temperature*	*Solar Radiation*	*Wind*	*Sky Radiation*
WF1. Ideal	✗	✗	✗	✗
WF2. Original (Typical Year, Gatwick UK)	✓	✓	✓	✓
WF3. Only Varying External Temperature	✓	✗	✗	✗
WF.4 Only Solar Radiation	✗	✓	✗	✗
WF.5 Only Wind	✗	✗	✓	✗
WF.6 Only Sky Radiation	✗	✗	✗	✓
WF.7 No Varying External Temperature	✗	✓	✓	✓
WF.8 No Solar Radiation	✓	✗	✓	✓
WF.9 No Wind	✓	✓	✗	✓
WF.10 No Sky Radiation	✓	✓	✓	✗

- Daily averaging is needed in an attempt to smooth over dynamic effects throughout the course of the day.
- The result is highly weather dependent. A suitable range in external temperatures, and hence ΔT, and solar radiation is needed to perform the regression analysis and accurately determine the heat loss coefficient and solar aperture.

These three factors all result in a typical test duration 2–3 weeks during a testing season of October to March. Even with such long testing periods, an accurate result is not guaranteed and importantly the uncertainty in the measurement is not well understood or easily defined.

This has led to the limited use of the co-heating method with only approximately 100 tests carried out in the UK to date. There are good examples how co-heating and additional evaluation tools can improve both our fundamental understanding of building heat loss (Lowe, 2007b), and also provide effective feedback to developers to improve actual performance (Wingfield et al., 2011; Miles-Shenton et al., 2011). However, to be integrated in to a wider quality assurance structure and perform post-construction evaluation on the scale needed to ensure 2050 and intermediate emissions targets are met within the built environment, this type of testing method needs to become much more applicable and reliable.

Research Method

Only a very small number of co-heating tests have been performed and one off testing of individual houses will only provide information on the reliability of the test on that particular house, under those particular weather conditions. Longer term or repeated testing of dwellings can build on this but are also time intensive and still offer only limited information. Therefore, an approach using simulated co-heating tests has been sought to provide an overview over a wider range of weather conditions. This extends work by Everett (1988) where the potential of the co-heating method and its interaction with weather was investigated with synthetic weather data.

Simulated co-heating tests were performed in Energy Plus following the co-heating field method. An advantage of the simulated method is that the parameters we wish to extract from the test, i.e. the heat loss coefficient, are inputs into the building model so are therefore precisely known. A typical, simple detached house was modelled, with two floors, glazing on the north and south facades and an unheated attic. The house is of a simple brick construction with modern standards of insulation and airtightness.

This paper specifically focuses on the effect on the co-heating test of key weather variables, namely: varying external temperatures, solar radiation, wind and sky radiation. These are key sources of uncertainty in the co-heating method, disrupting the energy balance, but little is yet understood of their direct effects. Using the simulation framework, co-heating tests are explored under a number of weather scenarios. A number of dummy weather files have been generated, exploring the test output with and without each of these key weather variables. These dummy weather files are adapted from an original weather file and form only hypothetical scenarios, but do allow the effects of each variable to be disaggregated in a way not possible in field tests. This allows their effect on the derived heat loss coefficient to be gauged and the uncertainty they generate estimated.

It is important to note that there are many additional drivers behind uncertainty in the co-heating method beyond those explored here. For example, the presence of moisture in the fabric, particularly in new builds, can reduce thermal performance and add a latent load to the energy balance equation associated with the building 'drying out'. This systematic source of uncertainty can be significant and should not be neglected (Stamp et al., 2012). However, these are not included in the scope of this paper and remain areas for future research.

Results & Discussion

COMPARISONS TO IDEAL CASE

Initially the four weather variables were compared independently to a baseline ideal case in which all weather conditions were absent or held constant. This allows any trends across the year to be identified. Multiple linear regressions were performed on the resulting datasets and the residuals are shown in Figure 2.

This approach is useful in eliciting the trends generated by each variable when in isolation. In this arrangement the residuals generated from solar radiation appear to be the largest, becoming larger during the summer. Even when there is no error in the calculation of the solar aperture these residuals remain present as a result of thermal mass effects between successive days. Residuals can become even greater in the presence of in-

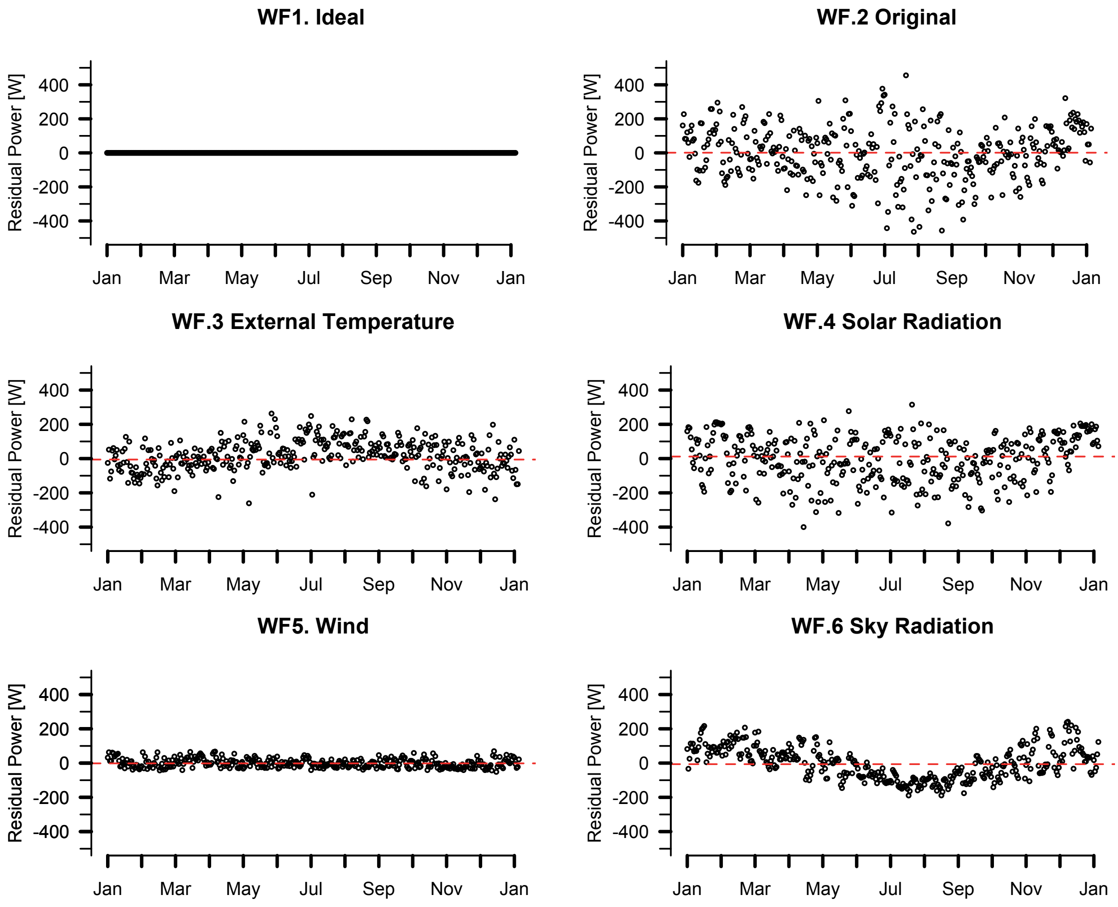

Figure 2. Residuals in comparison to ideal. Here the residuals from a multiple linear regression across the entire year are shown.

ternal overheating, i.e. when more power is provided through solar gains than needed to maintain a temperature of 25 °C, although little overheating was observed in this case.

In this case a varying, rather than constant, external air temperature also increases the residuals significantly. The changing external temperature is creating a lag and a thermal mass effect between successive days. An unusual trend can also be noted here, as there is a positive bias in the summer where more heating power is needed

As the building simulated in this case follows modern guidelines on airtightness the wind generated residuals are relatively small and have a uniform distribution. This does not mean that wind should be ignored. In small data sets, outliers can still be generated and this influence increases greatly when testing older dwellings with lower levels of airtightness. Current protocol recommends local wind measurements are taken and daily tracer gas decays tests can also be used to measure daily infiltration rates. It should be noted that theoretical considerations indicate that wind effects will be inherently non-linear and intertwined with variations in external temperature.

A clear trend can be seen in the residuals generated by sky radiation losses as the long wave radiation exchange varies throughout the year. This effectively introduces a small bias into the heat loss measurement, depending on the time of year testing occurs. In individual tests however, the scatter created on a day-to-day basis may in fact be more significant. Current co-heating methodology leaves sky radiation losses as an unmeasured and unregulated heat loss. The bias and size of the residuals seen here would indicate that this should be measured locally, through the use of a pyrgeometer or net radiometer. Field measurements using such a device could provide supporting evidence to this simulated observation.

Another interesting point to note is that under the presence of sky radiation losses the true heat loss coefficient actually increases. Under ideal conditions, the heat loss coefficient is the same as that of a building audit description, essentially the sum of u-values across the building envelope plus infiltration losses. However, under conditions in which sky radiation is present there is an additional heat loss mechanism, which therefore increases the heat loss coefficient. This depends on the level of radiation losses but this increases the heat loss coefficient by 10% when average sky radiation losses experienced over the testing season are assumed. This is not insignificant and increases in cases in which the attic space is heated. An awareness of this is important when measured heat loss coefficients are compared to design intent, which may not have accounted for this extra heat loss. This implication is important in regards to giving feedback on as-built performance and quality control.

COMPARISONS TO THE ORIGINAL CASE

The full original weather file was then compared to weather files in which each of the key variables was either removed or held constant (WF7-10). Analysing the square sum of residu-

Table 2. Reduction in mean residual sum of squares by absence of weather variables in the testing season.

	October	*November*	*December*	*January*	*February*	*March*
Total RRS WF.2 Original	602	383	426	389	518	483
Reductions in RSS						
WF.7 *No External Temp*	-2 *(0%)*	158 *(41%)*	213 *(50%)*	58 *(15%)*	121 *(24%)*	74 *(15%)*
WF.8 *No Solar Radiation*	130 *(22%)*	1 *(0%)*	-58 *(-14%)*	42 *(11%)*	202 *(39%)*	229 *(47%)*
WF.9 *No Wind*	10 *(2%)*	-5 *(-1%)*	5 *(1%)*	35 *(9%)*	-4 *(-9%)*	89 *(19%)*
WF.10 *No Sky Radiation*	72 *(12%)*	23 *(6%)*	35 *(8%)*	71 *(18%)*	23 *(4%)*	144 *(30%)*

als (RSS) in this case it would be expected that the total would be reduced as a variable generating additional uncertainty was removed. The larger this reduction the more influential the variable, or the more scatter it generated. These reductions are presented in table using data from regressions over each month in the testing season.

Again Table 2 displays interesting trends that can inform the co-heating test method and the sources of error in this test dwelling. Solar Radiation has a limited impact in November, December and January but becomes much more significant in October, February and March in particular. The higher overall residuals seen in these months are likely to originate from this solar component. This type of result indicates the need to consider timing of performing field tests. If, for example, a test were to be performed on a highly glazed property, sensitive to the uncertainty induced by solar radiation, then testing in November-January would be significantly preferable, albeit still with a risk of uncharacteristically sunny weather. If testing in March, or more specifically under conditions of high solar radiation, there may also be a need for high-resolution solar radiation measurements to be made and for longer than daily averaging periods to account for solar generated thermal mass effects between successive days.

Despite long wave sky radiation losses being unregulated in the co-heating test method in March, they generated as much as 30 % of the overall residuals and also made significant contributions in October and January. As a variable this clearly has the potential to increase the scatter, which could be particularly influential if there are only a limited number of data points in the data set and this again reinforces the argument for this variable to be measured locally as part of the test protocol.

WEATHER VARIABLES EFFECT ON DERIVED HEAT LOSS COEFFICIENT

Finally, it is useful to look at the effect each weather variable has on the derived heat loss coefficient. Again we look at the cases when each weather variable is removed and compared to the original weather file. Figure 3 shows histograms plotting the derived heat loss coefficient from a continuous series multiple regression performed throughout the heating season, each using 14 days of data (i.e. The model on day 1 is a regression using days 1–14 and so on). Here, tighter distributions in the absence of a weather variable indicate its strength when present.

Again, Figure 3 makes it extremely clear how much the result improves in the absence of solar radiation. The shift in 'true' heat loss coefficient also shifts down when sky losses are removed.

Conclusion

The method of performing simulated co-heating tests adopted here offers an opportunity to investigate the effects of four key weather variables; external temperature, solar radiation, wind and long-wave sky radiation. Adapting weather files to include or exclude these variables and observing their residuals and the resulting heat loss coefficients derived across the year can be used to identify areas of bias, as seen in the case of sky radiation, or periods of higher uncertainty, as in the case of solar radiation.

The results show that solar radiation in particular generates a high proportion of the residuals seen in the linear regression used to derive the buildings heat loss coefficient. The solar driven uncertainty increases significantly in months associated with more sunlight. It should also be noted that the reliability of the measured heat loss coefficient drastically increases in the absence of solar radiation.

There are two major implications here. The first involves determining at what point in the year houses can accurately undergo co-heating tests. This example dwelling is not particularly highly glazed, in respect to many modern house designs, yet the effect of solar radiation on the result was still high. Testing in December or January would therefore seem prudent in highly glazed dwellings. The second issue is the importance of accurately determining the solar aperture. Calculating this building parameter from glazing characteristics relies on significant assumptions whilst experimentally measuring it as part of the co-heating test puts even more onus on experiencing suitable weather conditions for successful regression. A further method of deriving the solar aperture, experimentally or otherwise, may be required to improve the reliability of the co-heating method.

The second branch of conclusions from this investigation concerns the long-wave sky radiation weather variable. This is an external variable that remains un-measured in current test protocol but has been shown to have a significant effect on the derived result, both in terms of a bias throughout the year and in generating scatter. It is proposed that a sensor is locally deployed to measure long-wave radiation to account for this loss mechanism.

A further point is that the presence of sky radiation can increase the expected or true building heat coefficient. Audit descriptions will often neglect this loss mechanism but the co-heating measurement of the heat loss coefficient will not. Therefore when establishing whether or not a building meets its design intent, it is important to factor this loss mechanism in, otherwise the comparison will lead to a upward bias in the measured value.

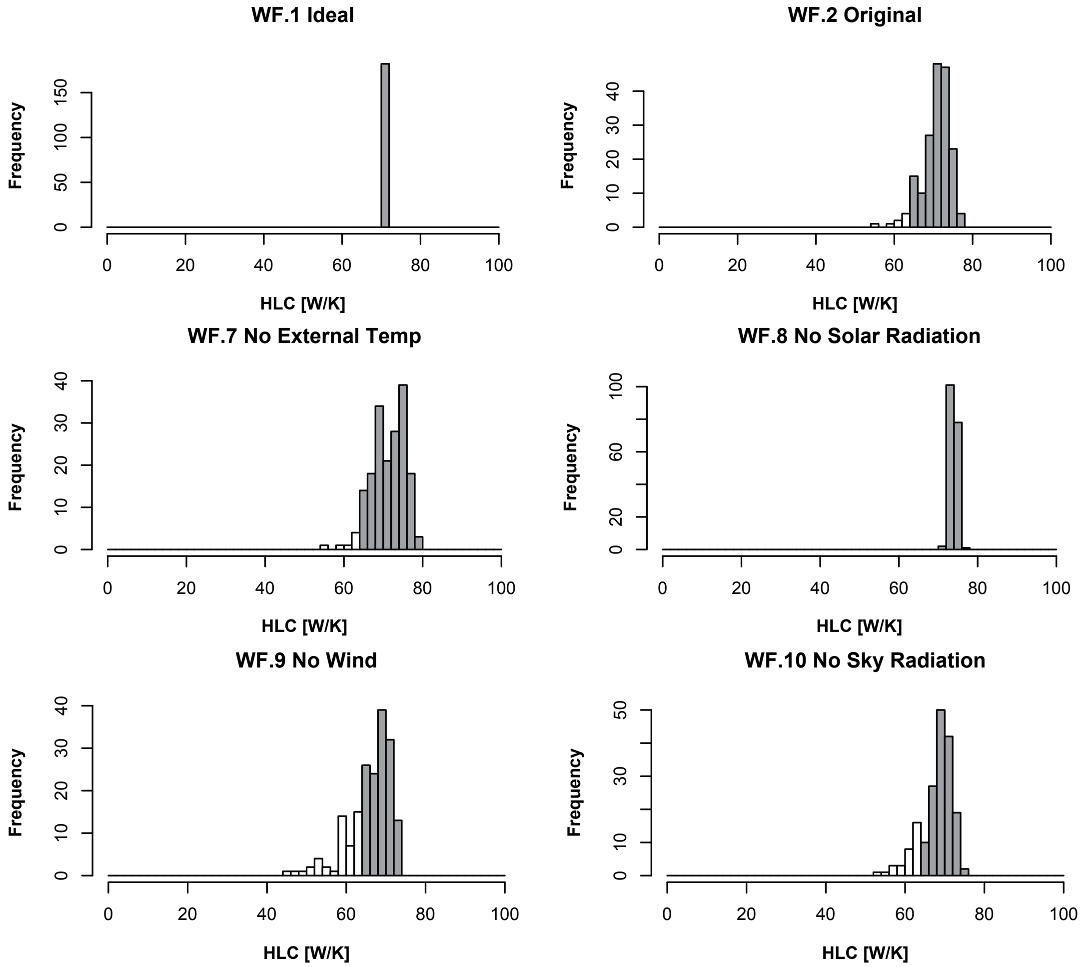

Figure 3. Histograms of derived heat loss coefficient throughout the heating season. Grey shaded bars indicate results that fall within 10 % of the true heat loss coefficient.

Of course this study is not without its limitations. The uncertainty in the co-heating test is driven by both the weather and its interaction with the test building's characteristics. The scope and complexity of these interactions is expansive and complex to decipher. What is offered here is only an example of the method used in a representative dwelling under typical weather conditions. A large body of research could be pursued using this general approach. It might even become the case that tailored simulations could be used to support the field-test results themselves, e.g. by providing improved estimates of error under certain conditions.

Further work is needed to truly understand the nature of the co-heating measurement and the drivers behind uncertainties in the result. A fuller picture of these will allow the true limitations in the method to be understood. This is key to improving the method itself, its application to the construction industry and reliability as a research tool. This is essential in reaching the target of zero carbon homes, to effectively retrofit the existing stock and to ensure the built environment plays its role in meeting 2050 emission targets.

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