Meta-study of the energy performance gap in UK low energy housing

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Abstract

This paper presents new evidence from a nationwide meta-study investigating the magnitude and extent of the difference between predicted and measured energy performance (energy performance gap) of over 50 low energy dwellings in the UK. Statistical testing of predicted and measured energy use is undertaken to assess the impact of occupancy related factors (number of occupants, occupancy type, pattern) on energy performance, and to predict the likelihood of the space heating energy performance gap in UK new build housing. The dataset was drawn from the UK Government's National Building Performance Evaluation programme – which included the final reports, Standard Assessment Procedure (SAP) calculations and Domestic Energy Assessment and Reporting Methodology (DomEARM) results – and comprises 30 Passivhaus (PH) and 62 non-Passivhaus (NPH) dwellings, covering different built forms and construction systems. The majority of the sample comprised social housing dwellings built with masonry and timber frames and equipped with mechanical ventilation heat recovery systems. Although the average annual energy use (gas and electricity) in the PH and NPH dwellings was found to be 73 kWh/m^2 and 117 kWh/m^2 respectively, electricity use was not significantly different between the two groups. All dwellings in the sample performed better than UK Building Regulations, however average energy use was higher than predicted by an average of 60 %, but as much as 147 % in PH and 241 % in NPH dwellings. The overwhelming majority – 13 out of 14 PH and 35 out of 43 NPH dwellings – did not meet the predicted energy use, demonstrating a performance gap of 22 kWh/m^2/year and 45 kWh/m^2/year respectively. Occupancy was found to influence 45 % of total energy use, with occupancy pattern being more critical than occupancy type and number of occupants. Despite the high levels of fabric thermal standards, space heating was found to be the largest energy end use (28 % in PH and 42 % in NPH dwellings) followed by domestic hot water (28 %) and small appliances (21 %), while the ratio of regulated to unregulated energy was found to be 70:30. The probability of an energy performance gap in space heating occurring in the population of new build housing was found to be over 80 %. The study findings are important for bridging the gap between intent and actual performance of new low energy housing.

Introduction

More than a quarter of the UK's energy use, and consequent CO_2 emissions, comes from the domestic sector (Department of Energy and Climate Change, 2015). With the UK government's legally binding target of an 80 % reduction in greenhouse gas emissions by 2050, several policies have been introduced to encourage energy efficiency measures in domestic buildings (HM Government, 2018), which are seen as offering the largest low-cost reduction potential at a sectorial level (Working Group Intergovernmental Panel on Climate Change and Intergovernmental Panel on Climate Change, 2007).

However, despite these policies creating better thermal standards for new housing, it is becoming increasingly apparent within academia, industry and policy-making that there is a disparity between modelled and in use energy efficiency

(Gupta and Gregg, 2012), with both domestic and non-domestic buildings often underperforming relative to their design specifications (Carbon Trust, 2011 and Li et al., 2014). Indeed, studies by Monahan and Gemmell (2011) and Thompson and Bootland (2011) identified in-use energy being between three and five times greater than design predictions. This energy performance gap is the result of multiple factors, including discrepancies between energy modelling predictions and in-use performance (Menezes et al., 2021), the thermal performance of the building fabric (Marshall et al. (2017) and occupant behaviour. If this performance gap is not clearly understood, quantified and minimised, national policy targets (as outlined in the UK government's 'Clean Growth Strategy' (HM Government, 2018)) will be more difficult to achieve.

In response to this, Building Performance Evaluation (BPE) is often used as a diagnostic tool for gauging a building's actual performance, identifying and quantifying any energy performance gap and pinpointing the specific causes of this gap (Preiser and Schramm, 2006). This then facilitates a response to rectify, or at least reduce, the performance gap in the building(s) evaluated and can provide knowledge and understanding that can be used in future builds to minimise this gap.

Several studies have been conducted with the aim of understanding the energy performance gap. However most of these have tended to adopt a case study based approach, so the findings remain largely fragmented and can be difficult to compare. At best, actions or suggestions based on the results of building performance evaluation may have helped in fine-tuning the studied buildings' performance but attributing the improvement in performance to the changes made amidst a host of other influencing factors remains problematic. Searches using "Web of Science" and "Google Scholar" indicate that there is a lack of large-scale studies especially focussed on the gap between predicted and measured energy performance of new dwellings.

This study presents new evidence from a meta-study of building performance evaluations conducted on 'low-energy' dwellings throughout the UK. The dataset was gathered as part of the UK Government's National research programme on Building Performance Evaluation (EBP). The analysis focuses on energy performance gap with particular consideration given to space heating, for a sample of 92 'low-energy' dwellings: 30 certified Passivhaus (PH) homes and 62 non-Passivhaus (NPH) homes. Statistical analysis was conducted to identify any occupancy related factors (number of occupants, type of occupants and patterns of occupancy), which may have had a correlation with measured energy use and energy performance gap for a sub-set of dwellings where these data were available.

Evidence to date

Most of the studies on energy performance gap have tended to focus on assessing and understanding the difference between 'as-designed' and 'as-built' performance (e.g. Gaze, 2014; ZCH, 2014). There is much less research on comparing predicted energy use with actual (measured) energy use of new dwellings, and where this research does exist, it tends to be case-study based, thus making it difficult to draw out general principles that could be applied to the broader housing stock. A comprehensive review of the evidence of a gap between designed and as-built energy performance gap conducted by the Zero Carbon Hub in 2014 identified a wide range of issues considered likely to have a significant impact on the energy performance gap (ZCH, 2014). Fifteen issues were classified as 'priority for action' including problems in the detailed design and construction, and seventeen further issues were classified as 'priority for research'. Three crosscutting themes were identified as significant barriers to improving the performance gap: knowledge and skills; responsibility and communication.

While the gap between 'as-designed' and 'as-built' energy performance is challenging to address, more complex is the gap between 'as-designed' and actual 'in-use' energy performance, especially when UK Government's National Assessment Procedure (SAP), which is used to calculate the energy use of a dwelling, uses a standard occupancy profile and ignores any potential effect, occupancy and occupant lifestyle may have on energy performance (HM Government, 2013). While SAP includes energy used for space heating, water heating, pumps, fans and lighting, it ignores energy used in cooking and small appliances, with the result that some discrepancy between predicted and measured energy use is to be expected.

A limited number of studies have focussed on measured (in use) energy performance of new dwellings in the UK and have revealed significant differences between expected and actual energy use. While two BPE studies that evaluated in-use energy performance of new dwellings (Wingfield et al, 2011; Gaze, 2014) attributed the energy performance gap to discrepancies which arose across the building process, the understanding, comfort and behaviour of occupants was found to impact energy consumption by a factor of 2–3 in physically identical homes (Steemers and Yun, 2009, Gram-Hanssen, 2010).

Several factors relating to the occupants' relationship with their building have been identified to have a significant impact on building energy performance (Kapsali & Gupta, 2015; Gupta et al, 2013; Gupta & Dantsiou, 2013; Stevenson et al, 2013; Gill et al, 2010; and Lomas et al, 2006). These include the quality of handover procedures and guidance for new occupants, the expectations and attitudes of the occupants (especially in relation to their thermal comfort needs) and the occupants' understanding of controls and user interfaces – which influence behaviour and the ability to interact with building elements such as heating and ventilation controls. In a study of two neighbouring homes built to different energy principles (2010 Scottish Building Standards and Passivhaus standard), Bros-Williamson et al. (2016) found that occupancy behaviour, weather conditions and quality of construction all contributed to the design vs. actual' performance gap and recommended an extended period of monitoring (the case study lasted three years) in order to more fully understand the potential causes of the energy performance gap. It is worth noting that a common factor in all of these studies is that they are case-study based, predominantly based around a single site and with fewer than ten case study buildings, making it difficult to extrapolate their findings to the broader housing sector.

In a comparative study of six dwellings across three different developments, the actual energy use exceeded the SAP 'as-designed' predictions in all cases, even when the standard SAP model was extended to include unregulated energy use (Gupta & Kapsali, 2014). There was also variation in the energy use of households within the same development (homes therefore designed to the same standards and with similar occupancy patterns). This indicated that occupant behaviours, expectations and understanding of energy use had a significant effect on the variation of energy use. In a longitudinal study of the Milton Keynes energy park, the 'high-usage' group of occupants was responsible for the greatest increase in energy use: gas use rose by 20 % and electricity use by 75 % (Summerfield et al., 2007).

It is clear that studies addressing the gap between 'as designed' and 'in use' energy performance are limited and contextual given their case-study focus. Although occupant related factors have been identified as having a potentially major influence on measured energy use, these have not been explored in great depth. This paper aims to address both of these issues by examining the influence of occupant-related factors on measured energy use of new dwellings, using a meta-study approach. Inherent in the meta-study approach is the fact that it will not go into the depth of analysis that case-study-based research can achieve, but instead it aims to provide a better understanding of the recurring factors identified in the individual studies.

Methods and overview of the BPE dataset

This paper analyses data gathered from 92 dwellings in 28 developments throughout the UK. The authors did not collect any of the raw data themselves; rather this is a meta-study bringing together data from a national £8 million (€9 million) 'BPE programme' (2010–2014), funded by Innovate UK. The size of developments ranged from a single dwelling to over 787 dwellings. Of the 92 dwellings 30 were certified PH (6 bungalows, 7 flats and 17 houses) and 62 NPH (28 flats and 34 houses) dwellings (built to contemporary low energy standards such as 'Eco Homes' and 'Code for Sustainable Homes').

The database for the meta-study was built using a range of outputs from the BPE programme including the final report, the SAP[1] and the DomEARM[2] spreadsheets of each study within the programme. SAP is the methodology used by the UK Government to assess and compare the energy and environmental performance of dwellings. DomEARM is the energy assessment and reporting methodology for domestic applications developed by Ove Arup and Partners Ltd in collaboration with Oxford Brookes University. The study database comprises energy performance data on annual energy use, space heating and electricity end-uses for a sub-set of 92 dwellings.

The gathered data were subjected to quality checks to ensure high fidelity of the developed database which comprised 62 NPH and 30 PH dwellings, including 51 houses, 35 flats and 6 bungalows with floor areas from 39 m² to 346 m², designed to diverse standards from Passivhaus and Fabric First approach to Code of Sustainable Homes (CSH 2–6) and Building Regulations. Figure 1 summarises the percentage distribution of the physical characteristics for the PH and NPH dwellings. The majority of construction types were either traditional masonry (38 %) or timber framed (50 %), but also included structural insulated panels (SIPs) and concrete/steel. Ventilation in all of the NPH dwellings and 56 % of PH dwellings was provided by Mechanical Ventilation with Heat Recovery (MVHR) due to the high thermal standards adopted, although a significant proportion of PH dwellings used natural ventilation (NV) (35 %) and mechanical extract ventilation (MEV) (9 %). Social housing was the most common tenure type (64 %). In summary, Table 1 shows how many dwellings had data for each of the categories considered in the analysis.

A statistical approach was used in the meta-study, which allowed for conclusions to be applicable to the wider new build population. The quantitative performance data were analysed using the Statistical Package for Social Sciences (SPSS). Descriptive statistics (such as mean, minimum and maximum) were analysed for each sample of data, while standard deviation was used to identify the extent of the gap. Regression analyses were used to investigate the strength of relationship between building characteristics and energy performance gap, enabling the cases in which the gap is more likely to occur to be identified. Finally, probability analyses such as the 'probability density function' and the 'Monte Carlo simulation' were applied to predict the likelihood of performance gap occurrence in new build housing in the UK, based on the sample analysed.

Results: measured energy use and end uses

Measured energy consumption across the sample of 92 dwellings was found to be within the range of 35–232 kWh/m²/year, with a mean consumption of 103 kWh/m²/year (Table 2), which is approximately half the UK national average in 2013. The mean energy consumption in PH dwellings was found to be 73 kWh/m²/year whereas in NPH dwellings it increased to 117 kWh/m²/year. Subsequently, the PH dwellings used on average 62 % less energy than NPH dwellings (T-test, significant at $p<0.05$).

Both predicted and measured energy use data (from SAP) were available for 57 dwellings (14 PH and 43 NPH), as presented in Figure 2. 13 of the 14 PH dwellings showed measured energy use greater than predicted energy use, averaging 50 % more measured than predicted up to 147 %. Similarly, 35 of the 43 NPH dwellings (81 %) showed measured energy use greater than predicted energy use, averaging 63 % more measured than predicted, up to 241 %. The statistical relationship between predicted and measured energy use is virtually non-existent ($R^2 = 0.06$ for PH and 0.03 for NPH dwellings). Interestingly, of the 13 PH dwellings which had measured energy use greater than predicted energy use, the magnitude of the average performance gap was 22 kWh/m²/year. In comparison, of the 35 NPH dwellings which had higher measured energy use than predicted, the magnitude of the average performance gap was 45 kWh/m²/year – more than double that for PH dwellings.

1. Standard Assessment Procedure (SAP) is the methodology used by the Government to assess and compare the energy and environmental performance of dwellings. Its purpose is to provide accurate and reliable assessments of dwelling energy performances that are needed to underpin energy and environmental policy initiatives. SAP works by assessing how much energy a dwelling will consume, when delivering a defined level of comfort and service provision. The assessment is based on standardised assumptions for occupancy and behaviour. This enables a like-for-like comparison of dwelling performance.

2. DomEARM is the energy assessment and reporting methodology for domestic applications developed by Ove Arup and Partners Ltd in collaboration with Oxford Brookes Institute for Sustainable Development. The methodology has been developed to be applied to both existing and newly constructed dwellings and includes 3 levels of assessments. Level 1 is essentially a way of rating an occupied dwelling based on metered data and compared against appropriate benchmarks. Level 2 provides better resolution of the assessment accommodating the type of heating and hot water systems and the inclusion of renewable energy sources. Level 3 allows a breakdown to be made of the energy into end use – the fixed systems and appliances that are commonly used in dwellings.

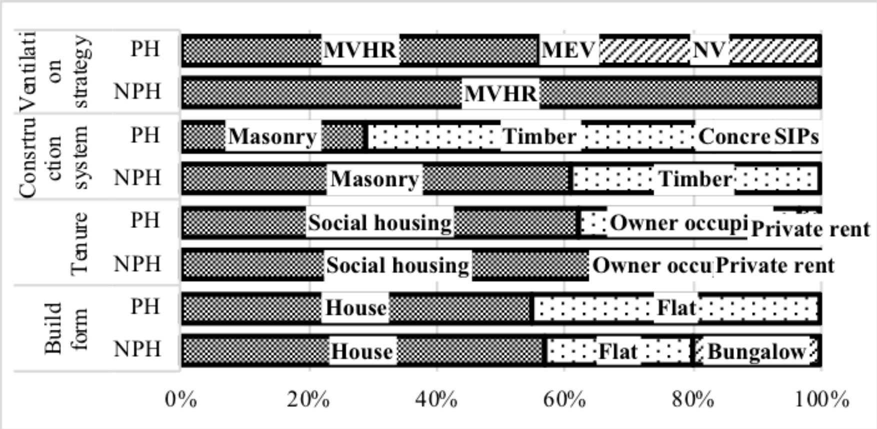


Figure 1. Build form, tenure type, construction system and ventilation strategy for the 30 Passivhaus (PH) and 62 non-Passivhaus (NPH) dwellings in the study database.

Table 1. Total number of dwellings with data for each of the subsamples.

Subsample	All dwellings	Passivhaus	Non-Passivhaus
All dwellings	92	30	62
Physical characteristics	92	30	62
SAP and measured space heating	62	12	50
SAP and measured energy	48	9	39
Energy end-use sub-categories	48	9	39

Table 2. Annual energy use for 92 dwellings.

	Measured Total Energy (kWh)					Measured Total Energy (kWh/m²)				
	Mean	**Median**	Min	Max	Std. Dev.	**Mean**	**Median**	Min	Max	Std. Dev.
Passivhaus (N = 30)	**5,893**	**4,890**	2,728	16,581	3,001	**73**	**71**	38	198	30
Non-Passivhaus (N = 62)	**10,350**	**8,964**	1,776	37,353	6,544	**117**	**110**	35	232	50
Overall (N = 92)	**8,897**	**7,484**	1,776	37,353	5,999	**103**	**95**	35	232	49

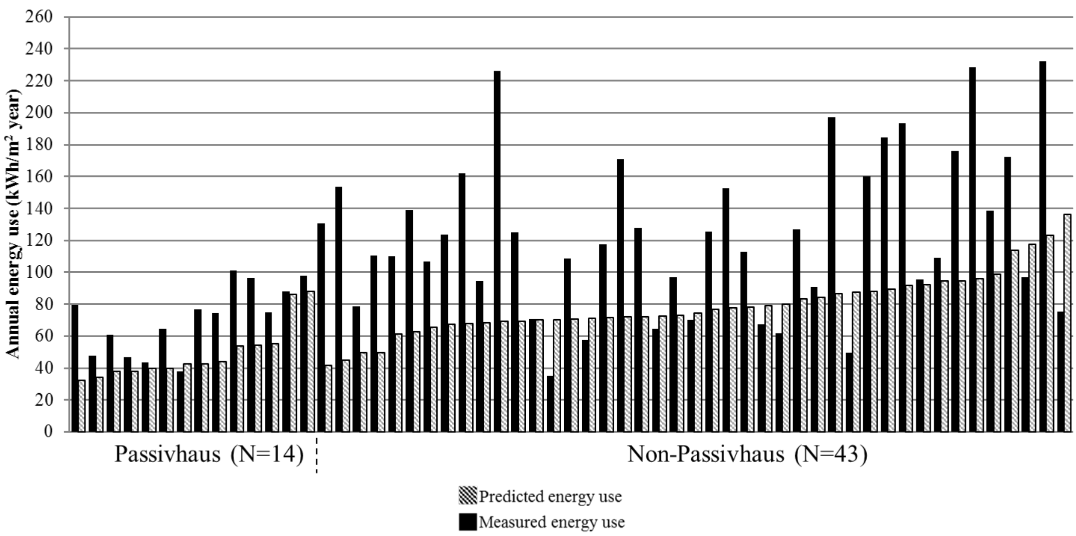


Figure 2. Comparison of predicted (SAP) and measured energy use (N=57).

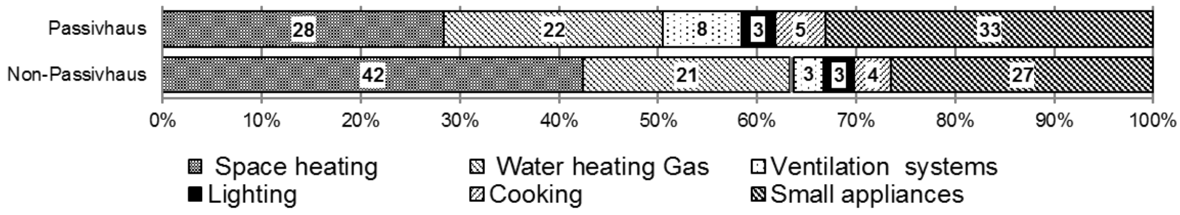


Figure 3. Breakdown of energy use categories for the 48 dwellings (9 Passivhaus, 39 non-Passivhaus) with percentages shown. Note: water immersion electricity was less than 0.5 % in both PH and NPH.

Table 3. Descriptive statistics for measured space heating.

	Measured Space Heating (kWh/m²)			
	Mean	Min	Max	Std. Dev.
Passivhaus (N = 12)	23.0	4.8	50.3	13.8
Non-Passivhaus (N = 56*)	55.3	2.6	175.0	37.2
Non-Passivhaus (N = 50)*	*58.3*	*3.3*	*175.0*	*37.3*

*6 NPH dwellings had no SAP heating energy data. The lower row (N = 50) gives the statistics when these 6 dwellings are excluded from the calculations.

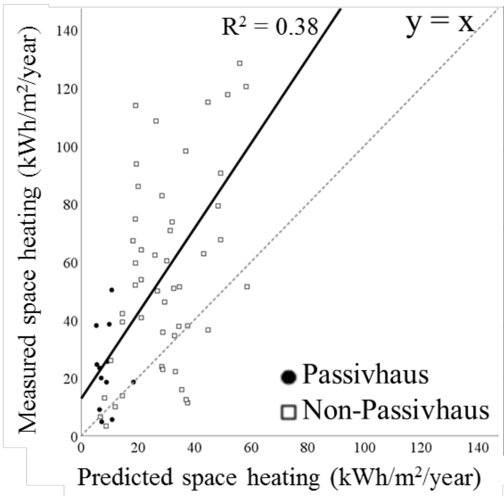
The energy breakdown by fuel was significantly different for PH and NPH dwellings. In PH dwellings, a mean of 37 % (36 kWh/m²/year) was provided by fossil fuels (including gas and LPG), 14 % (14 kWh/m²/year) by biomass and 48 % (47 kWh/m²/year) by electricity, whereas in NPH dwellings, a mean of 46 % (87 kWh/m²/year) was provided by fossil fuels, 25 % (48 kWh/m²/year) by biomass and only 29 % (55 kWh/m²/year) by electricity. These results show that, on average, the PH dwellings used much less fossil fuel and biomass per square metre of floor area than electricity (non-heating) because of their high thermal standards. Non-Passivhaus dwellings, on the other hand, used a considerably higher amount of fossil fuel compared to electricity and biomass. Interestingly there was a small difference found in electricity use between PH and NPH dwellings (1.2 times higher in NPH dwellings), whereas fossil fuel and biomass (for heating) use were on average 2.4 and 3.3 times higher in NPH dwellings.

Data for the energy end use categories (space heating; water heating (gas); water immersion (electricity); ventilation systems (MVHR/pumps and fans); lighting; cooking; small appliances) were available for 48 (9 PH and 39 NPH) out of the 92 dwelling sample. The breakdown of energy use categories revealed that space heating was still the largest end use of energy, accounting on average, 28 % of the total energy use in PH and 42 % in NPH dwellings, but reached to a maximum of 52 % and 76 % in PH and NPH dwellings respectively (Figure 3). As the second and third largest energy end uses, DHW (water heating gas and water immersion) and small appliances are comparable, accounting for 28 % and 21 % respectively of the total energy use in both PH and NPH dwellings. The highest proportions of energy use by small appliances – 49 % in PH and 63 % in NPH – highlighted the impact that the number, type and use of appliances can have on energy use. The results also demonstrated that despite the design intention to radically cut down space heating demand in low energy dwellings, space heating and DHW were on average, responsible for 50 % of the total energy use in PH dwellings and 63 % in NPH dwellings respectively. Although this is significantly lower than the figure of 80 % (62 % space heating + 18 % water heating) from the UK Housing Fact File (Palmer and Cooper, 2013), it is still high for dwellings designed as 'low energy'.

The end uses of cooking and small appliances (plug loads) represent the unregulated portion of measured energy use. About 44 (out of 92) dwellings had a complete dataset for at least three major end uses: *space heating, hot water* and *small appliances*. Analysis of these dwellings showed that unregulated energy use averaged 38 % of total measured energy use in PH dwellings, and 29 % of total measured energy use in NPH dwellings, highlighting how significant the unregulated segment of energy use can be in ultra-low energy homes. This is especially important since unregulated energy use is not currently addressed in UK Building Regulations.

Data for measured space heating energy were available for 68 dwellings (12 PH and 56 NPH). The descriptive statistics (Table 3) showed that average space heating energy use in NPH dwellings (55 kWh/m²/year) was nearly two and a half times more than PH dwellings (23 kWh/m²/year) since the latter were designed to high thermal standards.

Out of the 68-dwelling sample, modelled (predicted by SAP) and measured space heating energy data were available for 62 dwellings (12 PH and 50 NPH). When measured space heating energy use was correlated with modelled space heating energy for the 62-dwelling sample, a weak but statistically significant relationship (Figure 4) emerged. The relationship was found to be even weak in the subset of NPH dwellings ($R^2 = 0.29$), while no statistically significant relationship could be identified in the PH dwelling sample due to the small sample size (n: 12). Although measured space heating was found to be nearly twice that of predicted space heating energy in NPH dwellings, and increasing to three times more in PH dwellings (Figure 4, right), the magnitude of the gap was much lower in



	Modelled space heating (kWh/m²)			
	Mean	Min	Max	Std. Dev.
Passivhaus (N = 12)	**8.8**	5.3	18.4	3.6
Non-Passivhaus (N = 50)	**30.5**	6.8	64.2	14.2
	Measured space heating (kWh/m²)			
	Mean	Min	Max	Std. Dev.
Passivhaus (N = 12)	**23.0**	4.8	50.3	13.8
Non-Passivhaus (N = 50)	**58.3**	3.3	175.0	37.3

Figure 4. Relationship between measured and predicted (SAP) space heating energy (N = 62: 12 Passivhaus and 50 Non-Passivhaus) (left) and descriptive statistics (right). The linear trendline (R^2=0.38) is plotted, with the y=x line shown for comparison.

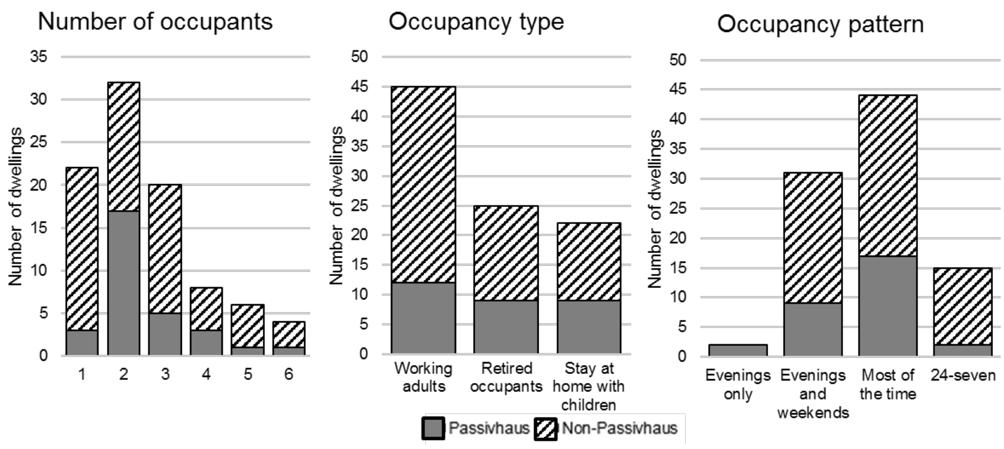


Figure 5. Distribution of occupancy related variables for Passivhaus and non-Passivhaus dwellings (N=92: 30 Passivhaus, 62 non-Passivhaus).

PH dwellings (14 kWh/m²/year in PH versus 28 kWh/m²/year in NPH dwellings).

The predicted and measured space heating data were used as input data to Monte Carlo simulations, which predict the probability of the performance gap occurring in the population of new-build dwellings (approximately 200,000 dwellings per year (Ministry of Housing, Communities and Local Government, 2018). The stopping criterion was achieved, and the results are based on 52,373 simulated cases. The "predicted" mean and median values were 27 kWh/m² and 22 kWh/m² respectively. There was a 5 % probability that the space heating gap would be up to 14 kWh/m² and a 95 % probability that it would be up to 87 kWh/m². The probability of any performance gap was 81 %. It should be also noted that a similar analysis was conducted using the same sample of dwellings but with the raw (rather than normalised per floor area) space heating energy data. The probability of a performance gap in this case was 79 % which compared very well with the probability of 81 %.

Influence of occupancy related factors on actual energy use

The total (annual) measured (actual) energy use data (normalised for floor area: kWh/m²/year) for the 92-dwelling sample were statistically analysed against three key occupancy related factors that included (1) *Number of occupants*, (2) *Occupancy type* (working adults, retired occupants, stay at home with children) and (3) *Occupancy pattern* (evenings only, evenings and weekends, most of the time, 24–7). The ages of adult (and child) occupants were not recorded, although the occupancy type gives some indication of the broad age ranges represented. Figure 5 shows the distribution of the sub-categories of these factors for PH and NPH dwellings. Due to the small sample size of PH dwellings (N=30), the subcategories presented low frequencies, particularly for number of occupants and occupancy pattern.

As shown in Figure 6, it was found the *number of occupants* had little impact on measured energy use for both PH and NPH dwellings given the weak statistical relationship between the two. Regression analysis of PH dwellings implied that for each additional occupant, the average energy consumption would increase by 6.7 kWh/m²/year. For the NPH dwellings, regression analysis indicated that for each additional occupant the average energy consumption increased by 7.8 kWh/m². Both results were found to be statistically significant ($p<0.01$).

Occupancy type was found to have a significant impact on the total (measured) energy used. For the 92 dwelling sample, occupants who stayed at home with children used an average of 119 kWh/m²/year compared to 107 kWh/m²/year for retired occupants and 92 kWh/m²/year for working adults. Interestingly, the PH dwelling sample (N=30) showed a different trend to the NPH sample (N=62), with *working adults* (N=12) using more energy per m² than both *retired occupants* and *occupants that stayed at home with children* (Figure 7). This may be an anomaly due to the smaller sample sizes of the different occupancy types among PH sample (see Figure 5 above, although no outliers were evident in the datasets) and/or the number of occupants and occupancy pattern of the working adults in the PH sample. Further investigation would be necessary to understand the cause of this anomaly. (These differences were statistically significant at $p<0.05$).

It is also worth noting that similar trends were observed for space heating energy use, wherein *working adults* and *stay at home with children* in PH dwellings used significantly more space heating energy (per m²) than *retired occupants*. However *number of occupants* was found to have no statistically significant impact on measured space heating energy use in neither PH nor NPH dwellings.

Grouping dwelling energy use by *occupancy pattern* showed the greatest differences. As expected, the more time occupants spent in their dwellings, the greater their energy use was. The percentage variation in energy use by category was greater in the 30 PH dwellings than in the 62 NPH dwellings. While in PH dwellings, measured energy use was 84 % and 73 % higher when occupancy was '24/7', as compared to 'most of the time' and 'evenings and weekends' respectively, in NPH dwellings, measured energy use was 22 % higher when occupancy was '24/7' compared to 'most of the time' and 70 % higher when occupancy was '24/7' compared to 'evenings and weekends'. The statistical significance of these results were confirmed by the Analysis of variance (ANOVA) for both PH and NPH dwellings.

A regression model was then developed to compare the relationship between the three occupancy related variables and

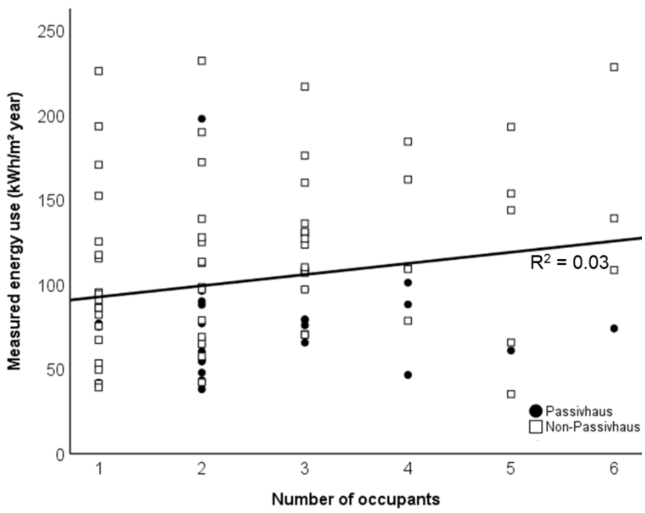


Figure 6. Relationship between number of occupants and normalised measured energy use (N = 92: 30 Passivhaus, 62 non-Passivhaus).

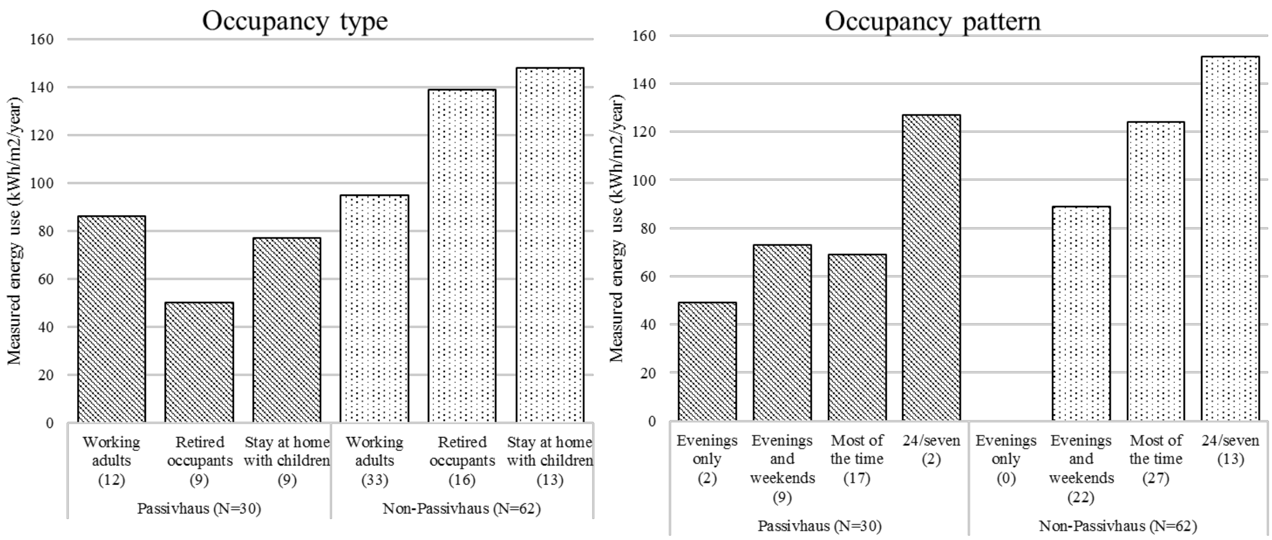


Figure 7. Average energy use by type of occupancy (left) and occupancy pattern (right) for Passivhaus and non-Passivhaus dwellings.

Table 4. Coefficient correlations and covariances for occupancy related variables (where measured energy use was the dependent variable).

		Occupancy pattern	Number of occupants	Occupancy type
Correlations	Occupancy pattern	1.00	-0.17	-0.41
	Number of occupants	-0.17	1.00	-0.18
	Occupancy type	-0.41	-0.18	1.00
Covariances	Occupancy pattern	51.24	-4.32	-18.94
	Number of occupants	-4.32	13.11	-4.23
	Occupancy type	-18.94	-4.23	41.75

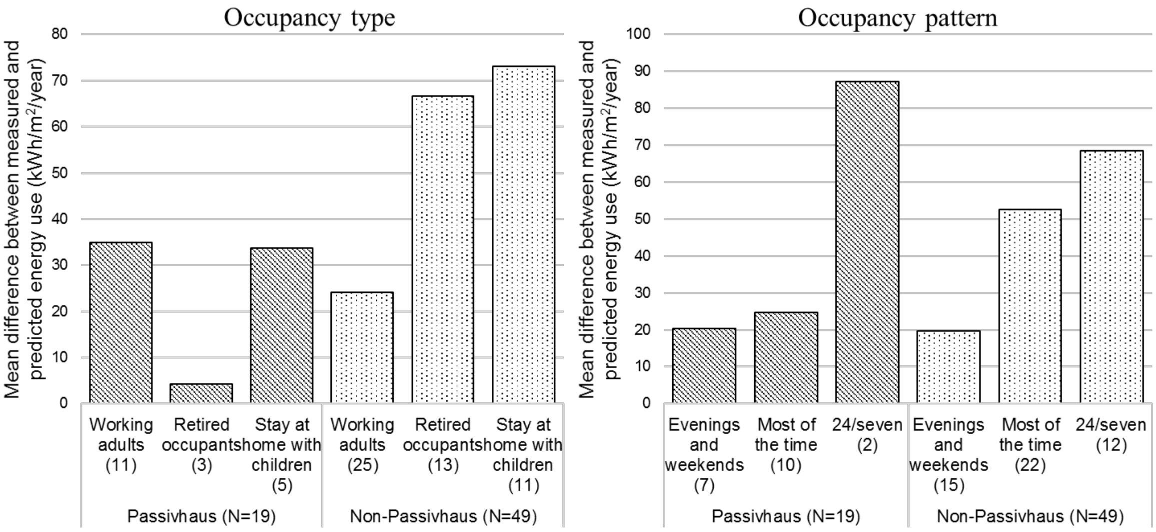


Figure 8. Mean difference between measured and predicted energy by occupancy type (left) and occupancy pattern (right).

measured energy use (Table 4). Such a model assumes that energy use is dependent solely on occupancy related variables, which is not the case but served the purpose of evaluating the relative strength of these variables in explaining energy use.

The model was found to be significant at $p<0.01$ and showed that the combination of number of occupants, occupancy type and occupancy pattern explain 45 % of the measured energy use. (The standardised coefficient Betas for the three independent variables were 0.067 for *number of occupants*, 0.017 for *occupancy type* and 0.418 for *occupancy pattern*, indicating that *occupancy pattern* had the largest unique contribution to the variance in measured energy use). The variable making the strongest contribution to explaining energy use was *occupancy pattern*. It should be also noted that the standardised coefficients for the variables *number of occupants* and *occupancy type* are not significant at $p<0.05$ indicating that the two variables have (statistically) no significant contribution in explaining energy use. This was also confirmed from a stepwise regression analysis where only *occupancy pattern* remained in the model, explaining itself 45 % of the measured energy use.

Having quantified the influence of occupancy number, type and pattern on measured energy use, statistical analysis was also conducted to investigate the impact of occupancy related factors on the mean difference between measured and predicted energy use (energy performance gap). Correlation analysis revealed a relationship between both *occupancy type* and *occupancy pattern* and energy performance gap. Figure 8 illustrates these trends.

No statistically significant correlation was found between the number of occupants and the difference between measured and predicted energy use. Differences in the PH sub-set were possibly due to the very small sample sizes. Combining *occupancy type* and *occupancy pattern* showed that 'Retired occupants' and 'Stay at home with children' occupancy types who also had '24/7' occupancy pattern were the groups associated with the greatest differences between measured and predicted energy use. The analysis showed that the *pattern and type of occupancy* were key factors that contributed to higher (measured) energy use and consequently higher mean differences between predicted and measured energy use (i.e. the energy performance gap).

Discussion

The meta-study used statistical analysis to assess the extent and magnitude of energy performance gap in a sample of 92 low-energy dwellings in the UK, and focussed on measured energy use, its end uses, the proportion of energy used for space heating and the role of occupant related factors on measured energy use. The average energy consumption in the sample was found to be 73 kWh/m^2/year for PH dwellings and 117 kWh/m^2/year for NPH dwellings, which was much less than the UK national average of 200 kWh/m^2/year. Passivhaus dwellings were found to use 62 % less energy than NPH (low energy) dwellings but showed similar proportions of energy usage by space heating. Despite the dwellings being designed to very high thermal standards (including PH), energy used for space heating and hot water were responsible for 50 % of the total annual energy use; space heating remained as the single largest contributor amounting to 28 % in PH dwellings and 42 % in NPH dwellings. In comparison, the UK domestic sector uses around 80 % of its final energy consumption on space and water heating, the majority of which is provided by gas (HM Government, 2018b). Interestingly, only 17 % and 5 % of UK domestic electricity consumption is accounted for by space heating and water heating respectively (ibid.).

These findings imply that in addition to thermal standards of the building fabric and efficiency of the heating system (the current focus of Building Regulations in the UK), other factors such as occupancy related are also important in determining space heating demand and should therefore be considered in future iterations of Building Regulations, which should not only focus on as-built performance (without occupants) but also the in-use energy performance of dwellings. Gram-Hanssen et al (2018) have recommended how (Danish) building regulations could be redesigned to regulate energy use during the occupancy phase by developing alternative measures to energy per square meter, producing more advanced models simulating occupancy and the increased use of post-occupancy evaluations.

Currently in the UK different contributing factors are considered in predicting domestic energy usage (Department of Energy and Climate Change, 2013), which include number of bedrooms, property type, property age, property tenure, household income, location and number of adults in the property. Domestic energy use based on the number of occupants in the household had not been analysed until this 2013 publication (DECC, 2013), which reported that as the number of adults increased, the energy use increased i.e. about 24 % increase in gas use between 1 and 2 adults, 9 % increase for each subsequent adult and 42 % increase in electricity use between 1 and 2 adults, with much smaller increases per adult from 3 upwards. However, the current study found that the *occupancy pattern* (in effect, the hours that the building is occupied) had a much more significant role to play in determining the overall energy use than the number of occupants living in each dwelling. Indeed, statistical analysis revealed that 45 % of the variance in measured energy use could be explained by the variance in occupancy pattern. It therefore seems imperative that these factors be included in domestic energy models. Usually domestic energy use is normalised by calculating energy use per square metre per year (kWh/m^2/year). In order to include *occupancy pattern* (hour of occupation), energy use could also be normalised for hours of occupation in the form of kWh/m^2/hour of occupation. In this way, a dwelling which is occupied for 80 % of the time and uses 80 kWh/m^2/year could be compared more fairly against a dwelling which is occupied for 20 % of the time and uses 50 kWh/m^2/year. It should be noted, however, that the occupancy patterns and types are based on occupant feedback in surveys and interviews – rather than any definitive measure such as recording exactly when an occupant is at home or out – and are also provided as quite broad ranges (e.g. "some of the time", "most of the time"). They are therefore susceptible to respondent bias and significant margins of error. The surveys would also need to consider all of the occupants within the dwelling: for example, a family with one working parent, one at-home parent and two young children may have significantly different patterns of energy use to a family with two working parents and two teenage children.

The study has also shown that performance gap between predicted and measured overall and especially space heating energy remains widely prevalent within the new build population, even those designed to be low-energy. Only one of 14 PH dwellings and eight of 43 non-PH dwellings had measured total energy use lower than their predicted use, with 79 % of PH and 76 % of NPH dwellings using at least 10 % more energy than their predicted use. Unless this energy performance gap can be firmly addressed by considering both technical and occupancy related factors, the building sector will not be able to achieve its carbon reduction targets.

Conclusions

This cross-project meta-study based approach has statistically assessed the energy performance of 92 low-energy dwellings (30 PH and 62 NPH) located throughout the UK, and has revealed that the gap between predicted energy use and measured energy use is prevalent across the majority of dwellings. Despite being designed and built to higher thermal standards than conventional new-builds, the findings revealed that space heating makes up a significant proportion of the overall energy use within both PH and non-PH dwellings. Although physical factors (fabric, services) have undoubtedly contributed to this, the findings of this analysis imply that occupancy related factors also have a significant role to play and should not be overlooked, particularly by Building Regulations. This trend may change as domestic heating energy moves from gas to electricity due to the efficiency of devices such as heat pumps: for example, 1,000 kW of heating energy currently provided by 1,100 kWe of gas could instead be supplied by 400 kW of electricity from a heat pump.

The study also revealed that unregulated energy use for cooking and small appliances makes up a significant proportion of overall energy use. Although devices tend to become more energy efficient as technology develops, this is counteracted by the trend towards using more appliances that are used more often, indicative of the need to consider 'sufficiency' rather than 'efficiency' when considering efforts to reduce overall energy consumption (Derby, 2007). As space heating demand decreases, the proportion of total energy use going towards unregulated categories is likely to increase further. It is therefore important that unregulated energy use is included in any design and modelling calculations, as well as Building Regulations.

Finally, the analysis revealed that the most important occupant-related factor influencing overall energy use is not the number of occupants, but rather the type of occupants and even more so the occupancy pattern. It is therefore essential that these factors are considered in any models, and it is recommended that they be included in any future analysis of dwelling energy use.

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