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Estimation of building heat transfer coefficients from in-use data

Impacts of unmonitored energy flows

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Abstract

Purpose – The purpose of this paper is to identify the impact of traditionally unmonitored energy sources and sinks on assessment of the as-built thermal performance of occupied homes. The analysis aims to demonstrate the potential scale of uncertainties introduced in a heat balance estimation of the heat transfer coefficient (HTC) when using in-use monitored data.

Design/methodology/approach – Energy flows for two UK homes – one a 1930s dwelling with high heat loss, the second a higher-performing 2014-built home – are predicted using the UK Government's standard assessment procedure (SAP) and visualised using Sankey diagrams. Selected modelled energy flows are used as inputs in a quasi-steady state heat balance to calculate in-use HTCs as if from measured data sets gathered in occupied homes. The estimated in-use HTCs are compared against SAP-calculated values to illustrate the impact of including or omitting various heat sources and sinks.

Findings – The results demonstrate that for dwellings with low heat loss, the increased proportion of heating demand met by unmetered internal and solar gains informs a greater sensitivity of a heat balance estimation of the HTC to their omission. While simple quasi-steady state heat balance methods may be appropriate for dwellings with very high heat loss, alternative approaches are likely to be required for those with lower heat loss.

Originality/value – A need to understand the impacts of unmetered heat flows on the accuracy with which a building's thermal performance may be inferred from in-use monitored data is identified: this paper illustrates the scale of these impacts for two homes at opposite ends of the energy performance scale.

Keywords Building thermal performance, Heat transfer coefficient, In-use measurement, Occupied homes, Unmonitored energy flows

Paper type Research paper

1. Introduction

Discrepancies between as-designed and as-built thermal performance of dwellings are widely reported (Kelly *et al.*, 2012; Stafford *et al.*, 2012; Johnston *et al.*, 2016), and *in situ* measurement is recognised as essential for identifying and addressing the "performance gap" (Gori *et al.*, 2018). Space heating accounts for 63 per cent of UK domestic energy demand (BEIS, 2018), and is a key target for reducing greenhouse gas emissions in the 2011 UK Carbon Plan (HM Government, 2011); however, no compulsory whole-dwelling thermal performance tests have been adopted in the UK to date. The coheating test method described by Johnston *et al.* (2013) allows estimation of the *in situ* heat transfer coefficient (HTC) – which describes the net rate of heat losses (W) from a building per unit indoor-outdoor temperature difference (K) – with an uncertainty of ±10 per cent (Jack *et al.*, 2017); however, the test is both intrusive and energy-intensive, requiring heating of a

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vacated dwelling to an elevated indoor temperature for one to three weeks (Jack *et al.*, 2017). Development of alternative methods for inferring the HTC using data gathered from occupied, in-use dwellings is ongoing, with many efforts being focused through IEA EBC Annex 71 (Roels, 2017).

The ongoing UK smart-metering roll-out is expected to automate the collection of dwelling-level gas and electricity demand data (DECC, 2015), while the UK Smart Systems and Flexibility Plan (BEIS and Ofgem, 2017) aims to remove barriers to "smart technologies" which may allow monitoring of further and more varied in-home energy performance data. The availability of such a wealth of monitored data presents an opportunity for a step-change in the way building thermal performance is evaluated, allowing homes to be rated on their actual – rather than expected – performance. However, in any monitoring setup there will inevitably be heat sources and sinks that go unmeasured, leading to inaccuracies in the estimated rate of building heat loss. Understanding the impacts of unmetered heat flows will be key to establishing the accuracy with which a building's HTC may be inferred from in-use monitored data.

This paper presents modelled energy flows for two UK dwellings: one a 1930s semi-detached property situated in Loughborough, with comparatively poor thermal performance; the second a high-performing house situated in Gainsborough, built in 2014 and certified to Level 5 of the Code for Sustainable Homes. Energy flows are predicted using the UK Government's standard assessment procedure (SAP): a normative model in which standard occupancy, activity and dwelling heating patterns are applied; subsequent calculation of whole-dwelling energy demand is consistent with BS EN ISO 13790 (BRE, 2014).

The modelled energy flows are used to calculate estimated in-use HTCs, as if from measurement in occupied dwellings. Applying a quasi-steady state heat balance, the whole-building heat loss is equated to the incoming heating energy demand required to maintain the model-predicted indoor air temperature. The "measured" heating demand is in turn estimated by summing selected incoming energy flows, ranging from using only metered gas and electrical energy demand, through to including traditionally unmonitored flows including domestic hot water (DHW) losses and solar and metabolic gains. The estimated in-use HTCs are compared against SAP-calculated HTCs, providing insight into the impact of the inclusion or omission of the selected energy flows for both dwellings. Implications for the use of in-home energy-performance data to infer the as-built thermal performance of in-use dwellings are discussed.

2. Definition and measurement of the heat transfer coefficient

2.1 Theoretical definition of the HTC

The concept of an HTC is defined in BS EN ISO 52016:2017 as the "heat flow rate divided by the temperature difference between two environments; specifically used for heat transfer coefficient by transmission or ventilation" (British Standards Institution, 2017a, b). In the context of building thermal performance, a building's total HTC – hereafter denoted as H – is the heat flow rate from the internal air mass to the surrounding external environment divided by the indoor-outdoor air temperature difference. BS EN ISO 13789:2017 (British Standards Institution, 2017a, b) defines H as the sum:

$$H = H_T + H_V \left(\mathrm{W\,K^{-1}}\right), \tag{1}$$

where H_T, the transmission HTC, is the "heat flow rate due to thermal transmission through the fabric of a building, divided by the difference between the environment temperatures on either side of the construction", in W K^{-1}; H_V, the ventilation HTC, is the "heat flow rate due to air entering an enclosed space either by infiltration or ventilation, divided by the difference between the internal air temperature and the supply air temperature", in W K^{-1}.

By convention, the direction of heat transfer by transmission and ventilation is from inside to outside (British Standards Institution, 2017a, b): positive values for H_T, H_V indicate that heat is lost when the indoor temperature exceeds the outdoor temperature.

The formulation of H applied in this paper follows that prescribed by the UK Government's SAP (BRE, 2014):

$$H = \underbrace{H_{\mathrm{UA}} + H_{\mathrm{TB}}}_{H_T} + H_V \left(\mathrm{W\,K^{-1}}\right), \tag{2}$$

where H_{UA} corresponds to transmission through plane building envelope elements, and H_{TB} to transmission via thermal bridges. H_{UA}, H_{TB} and H_V are calculated as per the following equations:

$$H_{\mathrm{UA}} = \sum U_i A_i, \tag{3}$$

$$H_{\mathrm{TB}} = y \sum A_{\mathrm{exp},i}, \tag{4}$$

$$H_V = 0.33\left\{n_{\mathrm{in}} + \left(1 - \eta_{\mathrm{hr}}\right) n_{\mathrm{ve}}\right\} V, \tag{5}$$

where U_i is the U-value of the ith planar building envelope element, in W m^{-2} K^{-1}; A_i is the area of the ith planar building envelope element, in m^2; y is a thermal bridging factor, in W m^{-2} K^{-1}; $A_{\mathrm{exp},i}$ is the total area of the ith exposed plane building envelope element, in m^2; n_{in} is the whole-dwelling air change rate due to infiltration, in air changes per hour (ACH); n_{ve} is the whole-dwelling air change rate due to ventilation, in ACH; η_{hr} is the efficiency of the ventilation system's heat recovery device after allowance for an in-use factor ($0 \leqslant \eta_{hr} \leqslant 1$; $\eta_{hr} = 0$ when no heat recovery device is present); V is the dwelling volume, in m^3; 0.33 is the assumed heat capacity of air per unit volume, in Wh m^{-3} K^{-1}.

2.2 Measuring the HTC: a heat balance approach

The following equation represents a single zone dynamic heat balance for an occupied dwelling, obtained by introducing an occupant-related internal heat gains term $\mathbf{\Phi}_{\mathrm{int}}$ to the single zone dynamic heat balance established by Bauwens (2015) for an unoccupied dwelling:

$$C_i \frac{dT_i}{dt} = \Phi_h + \Phi_{\mathrm{int}} + \Phi_{\mathrm{sol}} + \Phi_l + \Phi_{\mathrm{tr}} + \Phi_v + \Phi_m, \tag{6}$$

where C_i is the heat capacity of the indoor air mass, in J K^{-1}; T_i is indoor air temperature, in K (assumed uniform); (d/dt) is the derivative with respect to time t, with t measured in seconds; and each of the terms on the right-hand side of Equation (6) represents rates of heat flow into the indoor air mass, in W: $\mathbf{\Phi}_h$ is the heating power supplied by the heating system(s); $\mathbf{\Phi}_{\mathrm{int}}$ the heating power supplied by internal gains arising from the presence of occupants (metabolic gains), use of electrical appliances/systems, lighting and DHW; $\mathbf{\Phi}_{\mathrm{sol}}$ the heating power supplied by solar gains; $\mathbf{\Phi}_l$ the latent heat flow rate into the indoor air mass, associated with hygroscopic loading and unloading of building fabric elements; $\mathbf{\Phi}_{tr}$ the rate of heat gain through fabric transmission; $\mathbf{\Phi}_v$ the rate of heat gain through ventilation and infiltration; $\mathbf{\Phi}_m$ the rate of heat gain due to thermal discharge from capacitive building fabric and indoor furniture.

Noting that H_T, H_V, respectively, describe the rates of heat loss through fabric transmission and ventilation divided by the indoor-outdoor temperature difference, we have:

$$H = H_T + H_V = -\frac{(\Phi_{tr} + \Phi_v)}{\Delta T}, \tag{7}$$

where $\Delta T = T_i - T_o$ is the difference between indoor temperature T_i and outdoor temperature T_o in K. Combining Equations (6) and (7), we can obtain:

$$H = \frac{\left(\Phi_h + \Phi_{\text{int}} + \Phi_{sol} + \Phi_l + \Phi_m - C_i\left(dT_i/dt\right)\right)}{\Delta T}. \tag{8}$$

Thus, measurement of H may be achieved by measurement of the variables on the right-hand side of Equation (8).

Under quasi-steady state assumptions, there is no net change in the thermal energy stored in the building fabric and indoor air mass over a diurnal cycle: thermal loading during times of heating is assumed to be balanced out by thermal unloading during cooling, and therefore it may be assumed that $\Phi_m = (dT_i/dt) = 0$ on diurnal timescales. Similarly, gains and losses associated with latent heat and are assumed to approximately balance out over the course of each diurnal cycle, and therefore $\Phi_l = 0$. Under these quasi-steady state assumptions, Equation (8) yields:

$$H = \frac{\Phi_h + \Phi_{\text{int}} + \Phi_{\text{sol}}}{\Delta T}, \tag{9}$$

and H can therefore be estimated as:

$$H = \frac{\overline{\Phi_h} + \overline{\Phi_{\text{int}}} + \overline{\Phi_{sol}}}{\overline{\Delta T}}, \tag{10}$$

where $\overline{\Phi_h}$, $\overline{\Phi_{int}}$, $\overline{\Phi_{sol}}$, $\overline{\Delta T}$ are mean values calculated over a period made up of complete diurnal cycles. Assuming the validity of the governing physical equations and quasi-steady state assumptions, the accuracy of HTC calculations using Equation (10) is contingent on accurate estimation of the heating power Φ_h, internal gains Φ_{int}, solar gains Φ_{sol} and the indoor-outdoor temperature difference ΔT.

3. Case study dwellings

Two UK case study dwellings are considered:

(1) a 1930s semi-detached property in Loughborough (LBRO), which has received no energy-driven refurbishments to the building envelope; and

(2) a 2014-built semi-detached property in Gainsborough (GBRO), certified to the Code for Sustainable Homes Level 5.

The areas and assumed U-values of the building envelope elements for the two dwellings are presented in Table I, while additional dwelling properties are presented in Table II. SAP formulation of the ventilative HTC H_V includes a wind factor to account for location-specific variation in average monthly wind speeds; however, a standard outdoor wind speed of 4 ms^{-1} has been applied for this paper.

4. Calculation of energy flows

The SAP model of building energy use is based on the BRE Domestic Energy Model (BREDEM), which applies a methodology consistent with BS EN ISO 13790 for calculating monthly whole-dwelling energy use (BRE, 2014). The SAP calculation of energy flows centres around the use of a monthly heat balance to calculate the load E_h on the dwelling's heating system. For each month:

(1) Total heat loss E_{tot} is calculated as:

$$E_{\text{tot}} = H \times \Delta T \times d \times \frac{24}{1{,}000}\,(\text{kWh}), \tag{11}$$

Element	Dwelling LBRO Total area[a] (m^2)	U-value[b] ($W\ m^{-2}$)	GBRO Total area[c] (m^2)	U-value[d] ($W\ m^{-2}$)
External walls	81.6	1.5	72.8	0.14
Ground floor (suspended timber)	40.2	0.8	–	–
Ground floor (cast concrete)	5.4	0.7	–	–
Ground floor (suspended concrete)	–	–	32.1	0.12
Roof[e]	45.6	2.3	32.1	0.12
Windows	20.7	4.8	16.1	1.15
External doors	3.4	3.0	2.1	1.20
Party walls	42.2	0.5	41.2	0.00[b]

Notes: [a]Construction materials and areas from Beizaee *et al.* (2015); [b]U-values from RdSAP documentation (BRE, 2017); [c]areas derived from scale architectural drawings (Allan Joyce Architects, 2011); [d]U-values from Sodagar and Starkey (2016) unless marked otherwise; [e]roof areas correspond to horizontal areas (rather than pitched)

Table I.
Areas and U-values for building envelope elements of the case study dwellings

Parameter	Units	Dwelling LBRO	GBRO
HTC, H[e]	$W\ K^{-1}$	507.3	67.7
H_{UA}	$W\ K^{-1}$	393.9	38.9
H_{TB}	$W\ K^{-1}$	29.5	12.4
H_V	$W\ K^{-1}$	83.9	16.4
Dwelling dimensions[a]			
Volume	m^3	240	181
Width	m	8.02	4.40
Depth	m	5.69	7.30
Height	m	5.26	5.65
Total floor area	m^2	91.2	64.2
Main heating system[b]		Gas central heating	Gas central heating
Boiler model		Worcester Greenstar 30 CDi	Potterton Promax
Boiler efficiency[c]		89.4%	89%
Ventilation[b]		Naturally ventilated	MVHR (Vent-Axia Lo-Carbon Astra)
MVHR efficiency[c]		–	90%
MVHR in-use factor[d]		–	0.85
Open flues[d]		2	0
Intermittent fans[d]		1	0
Number of sheltered sides[d]		2	2

Notes: [a]Dwelling dimensions derived from Beizaee *et al.* (2015) (LBRO) and Allan Joyce Architects (2011) (GBRO); [b]heating system and ventilation parameters from Beizaee *et al.* (2015) (LBRO) and Sodagar and Starkey (2016) (GBRO) unless marked otherwise; [c]efficiencies obtained from the BRE product characteristics database (BRE, 2018); [d]ventilation parameters assumed as per UK SAP methodology (BRE, 2014); [e]calculated as per UK SAP methodology (BRE, 2014)

Table II.
Additional building parameters for the case study dwellings

where H is the SAP-calculated HTC, $\Delta T = T_i - T_o$ the average monthly indoor-outdoor temperature difference (T_i predicted using standard heating patterns; T_o obtained from UK average climatic data), d length of the month in days and (24/1,000) a conversion factor:

(2) Standard occupancy and activity profiles are used to calculate:

(a) total electricity demand for electrically powered devices (appliances, lighting, cooking, pumps and fans);

(b) DHW heating energy demand; and

(c) metabolic gains.

(3) Internal gains E_{int} are calculated as the sum of (a), (b) and (c) above, less internal losses to evaporation and losses due to external lighting, pumps and fans, DHW drainage, storage and distribution.

(4) Solar gains E_{sol} are determined using UK average climatic data and dwelling-specific glazing properties.

(5) The heating demand E_h that must be met by the dwelling's heating system in order to maintain the heat balance is given by:

$$E_h = E_{\text{tot}} - \eta(E_{\text{int}} + E_{\text{sol}}), \tag{12}$$

where $0 \leqslant \eta \leqslant 1$ is a utilisation factor corresponding to the proportion of internal and solar gains classified as "useful" gains that heat the dwelling.

In addition to calculating overall electricity demand and losses in Step 2 above, the SAP model also calculates total space and water heating fuel demand based on: heating demand E_h; DHW demand; and the efficiency of the space and water heating system(s). It is therefore possible to trace the paths of incoming energy sources (electricity, gas, metabolic and solar) that ultimately either contribute useful gains to the dwelling heat balance or otherwise do not heat the dwelling.

The calculation methodology described above was applied the case study dwellings to calculate whole-dwelling energy flows for each of the six months October through March. Each dwelling's monthly results were then summed to provide six-month totals: the resulting energy flows are visualised in Figures 1 and 2.

Normalising for total floor area, overall energy demand for the LBRO dwelling (277 kWh m^{-2}) is almost three times that for the GBRO dwelling (93 kWh m^{-2}), reflecting the comparative energy performance of the two buildings. For both dwellings, incoming energy is dominated by metered energy sources (gas and electricity), which constitute 89 per cent of total energy demand for LBRO, and 72 per cent for GBRO. Metered energy demand for LBRO is dominated by gas (90 per cent gas, 10 per cent electricity), while the comparatively low GBRO gas central heating demand results in a more even split (59 per cent gas, 41 per cent electricity).

Energy used to maintain the dwelling heat balance is represented by the "heat balance" nodes in Figures 1 and 2. Any energy not entering the heat balance is classified as "non-useful" in the context of heating the dwelling: while 86 per cent of all incoming energy enters the LBRO dwelling heat balance, only 67 per cent of incoming energy enters the GBRO heat balance.

5. HTC measurement: impact of unmonitored energy flows

The impact of omitting or including traditionally unmonitored energy flows on *in situ* HTC measurements from in-use dwellings is now explored using a quasi-steady state heat balance approach. Here, it is assumed that the behaviour of the case study dwellings and their occupants are exactly as predicted by SAP modelling, and the predicted energy flows are treated as idealised monitored data streams which may or may not be included in a heat balance calculation. The results of the subsequent analysis therefore reflect the thermal behaviour of the as-modelled dwellings, rather than their real-world counterparts, and as such are only illustrative of what may be expected from real-world *in situ* HTC measurement.

In the context of *in situ* measurement of dwelling HTCs, absolute accuracy would require direct measurement of the energy flows entering (or leaving) the heat balance nodes in

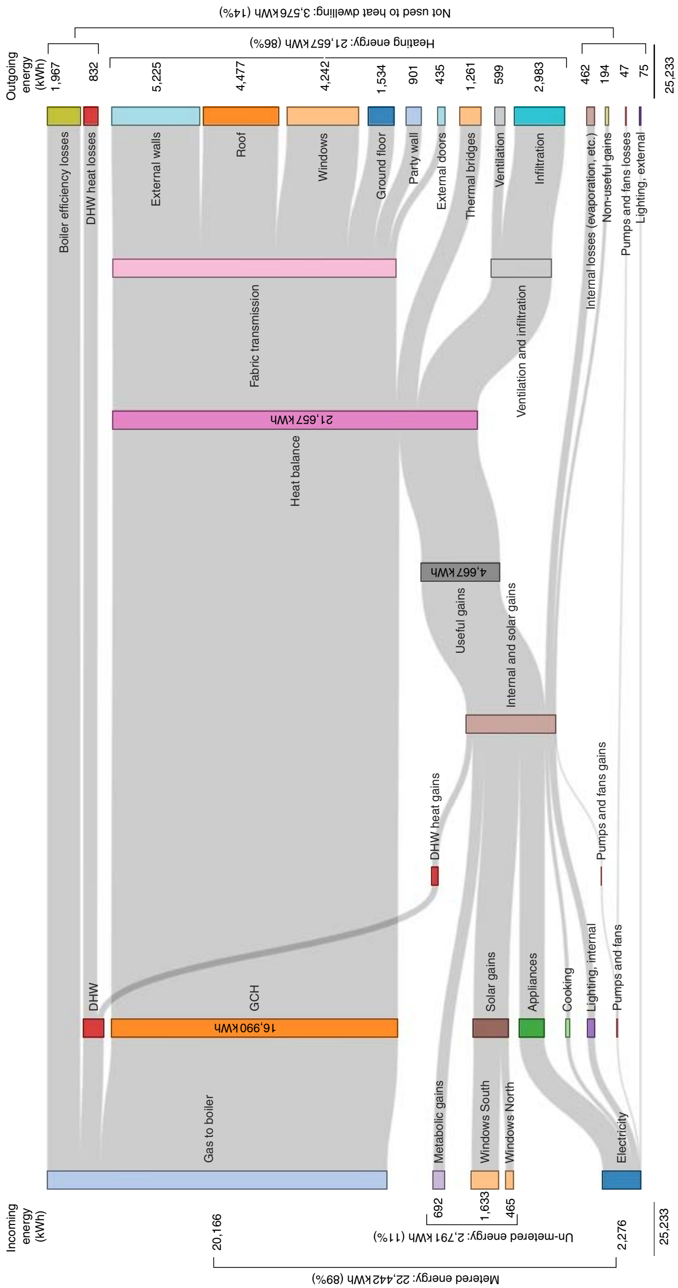

Figure 1.
Modelled energy flows for October to March heating season, LBRO

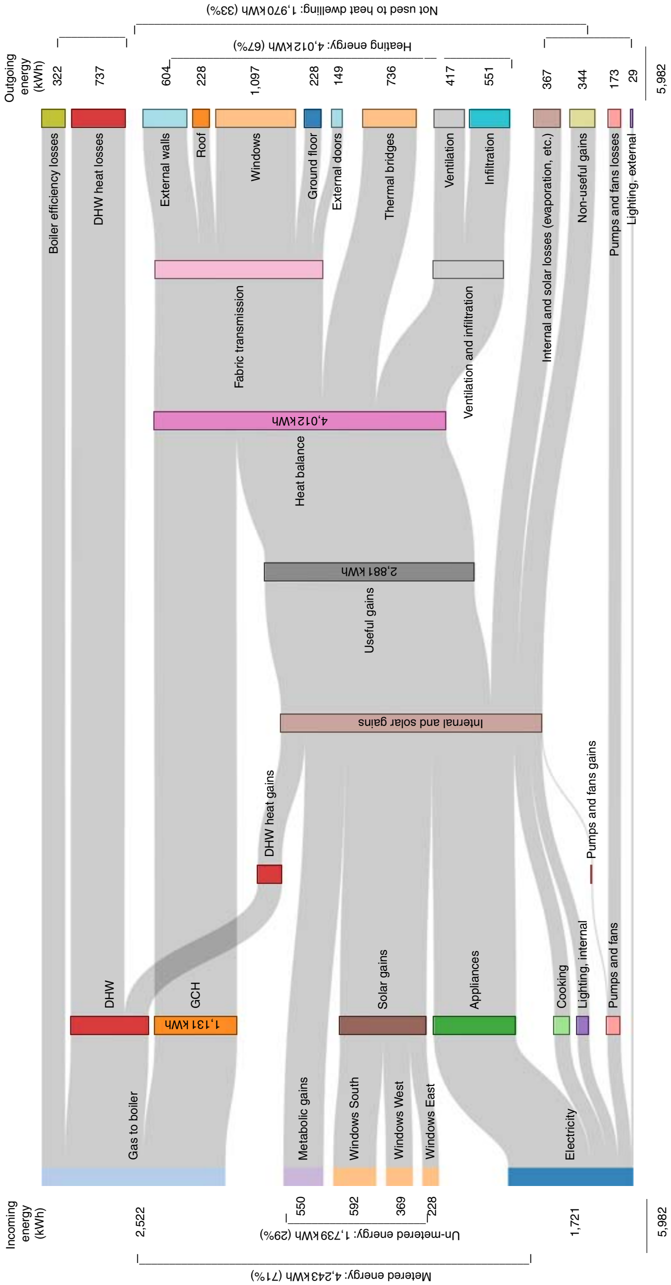

Figure 2.
SAP-predicted energy flows for October to March heating season, GBRO

Figures 1 and 2 – that is, the actual heating energy demand – along with the indoor-outdoor temperature difference. In the absence of such "perfect" monitoring, measurement of the energy flows further upstream (sources) or downstream (sinks) must be used to estimate heating energy demand, resulting in an estimated HTC. Figures 3 and 4 show estimated in-use HTCs for the case study dwellings, calculated using six approaches to estimating the dwelling heating demand from measured or assumed energy flows, compared against the SAP-calculated HTCs H_{LB} (LBRO) and H_{GB} (GBRO).

The energy flows used in the calculation of estimated in-use HTCs are as shown in Figures 1 and 2, with the exceptions of boiler efficiency and DHW energy losses: assumed boiler efficiencies are as listed in Table II, while DHW energy losses are accounted for by assuming that the energy content of all hot water drawn is lost to drainage (and therefore does not heat the dwelling). No consideration is given to measurement uncertainties: it is

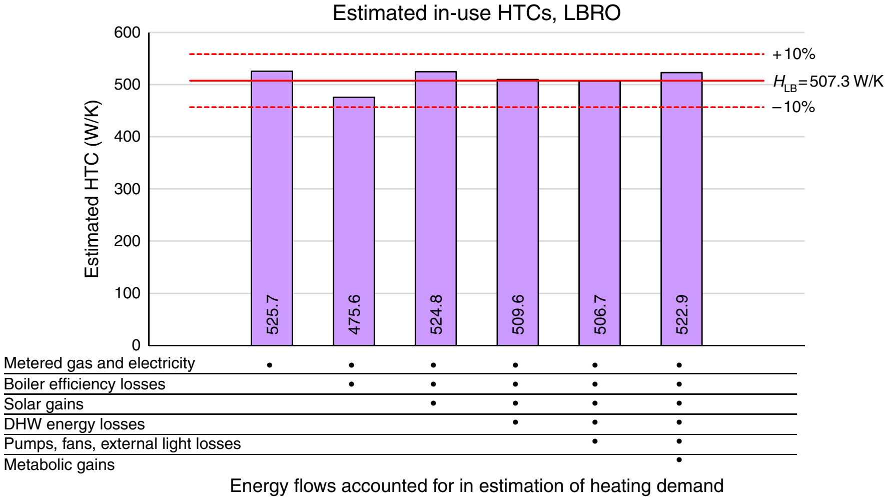

Figure 3.
Estimated in-use HTCs for the as-modelled LBRO dwelling, derived from various formulations of heating energy demand

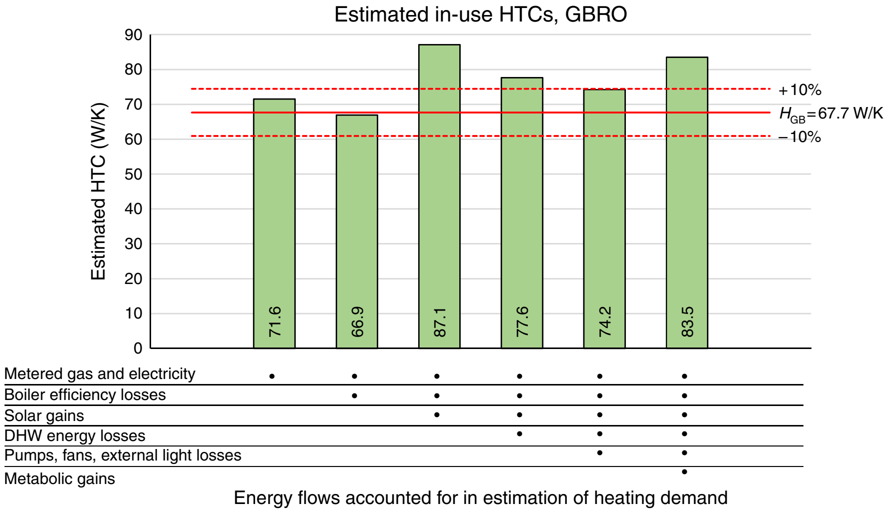

Figure 4.
Estimated in-use HTCs for the as-modelled GBRO dwelling, derived from various formulations of heating energy demand

assumed that each energy flow can be measured with absolute certainty, and therefore the estimated HTCs are point estimates.

In each scenario, it is assumed that indoor-outdoor temperature difference ΔT is monitored with absolute accuracy, while heating energy demand is estimated using increasingly detailed hypothetical monitored data sets:

- S1. Metered energy demand only: in this simplest scenario, in which the heating demand is estimated by the sum of household-level metered electricity and gas demand, both H_{LB} and H_{GB} are overestimated, indicating an overestimation of dwelling heating demand. Nonetheless, the estimated HTC falls within 10 per cent of the SAP-calculated HTC for both dwellings.
- S2. As for S1, less assumed boiler efficiency losses: assuming the boiler efficiencies listed in Table II reduces the estimated heating demand to the extent that both HTCs are now underestimated, although estimates remain within 10 per cent of SAP-calculated values. At approximately 1 per cent below the SAP-calculated HTC, the estimate of H_{GB} appears to be particularly accurate.
- S3. As for S2, plus solar gains: inclusion of accurate measurement of incoming solar gains results in overestimation of both H_{LB} and H_{GB}, but with a striking difference between dwellings: the error in the estimate of H_{GB} exceeds that for H_{LB} in both proportional and absolute terms. Greater overestimation of the GBRO heating demand (and therefore H_{GB}) may be explained by failure to account for internal losses and non-useful gains: comparing Figures 1 and 2, failure to remove these flows from the heat balance results in an 18 per cent overestimation of heating demand for the GBRO dwelling, compared with only 3 per cent for LBRO.
- S4: As for S3, less the energy content of DHW drawn: as expected, accounting for DHW losses reduces the estimated heating demand for both dwellings and improves the accuracy of the measured HTCs; however, the error in the estimate of H_{GB} remains above 10 per cent and continues to exceed that for H_{LB} in both proportional and absolute terms.
- S5. As for S4, less energy losses via pumps, fans and external lighting: accounting for losses via pumps, fans and external lighting further reduces the error in estimated HTCs for both dwellings. For LBRO, the estimated HTC is now within 0.6 W K^{-1} (0.1 per cent) of H_{LB}, while for GBRO the estimated HTC is 6.5 W K^{-1} (10 per cent) greater than H_{GB}.
- S6. As for S5, plus metabolic gains: the impact of including accurate measurement of metabolic gains is relatively small for LBRO, increasing the estimated HTC by only 3 per cent from S5; in contrast, a 13 per cent increase is observed in the estimate of H_{GB}. As with S3, the greater overestimation of H_{GB} appears to be a result of the comparatively larger impact of neglecting internal losses and non-useful gains in the GBRO heat balance calculation.

Comparing Figures 3 and 4, a similar pattern emerges insofar as the HTC is overestimated in the majority of scenarios. However, an increased spread of estimated HTCs suggests a greater sensitivity of GBRO HTCs to the inclusion of traditionally non-metered energy flows, a result that may be explained by the increased proportion of dwelling heating demand satisfied by non-metered gains.

6. Discussion and conclusions

This paper has demonstrated the potential impact of unmonitored energy flows on the estimation of whole-building HTCs for two in-use dwellings at opposite ends of the energy performance scale. In the 1930s-built LBRO dwelling (HTC 507.3 W K^{-1}), the comparatively high proportion of heating demand satisfied by metered gas and electricity means that the omission of unmetered heat sources (such as metabolic and solar gains, which contribute 11 per cent of heating) and sinks (such as hot water drainage and efficiency losses) have only minor impact on the HTC that may be estimated from in-use monitored data. In contrast, for the high-performing GBRO dwelling (HTC 67.7 W K^{-1}), the increased proportion (35 per cent) of heating demand met by unmetered metabolic and solar gains informs a greater sensitivity of the heat balance estimation of the HTC to their omission. Furthermore, the greater proportion of internal and solar gains not contributing to maintaining the heat balance in the GBRO dwelling ("internal losses" and "non-useful gains" in Figure 2) contribute to a 23 per cent overestimation of the HTC even when solar and metabolic sources, along with hot water and efficiency sinks, are accounted for. It is therefore suggested that quasi-steady state heat balance methods for in-use HTC estimation, while perhaps robust to unmetered energy flows for older dwellings such as the LBRO case study, may be poorly suited for use in newer, higher energy performant dwellings.

The energy flows calculated for this paper were produced with a normative model, assuming standard operation of the case study dwellings during an October to March heating season, and as such are only valid for these specifically modelled cases. The results presented in Figures 3 and 4 should not be taken to indicate recommended monitoring setups: it would be incredibly premature to conclude, for example, that monitoring only metered gas electricity and subtracting assumed efficiency losses would always provide an accurate measurement of H in a high-performing dwelling. It is nonetheless important to note that the accuracy of *in situ* HTC measurements can appear to be reduced by the measurement of more parameters: this apparent peculiarity arises because errors may cancel each other out in some cases; however, it is not possible to know in which cases such cancellation will occur, and therefore care must be taken when deciding on the parameters to be included in or omitted from heat loss calculations.

As noted in Section 5, the presented measured HTCs are point estimates with no consideration of uncertainties in the estimation of individual energy flows. Furthermore, only one quasi-steady state approach to inferring the HTC has been explored, and for only two dwellings. Further work is required to establish the accuracy with which individual energy flows may be estimated from monitored data (and indeed which data streams it may be necessary to monitor), and to establish whether and which alternative data analysis approaches may be best-suited to HTC inference in different types of dwelling and under varying occupancy and use patterns. Nonetheless, the demonstrated modelling of whole-dwelling energy flows using the UK SAP methodology may be considered a useful preliminary tool for estimating the impact of individual heat sources and sinks, thus informing the identification of appropriate techniques for estimating the HTC from in-use data. Developing analysis techniques immune to unmeasured heat flows may be particularly key to *in situ* HTC measurement for dwellings with high levels of insulation; however, the results of the present analysis do suggest that simple quasi-steady state heat balance methods may be appropriate for dwellings with very high heat loss.

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