

EXPLORING THE PERFORMANCE GAP IN UK HOMES: NEW EVIDENCE FROM SMART HOME AND SMART METER DATA

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ABSTRACT

The performance gap between measured and predicted energy consumption in buildings is long established. This paper explores the reasons for the performance gap using data collected in ten UK homes. Predictions made by steady state energy models were compared to measured building performance data. Model inputs relating to external conditions and occupant practices were changed to align with measured data. The results show that the performance gap in individual homes is still significant after accounting for occupant practices and suggests that more work is required to develop techniques to estimate the thermal properties of the building fabric using measured data.

INTRODUCTION

Steady state energy models are commonly used to assess building energy performance and compliance with building regulations (DECC, 2011; HM Government, 2010). Discrepancies between actual and predicted energy savings, the 'performance gap', are common (Bordass, 2001; Hong, 2006). Improving the accuracy of energy models is particularly important when considering the potential cost savings relating to energy efficient retrofits, which could be inaccurate if models have systematic errors (Sunikka-Blank, 2012).

There are three reasons that could explain the performance gap; 1) the model inputs relating to the thermal properties of the building are incorrect; 2) the model inputs relating to occupant practices are incorrect; 3) the fundamental principles of the models are incorrect. If the initial assumptions about the thermal properties of the dwelling are incorrect the energy predictions will also be wrong, for example if the heat loss via transmittance and ventilation are overestimated then the model will overestimate the energy use required for space heating. Model inputs relating to the heat loss of the building fabric are usually assumed based on the built form and construction age of the dwelling. Steady state energy models tend to use standard heating practices and this is consequently a likely source of model error as a significant variation in energy use is often observed in similar homes as a result of occupant behaviour (Guerra-Santin and Itard, 2010; Yohanis et al., 2008;

Kane et al., 2015). This paper describes the initial steps in assessing the performance gap. First, steady state models of ten UK homes were built and energy predictions were compared with measured values. Second, monitored data was used to align the models with external conditions to allow comparison with measured energy consumption. Third, model inputs relating to occupant practices were replaced with measured figures and again the performance gap was assessed.

DATA COLLECTION

The data used in this paper is based on 20 homes studied by the REFIT project, a collaboration between Loughborough University, the University of East Anglia and University of Strathclyde. REFIT aims to understand how new data streams coming from smart meters and smart homes can be used to inform retrofit decision making. The homes were recruited to take part in a study of smart home technologies and agreed to a number of data collection activities. The activities included; a building survey to collect the information required for model inputs; detailed monitoring of gas and electricity consumption; monitoring of internal temperatures in every room; and a number of qualitative interviews which are not the focus of this paper. External temperature and solar irradiation were monitored at the Loughborough University weather station, which was within 20km of all of the homes. Gas consumption was collected by monitoring the pulse output of the gas meter in half an hour blocks (Figure 1).



Figure 1. Gas monitoring equipment installed by SMS solutions

Table 1. Technical and social household descriptors of the ten study homes

	HOUSE TYPE	CONSTRUCTION TYPE	CONSTRUCTION AGE	FLOOR AREA (m ²)	NO. OF OCCUPANTS
House A	Detached	Cavity wall	1976-1982	120	2
House B	Detached	Solid wall (cavity wall in extension)	1900-1929	109	4
House C	Detached	Cavity wall	1991-1995	87	3
House D	Detached	Cavity wall	2003-2006	198	4
House E	Semi-detached	Cavity wall	1967-1975	78	2
House F	Detached	Cavity wall	1983-1990	169	6
House G	Detached	Cavity wall	1967-1975	139	2
House H	Detached	Cavity wall	2003-2006	183	2
House I	Detached	Cavity wall	1967-1975	102	4
House J	Detached	Solid wall (cavity wall in extension)	1900-1929	140	2

Whole house electricity consumption was measured using wireless current transformers, which communicated back to a central hub, the data were stored on a database built and maintained at the University of Strathclyde. Indoor temperatures were monitored using Hobo sensors installed in each room and logged temperatures every half an hour. For more detail about the recruitment and monitoring used in the homes, see Kane, et al (2015).

The basic characteristics of the ten homes are summarised in Table 1. The sample was dominated by detached dwellings. This was partly related to the constraints of the monitoring equipment, which prevented the selection of terraced homes where the gas meter was in the basement. All ten homes were heated via gas fired central heating systems. Eight of the ten homes were built using cavity wall construction. The two built prior to 1930 with solid walls have cavity wall extensions. The floor area of the houses ranged from 78m² to 198 m². There were a variety of occupancy types including retired couples and families.

METHODS

Steady state energy modelling

Steady state building energy models were built in MS Excel using the Standard Assessment Procedure (SAP) algorithms (DECC, 2011). The model inputs were based on data collected during the building survey and when assumptions were required, the suggestions outlined in the SAP documentation were used. SAP is the UK Government's building energy assessment tool and is used to prove compliance to the building regulations (HM Government, 2010). It is based on the Building Research Establishment Domestic Energy Model (BREDEM) and uses an energy balance approach (Anderson, 2002). Central to the SAP model is the heat balance equation, which calculates the space heating energy requirement (Equation 1).

$$\dot{\Phi} = H\{T_{int} - G_u / H - T_{ext}\} \quad (1)$$

Where:

$\dot{\Phi}$ is the mean output from the heating system (W)

T_{int} is the mean internal temperature (°C)

G_u is the mean useful gains (W)

H is the specific heat loss for the dwellings (W/°C)

T_{ext} is the mean external temperature (°C)

$$H = UA + 1/3n_t V \quad (2)$$

Where:

U is the average U-value of the building elements (W/m²°C)

A is the total area of the external building element (m²)

n_t is the total air change rate (ach)

V is the total volume of the heated space (m³)

The total energy use for space heating is the sum of the heat losses (Equation 2) minus the heat gains. Heat is lost from a building in two ways, thermal transmittance and ventilation. Thermal transmittance is the heat lost through the building fabric; each building element (including the ground floor) has a U-value, which is the rate of heat transfer. In SAP wall U-values are assumed based on the building type and construction age. The U-value of the ground floor is related to the floor type, for example, suspended or solid according to BS EN ISO 13370:2007 (British Standards, 2007). Ventilation is the heat lost by cold air entering the building through cracks in walls and openings such as open fires and is measured in the number of air changes per hour. SAP ventilation rates are estimated based on the number of open chimneys, flues, fans and vents. Additional structural infiltration is also added based on the construction type.

SAP uses standard climate conditions including external air temperature and horizontal solar irradiation. Solar gains are related to the solar irradiation, the size of windows, the solar

transmittance of the window material and the orientation of the dwelling (Equation 3).

$$G_{Solar} = 0.9 \times A_w \times S \times g_{\perp} \times FF \times Z \quad (3)$$

Where:

G_{Solar} is the average solar gain in watts

0.9 is a factor representing the ratio of typical average transmittance to that at normal incidence
 A_w is the area of an opening (a window or a glazed door), m^2

S is the solar flux on a surface, W/m^2

g_{\perp} is the total solar energy transmittance factor of the glazing at normal incidence

FF is the frame factor for windows and doors (the fraction of the opening that is glazed)

Z is the solar access factor

Internal gains from occupants (metabolic gains), lights, appliances and cooking are estimated based on the dwelling floor area. Additional gains relating to pumps and fans are also included. Domestic hot water requirement is calculated based on the dwelling floor area and total energy use accounts for losses in storage and distribution. Standard heating periods are used for weekdays (9 hours) and weekends (16 hours). The model assumes two zones, which are heated to $21^{\circ}C$ and $18^{\circ}C$ during the heating periods. The average monthly temperature is calculated based on the heating practice assumptions, heat gains and heat losses. For a complete description of the modelling techniques and assumptions used see (DECC, 2011).

Analysis steps

Initially a base case models using standard assumptions were built and then six additional predictions were made using inputs calculated using measured data. As a complete year of monitoring had not been completed, this work reports results for a single month, March 2014. Table 2 describes the seven predictions.

Prediction 1 was the base case SAP model. Prediction 2 built on the base case model and incorporated measured average external air temperature for March 2014. Prediction 3 built on the base case and included the monthly horizontal solar irradiation (W/m^2). The SAP method for converting solar irradiation to solar gain was not amended. Prediction 4 aligns the model with the measured external conditions by including both measured values for external temperature and solar irradiation. Prediction 5 built on prediction 4 but substituted the internal gains from electrical appliances, lighting, pumps and fans with the total measured electrical gain. To do this energy use figures measured in kWh were converted to the heat gains measured in Watts. It was assumed that all electrical energy used in the home would result in a heat gain. This will not always be the case, for example, some energy use

would be used for external lighting, which would not result in an internal gain.

Table 2. Description of the seven predictions made to compare with measured energy use figures

MODELLING CHANGES		
1	Base case	SAP prediction for the month of March using standard assumptions and model inputs
2	External temperature	Base case plus measured external temperature
3	Solar irradiation	Base case plus measured solar irradiation
4	External conditions	Base case plus measured external temperature and solar irradiation
5	Electrical gains	Base case with measured external conditions plus measured electrical gains
6	Internal temperature	Base case with measured external conditions plus measured internal temperature
7	Internal conditions	Base case with measured external conditions plus measured electrical gains plus internal temperature

Prediction 6 again built on prediction 4 but included the average internal air temperature measured in the home. This figure was calculated by weighting each of the temperature measurements by room volume, consequently, the temperature measured in a large living room had more influence on the final value than one measured in a small bathroom. The final prediction aligned the model with the occupant practices by using both the measured electrical gains and internal temperatures.

Regression analysis was used to assess whether the basic household characteristics were related to the magnitude of the performance gap. Thermal transmittance, infiltration and ground heat transfer were not measured in the study homes and consequently cannot be directly assessed.

Plausibility checks

To check that the SAP models were predicting reasonable figures a series of plausibility checks were undertaken. Figures for annual energy use and heat loss rate were compared to figures from previous research literature to confirm that they were within the expected range. The average heat loss rate was $395W/K$ this is very similar to the $386W/K$ calculated for all detached dwellings in the CDEM model (Firth et al., 2010).

CDEM reported average annual consumption for gas and electricity as $24,175kWh$ and $5,084 kWh$ again these figures are very close to the figures reported here. Minor variations are most likely a result of differences in floor area between the two samples. This suggests that the models used as the basis of this research are plausible and results are reasonably close to those reported by previous studies.

Table 3. SAP modelling outputs used for plausibility checks

	ENERGY USE (kWh)		HEAT LOSS RATE (W/K)
	SPACE AND HOT WATER HEATING	LIGHTS AND APPLIANCES	
House A	15926	3542	248
House B	38140	4683	658
House C	14629	3663	222
House D	36916	6340	523
House E	12777	2279	218
House F	25570	7383	420
House G	22130	4109	345
House H	29005	4874	385
House I	18405	4792	285
House J	34879	4140	649
Average	24838	4580	395

RESULTS

Comparison with base case

The first step used to assess the model inputs was to explore the variation in the input assumptions in the base case model. The average annual measured gas consumption for March 2014 from the ten homes was

Table 4. Difference between measured and SAP predictions in ten homes for March showing the relative impact of changes to model inputs

	Measured	SAP	Percentage difference (%)
	Mean (min, max)	Mean (min, max)	Mean (min, max)
Gas consumption (kWh)	1833 (702, 3202)	3182 (1603, 5001)	74 (128, 56)
Electricity consumption (kWh)	367 (244, 511)	401 (195, 658)	9 (-20, 29)
External temperature (°C)	7.9	6.8	-14
Solar irradiation (W/m ²)	703 (378, 1087)	635 (341, 983)	-10 (-10, -10)
Electrical gains (W)	273 (182, 380)	337 (168, 541)	23 (-8, 42)
Whole house temperature (°C)	18.7 (17.6, 21.1)	17.6 (16.3, 18.2)	6 (8, 16)

1833kWh (Table 4). Percentage difference is reported in the form (SAP – Measured)/ Measured x 100. The SAP prediction from the same period was 74% higher at 3,182kWh. The prediction of electricity use was closer to the measured data, and was higher on average by only 9%; however, in individual homes predictions were underestimated by 20% and overestimated by 29%. Space and hot water energy consumption was over predicted in all homes and was more than twice the measured value in four of the homes (Figure 3).

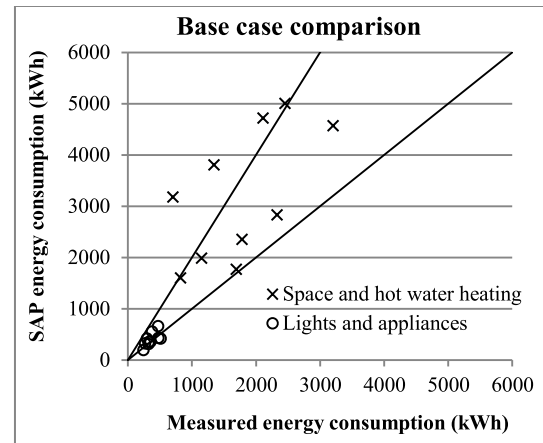


Figure 3. Measured against predicted energy consumption for the base case model

This may be partially related to the differing external conditions, however, the SAP monthly average external temperature for March (6.8°C) is only 14% lower than the measured monthly average external temperature measured in March 2014 (7.9°C) and is consequently unlikely to explain much of the performance gap.

The solar radiation used in the base case SAP models was 10% less than the measured figure. The average SAP electrical gains were higher than the measured

electricity gains; however, there was a range within the homes (Figure 4). The largest discrepancies between SAP and measured electrical gains were 8% lower and 42% higher. SAP whole house average temperatures were 6% lower than measured values. The lowest measured average indoor temperature was 17.6°C. Four of the dwellings had average temperatures that were more than 2°C higher than predicted by SAP. This was expected to have a significant impact on the performance gap as previous work has shown that steady state building energy models are sensitive to variation in internal temperatures (Firth, 2010).

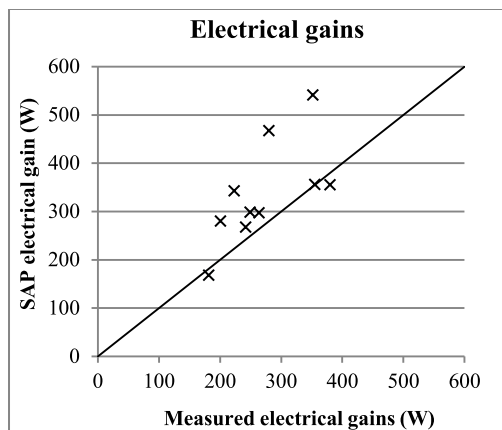


Figure 4. Measured electrical gains against SAP electrical gains

Although on average the electrical gains and internal temperature is over predicted by SAP, similar values for both of these inputs were found in some of the homes.

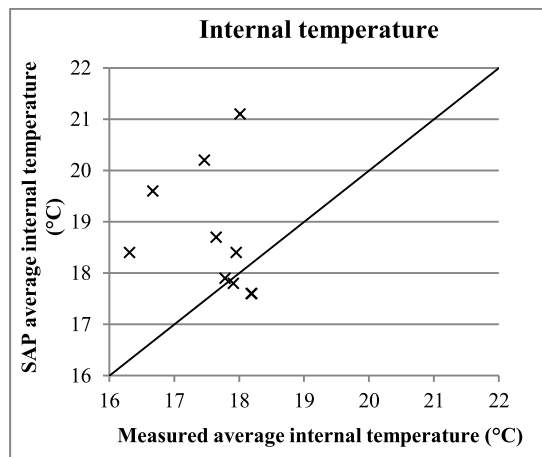


Figure 5. Measured average internal temperature for March 2014 against SAP average internal temperature

This, however, was not reflected in the month energy use for space heating figures, which were all over predicted. This suggests that there is an error in the thermal property inputs (U-values and number of air changes per hour).

Aligning external conditions

The second analysis step was to align the model with the measured external conditions. Three predictions were made by changing the model inputs to the measured external temperature, solar irradiation and then both. Results are shown in Figure 6 and Table 5.

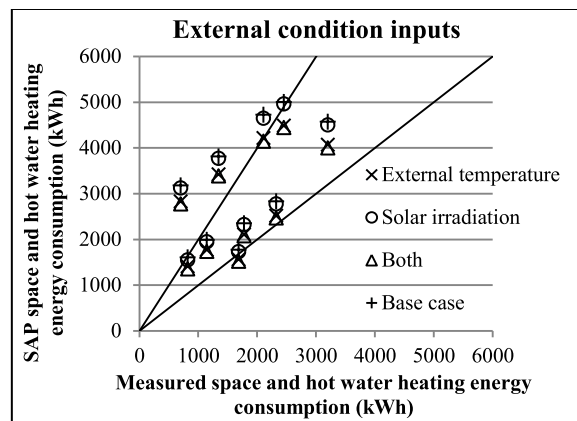


Figure 6. Space and hot water heating energy consumption measured against SAP values

Only results for gas consumption (space and hot water heating) are reported as model changes had no impact on predictions for electricity consumption and the discrepancy between measured modelled figures was small. It should be noted that the monitoring used in this study did not enable the disaggregation hot water heating. Consequently, when measured gas consumption is reported it is assumed that it relates to both space and hot water heating, while electricity consumption related to lighting and appliances. Further work will look into energy use for showers and cooking in more detail but is beyond the scope of this paper.

Table 5. Energy use for space and hot water heating measured in March 2014 and compare to four model iterations

	ENERGY USE FOR SPACE AND HOT WATER HEATING (kWh)				
	Measured	Base case	External	Solar	Both
House A	1149	1985	1773	1948	1736
House B	2454	5001	4484	4960	4443
House C	1689	1772	1565	1728	1522
House D	2110	4720	4215	4648	4143
House E	820	1603	1408	1550	1356
House F	702	3180	2830	3122	2773
House G	2326	2831	2519	2776	2465
House H	1345	3809	3422	3771	3385
House I	1781	2350	2104	2323	2078
House J	3202	4571	4067	4501	3998
Average	1758	1985	2839	3133	2790

Using the measured solar irradiation made little impact on the performance gap as the difference between predicted and measured solar irradiation was small and the model is not very sensitive to this input. When the measured external temperature was used in the model the discrepancy between measured and modelled energy use was reduced but on average was still large (55%). The best prediction was made for House C, where Prediction 2 was 7% lower than the measured figures. The worst prediction was

House F where the prediction was four times higher than the measured figures. It is likely that this is because the model does not account for the daily use of a large solid fuel burner. The energy consumption and heat output of the additional heating used in House F could not be assessed, as the heat output of the solid fuel burner was not monitored.

Aligning internal conditions

The third analysis step was to align the model with the measured internal conditions. Results are shown in Figure 7 and Table 6. Including the measured electrical gains had a very small impact on the performance gap. This was not surprising as electrical gains are related to electrical energy use, which was predicted reasonably well by the base case model. Occupant comfort preferences were incorporated into the model by adjusting the average monthly temperature, the average SAP whole house internal temperature was 17.6°C; 1.1°C lower than the average of the temperatures measured in the homes.

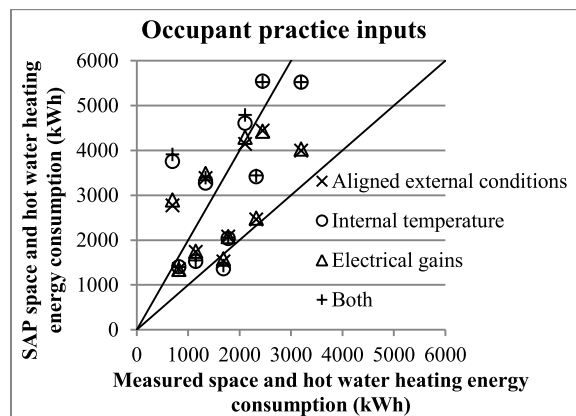


Figure 7. Space and hot water heating energy consumption for March 2014 measured against SAP prediction

The average SAP indoor temperature was 6% higher than measured figures; however, using the measured internal temperatures resulted in an increase of 25% in predicted energy use for space and hot water heating compared with the prediction using aligned external conditions. Again, this reflects the relative importance of certain model inputs (Firth et al., 2010). Including the internal temperature in the model resulted in an increased performance gap (the average SAP prediction is more than twice as large as the measured value for space and hot water heating). However, although on average the inclusion of the data that relates to occupant practices increased the performance gap this was not the case in three of the ten homes. This is because of the large range average internal temperatures observed in Figure 5. The most positive result of including an average measured internal temperature was seen in House A, however, the final prediction was still 34% higher than the measured figures suggesting that the heat

loss inputs are overestimated. If the result from House 16, where the model omitted to account for the solid fuel heating, are excluded the average discrepancy (between measured and predicted values after internal conditions were aligned) was 1376 kWh (72% higher than measured energy use for space and hot water heating).

Table 6. Energy use for space and hot water heating measured in March 2014 and compare to three model iterations

	ENERGY USE FOR SPACE AND HOT WATER HEATING (kWh)			
	Measured	Electrical gains	Internal temperature	Both
House A	1149	1754	1524	1544
House B	2454	4426	5545	5523
House C	1689	1582	1364	1431
House D	2110	4293	4607	4788
House E	820	1347	1405	1394
House F	702	2893	3754	3912
House G	2326	2490	3414	3444
House H	1345	3487	3270	3389
House I	1781	2078	2034	2060
House J	3202	4030	5520	5520
Average	1758	2838	3244	3301

No relationship between the size of the discrepancy and age of construction was evident which suggests that there is no systematic problem with the model's heat loss assumptions. However, regression analysis of the eight remaining detached dwellings suggest that the magnitude of the performance gap may be partially related to the size of the dwelling ($R^2 = 0.83$) (Figure 8). This is based on a very small sample of homes and should therefore be treated with caution; however, this finding suggests the heat losses from dwellings are increasingly overestimated as the floor area of dwellings increases. The prediction that was the closest to the measured figure was for House C, in the light of the potential relationship shown above this may be partly because House C has a relatively small floor area.

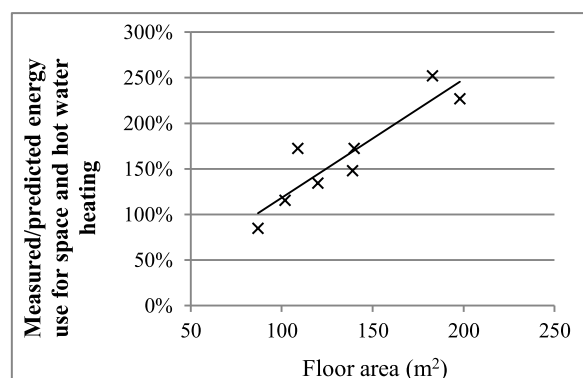


Figure 8. Measured/predicted energy use for space and hot water heating against floor area in eight detached dwellings heating using central heating

DISCUSSION

Six changes to the base case steady-state model used to predict monthly energy use for space and hot water heating were made for 10 homes. First the models were aligned to external conditions by using measured external air temperature and solar irradiance values. This allowed comparison with measured data. These changes reduced the gap between measured and predicted figures but the discrepancy was still large. Then measured internal temperature and electrical gains were used to incorporate occupant activities into the model. Including more accurate electrical gains in the model had little impact on the magnitude of the performance gap, as initial predictions of electricity use were reasonable. However, when more accurate average internal temperatures were used the model predictions were further from the measured figures. In five of the homes using the measured average internal temperature significantly increased the performance gap. This may be partially related to the method used to calculate the measured monthly internal temperature but suggests that there may be an error in some of the assumptions used to define the model inputs that relate to fabric heat loss. On average predicted energy use for space and hot water heating was greater than measured which suggests that the model overestimates the overall dwelling heat loss. This study did not measure thermal transmittance or ventilation rates and consequently cannot speculate which type of heat loss is overestimated. Regression analysis suggested that the performance gap was greater in larger homes; this suggests that the overestimation of heat loss becomes increasingly worse as the floor area of dwellings increase.

The large performance gap between measured and predicted energy use for space heating and the potential relationship with dwelling size suggests that there is potential to further improve the model inputs. It is noted that this work is focused only on steady-state models, due to their specific application to retrofit advice, however, the performance gap is equally problematic with dynamic modelling techniques but assessment of this was beyond the scope of this work.

Further work

The work presented here is the first step in developing an approach to assess the performance gap in dwellings. This work is continuing and will explore the potential of using measured data to develop the following model inputs.

- Measured gas consumption will be used to assess the number of days when heating was used each month.
- Temperature data will be used to identify the rate of cooling to assess the thermal transmittance of the homes.

- Temperature data will be used to explore the relationship between the heating period and set point temperature (of zone 1 and zone 2) and the relative sizes of zone 1 and zone 2 and how this relates to the average monthly temperature.

CONCLUSION

A study was conducted in 10 UK homes, gas and electricity consumption was monitored along with internal temperatures in every room of the dwelling. This work presents the first steps taken in using measured data from the homes to assess the performance gap between predictions made by steady state energy models and measured energy use figures. There are four main findings of this work:

- The performance gap was significant for energy use relating to space and hot water heating but not electricity use.
- After external conditions (temperature and solar irradiation) were aligned with measured values building energy model predictions were on average 52% higher than measured figures.
- After using measured figures to improve the model inputs relating to electrical gains and internal temperature the performance gap increased to 72%, which suggests that the whole house heat loss is overestimated.
- The relative performance gap was greater in larger homes, suggestion that the models overestimation of whole dwelling heat loss increases with floor area.

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