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Magnitude and extent of building fabric thermal performance gap in UK low energy housing

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HIGHLIGHTS

- Air-permeability, U-value and whole house heat loss data were statistically tested.
- Building fabric thermal performance gap was widespread in low energy dwellings.
- Airtightness gap was trivial in Passivhaus but significant in non-Passivhaus units.
- Gap increased by 0.8 $m^3/h/m^2$ for every 1 $m^3/h/m^2$ decrease in design air permeability.
- Building regulations should require in-situ tests to reduce fabric performance gap.

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ABSTRACT

This paper presents new evidence from a nationwide cross-project meta-study investigating the *magnitude* and *extent* of the difference between designed and measured thermal performance of the building fabric of 188 low energy dwellings in the UK. The dataset was drawn from the UK Government's national Building Performance Evaluation programme, and comprises 50 Passivhaus (PH) and 138 non-Passivhaus (NPH) dwellings, covering different built forms and construction systems. The difference between designed and measured values of air permeability (AP), external wall/roof thermal transmittance (U-value) and whole house heat loss were statistically analysed, along with a review of thermal imaging data to explain any discrepancies. The results showed that fabric thermal performance gap was widespread especially in terms of AP, although the magnitude of underperformance was much less in PH dwellings. While measured AP had good correlation with measured space heating energy for PH dwellings, there was no relationship between the two for NPH dwellings. The regression analysis indicated that for every 1 $m^3/h/m^2$ reduction in designed air permeability, the gap increased by 0.8 $m^3/h/m^2$@50 Pa. Monte Carlo analysis showed that likelihood of AP gap was 78% in NPH dwellings designed to 5 $m^3/h/m^2$@50 Pa or lower. The study provides useful evidence for improving the fabric thermal performance of new housing through in-situ testing.

1. Introduction

The domestic sector in the UK accounts for more than a quarter of the national energy use and associated CO_2 emissions [1]. Under the scope of UK's legally binding 80% greenhouse gas emissions reduction target to be met by 2050, various policies aimed at encouraging energy efficiency measures in domestic buildings have been put in place in the recent years [2]. However, there is an increasing concern within academia, industry and policy-making that in practice, energy efficiency standards are not being achieved [3], while a growing body of evidence suggests that domestic and non-domestic buildings often underperform as compared to the design specifications [4,5]. The so called *energy performance gap* between the design intent and the actual energy use in domestic buildings is the result of multiple factors, including occupant behaviour, building fabric thermal performance and actual systems efficiency. Behaviours, lifestyles and socio-economic aspects of

Abbreviations and acronyms: ACH, air change per hour; n50, air tightness @50 Pa; CSH, Code of Sustainable Homes; HLC, heat loss coefficient; ATTMA, Air tightness Testing and Measurement Association; TSL1, Technical Standard L1; SAP, Standard Assessment Procedure; ΔT, temperature difference between the inside and the outside of dwellings; BS EN, British version of European harmonised standard; DomEARM, Energy Assessment and Reporting Methodology for domestic applications; BPE, Building Performance Evaluation; PH, Passivhaus; NPH, Non Passivhaus; SIP, Structural insulated Panel; NV, Natural Ventilation; MEV, Mechanical extract ventilation; MVHR, Mechanical Ventilation with Heat Recovery; AP_m, Measured Air Permeability; AP_d, Design Air Permeability; AP_{mp}, difference between measured and design air permeability

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occupants may determine large variations of energy use, since they affect the choice and control of heating and cooling systems [6], the use of hot water for baths and showers [7,8] and the use of electric appliances [9]. The extent of the energy performance gap in residential building retrofits in Germany has been found to be as high as 300% in comparison to the expected energy savings [10]. An analysis on 121 LEED certified buildings has revealed that half of the buildings were performing worse, or much worse, than expectations [11]. In the UK, building performance evaluation studies carried out in low carbon domestic retrofits revealed that the effective reduction in annual CO_2 emissions was only 40% after the retrofit, while the estimation was 80% [12]. Monitoring studies recently carried out on flats and houses built to low energy standards in the UK also confirm higher consumptions compared to energy estimations [13].

The gap between modelled and measured energy use of dwellings is the result of multiple causes, spanning poor design and technical specification in the design stage, low quality of management and workmanship in the construction and handover phases, and differences between standard assumptions for energy modelling and actual operation of buildings determined by occupants [14]. Occupant behaviour is often indicated as one of the main causes of performance gap, and has been widely investigated using three main methodologies: (1) by correlating the actual energy use with the socio-economic characteristics of occupants [5,15,16], (2) by carrying out post occupancy evaluation studies [17,18] and (3) by simulating the impact of occupant related variable using dynamic energy models [19–21]. The results suggest that income and lifestyle have a higher impact on energy use for space cooling than space heating [5,16], while the impact of occupant behaviour on heating energy demand increases in homes designed to high performance standards [15,19,22,23]. Despite this, most of the variability of actual energy use in dwellings, is explained by building characteristics rather than occupant behaviours: a study on actual consumption of Dutch residential stock [15] revealed that building characteristics explain 42% of energy use variability, while occupant behaviour only 4.2%. For this reason, deeper understanding of the reasons for the gap between the design and actual thermal performance of building fabric is necessary to reduce the energy performance gap.

A key factor for the fabric thermal performance gap is the quality of workmanship in construction and commissioning phases, which may significantly reduce the performance of building fabric and systems with respect to the design intent. Furthermore, the widespread use of building energy rating and compliance tools to predict energy use at the design stage, such as the Standard Assessment Procedure (SAP) in the UK, leads to disparity between measured and modelled performance since SAP is reliant on the expertise of the user, quality of data input and appropriateness of the model to the particular context and SAP models are usually not updated with real performance data [24]. Marshall et al. investigated the impact of inaccurate modelling assumptions and demonstrated that the inclusion of empirical measurements of air permeability and U-value can considerably reduce the energy performance gap [25].

Despite the wealth of studies on energy performance gap, much of the work to date has been case-study based. For this reason, findings are largely fragmented and hardly comparable. This study aims at overcoming these limitations, by investigating all aspects of building fabric thermal performance (ventilation heat loss, thermal transmittance and whole house heat loss) through a cross-project meta-study of the primary data on designed and measured thermal performance of the building fabric and its effect on actual space heating energy use of 188 low energy dwellings in the UK. The study covers both houses and flats, and different construction systems, to comparatively evaluate (for the first time) the *magnitude*, *extent* and *reasons* for the fabric thermal performance gap in Passivhaus and Non-Passivhaus dwellings, using statistical tests. Findings from the study have strong implications for improving building energy modelling using empirical data.

2. Building fabric thermal performance: evidence to date

Heat transfer through building fabric occurs via convection, conduction and radiation, with the temperature difference being the driving force in all cases. Quality defects in construction affect building energy performance by increasing heat losses through the building fabric by unintended air leakage, thermal bridging and increased thermal transmittance [26]. In a new build dwelling, repeating and non-repeating thermal bridging can be responsible for 20–30% of the total heat loss [27] while the respective share due to air leakage may be up to 50% [28]. As a result, underperforming elements of the building fabric can have a significant impact on energy use and particularly on space heating, which is the largest energy end use in UK households, accounting for over 60% of total energy use [29]. An extensive house building process review of 200 plots across 21 sites undertaken by Zero Carbon Hub in the UK, revealed widespread shortfalls in the *as-built* performance of the stock, as well as a range of issues likely to have a significant impact on the performance gap, such as lack of integrated design between fabric and services, calculation assumptions for both fabric heat loss and thermal bridging unrepresentative of the reality of site construction and poor installation of fabric [30]. In another study, based on data from 39 eco-refurbished and eco-new builds dwellings in UK, the range of the 'fabric-only' heat loss performance gap was found to be between −9% and +58% [31]; the average performance gap of building fabric was found to be 26%, which means about 0.06 $MtCO_2eq$ more than necessary every year, only due to quality defects in new dwellings.

Several international studies have also empirically assessed the actual building fabric performance using airtightness and infiltration measurements. However in most cases, the empirical results were not compared to the designed values to reveal the extent of the 'performance gap'. A study of 20 single-family houses in Greece undertook airtightness and infiltration measurements, and found the average number of air changes per hour (ACH) varied from 0.6 ACH to 7 ACH (at a 50 Pa pressure) when the tracer gas or the Blower Door test methods were used; the results also identified linear relationships between total window frame length and airtightness [32]. An empirical study in 23 spaces of housing, office and school buildings in Portugal investigated the contributions of windows and roller-shutters to rooms permeability and found out that on average, windows contribute by15% and roller-shutters by 44% to the room permeability of typical heavy construction buildings of Southern Europe context [33]. Another Portuguese study carried our air permeability tests in five flats of a single building. Although the properties had the same size, components and construction characteristics, the results revealed wide variations in airtightness attributed to the quality of installation work [34]. Similar results were also found for nine semi-detached social housing dwellings in Ireland, where the measured and modelled airtightness result differed by up to 89% [35].

Field measurements using the standardized Blower Door pressurisation technique were also undertaken in 32 detached houses in Estonia. The study found a mean air leakage rate of $4.2\,m^3/h/m^2$@ 50 Pa and highlighted the number of storeys and quality of workmanship as significant determinants of airtightness [36]. The importance of workmanship was stressed in a study in Finland where 170 single-family detached houses and 56 apartments were tested for airtightness [37], as well as in a Dutch study where a number of air leakage paths including junctions and joints, openings, service penetrations and fittings were identified in the dwellings under investigation [38]. In terms of the impact of airtightness on space heating energy use, an evaluation of a typical modern detached house in Finland yielded an almost linear relationship between the average infiltration rate and heating energy use with the building leakage rate, associating 15–30% of the space heating energy to infiltration [39].

In the UK for new build dwellings, fabric thermal performance has been empirically measured through a range of studies using air-

Table 1
Details of studies in the UK measuring fabric thermal performance of new dwellings.

Study	No. of dwellings	Study elements		
		Air permeability	Ext. wall/roof U-value	Whole house heat loss
Good Homes Alliance 2014 [45]	2	✓	✓	✓
Farmer et al. 2014 [49]	2	×	×	✓
Johnston et al. 2016 [46]	3	✓	✓	✓
Littlewood JR, Smallwood I. 2015 [42]	4	✓	×	×
Gupta et al. 2013 [43]	5	✓	×	✓
Bell et al. 2010 [44]	6	✓	×	✓
Gupta R, Kapsali M. 2015 [61]	6	✓	×	×
Johnston D, Siddall M. 2016 [51]	7	×	×	✓
AIMC4 2014 [41]	17	✓	×	✓
Johnston et al. 2015 [48]	25	×	✓	✓
Wingfield et al. 2008 [40]	44	✓	✓	✓

permeability (AP) tests (blower door), whole house heat loss tests (co-heating) and thermal transmittance (U-value) measurements, as shown in Table 1, although most of the studies use AP tests to measure airtightness levels of dwellings. A detailed evaluation of the AP of 44 cavity masonry dwellings found that a third of the properties underperformed, wherein the simpler two-storey dwelling type demonstrated the best results, whereas the more complex 2-½ storey room-in-roof designs presented an airtightness performance gap due to issues relating to continuity of the air barrier around the junction between the wall and sloping section of ceiling [40]. Another study of 17 dwellings with varying construction systems designed to Code of Sustainable Homes (CSH) 4 yielded deviations of up to 2.4 $m^3/h/m^2$@50 Pa for over half the dwellings [41]. Similar results were found for four dwellings CSH 3&4, where deviations up to 3.8 $m^3/h/m^2$@50 Pa on air tightness values were observed [42]. Discrepancies in the range of 0.8–4.7 $m^3/h/m^2$@50 Pa were also identified in five dwellings built to EcoHomes Excellent and CSH 5&6 standards [43], while discrepancies of 6.2–8.6 $m^3/h/m^2$@50 Pa were observed in six timber-framed dwellings built to CSH 4, resulting in 50% higher heat loss [44]. Such discrepancies are prevalent in Passivhaus dwellings, although the gap is considerably smaller up to 0.7 $m^3/h/m^2$@50 Pa [45,46] between design target and actual measurement. Pan analysed data from 287 post-2006 new build dwellings in UK to understand the influencing factors for airtightness and found that critical factors include management context, build method, dwelling type as well as their interactions. A two-way interaction between dwelling type and build method was highlighted, suggesting that the influence of these two factors on measured air permeability is not synchronous but interactive. The analysis reported also that the dwellings built with precast concrete panels have significantly higher airtightness levels than timber-framed dwellings, whilst dwellings in masonry and reinforced concrete frame were found to be the worst [47].

Co-heating tests are currently the only established method of determining the thermal performance of a whole building envelope; the test is performed by heating the inside of an unoccupied dwelling to an artificially elevated internal temperature (25 °C in the UK) over a specific period of time to calculate the heat loss coefficient (HLC) for the dwelling. However the extent of publicly-available data on whole house heat loss results is not extensive. Nevertheless, the number of dwelling undergoing such tests is increasing, which reflects the recognised need to investigate post-construction performance. An investigation on 3 dwellings built to CSH 6 and EcoHomes Excellent highlighted deviations from the SAP calculations in the range of 3–23% [43], while a study on 25 dwellings built to Part L1A 2006 or better yielded to HLC values up to 1.5 times higher than predicted, denoting an average gap of 50% [48]. A wide range of discrepancies has been reported between measured and expected HLC of some CSH 4 dwellings; 12–15% in two detached dwellings [49], 54% across 6 timber-framed homes [44] and up to 131–189% across 7 dwellings of different construction types [41]. The performance evaluation of two detached timber houses revealed deviations of 8% and 21% in spite of both dwellings having achieved exceptional airtightness levels, beyond the design expectations [50]. Another study of 7 timber dwellings reported deviations in the range of 6–21% in 6 of the cases [51]; similarly, the fabric performance gap of 3 timber and masonry was found to vary from 6 to 18% [46]. Higher HLC values than calculated have been identified also in Passivhaus constructions, although the gap is generally of a lower magnitude.

Further evidence of the building fabric performance gap is provided by in-situ measurements of thermal transmittance (U-value). The large-scale study at Stamford Brook is a representative example in which the effective U-value of external walls of retrofitted dwellings was found to be twice the designed values, and those of floors and ceilings nearly three times [40]. Another study of 25 dwellings of different type and construction found that the measured whole building U-value was over 1.6 times higher than prediction [48]. Deviations from the design targets have been seen in Passivhaus dwellings as well, however, similarly to the air permeability and whole house heat loss, the thermal transmittance gap appears to be much lower and often negligible; in-situ measurements of external walls and roofs have revealed discrepancies in the range of 0.01–0.06 $W/m^2 K$ and 0.05–0.06 $W/m^2 K$ respectively [45,46,50]. Despite the wealth of studies on measuring the thermal performance of building fabric of dwellings, these are largely case-study based and not comparable. The present study seeks to adopt a statistical approach to undertake cross-project analysis of fabric thermal performance data for a large number of new-build dwellings in the UK, so as to predict the likely occurrence of this gap across the population.

3. Methods and data

The study uses *as designed* and *as built* fabric thermal performance dataset gathered through 53 building performance evaluation (BPE) studies of new build low energy dwellings in the UK. The studies were part of a national £8 million 'BPE programme' (2010–2014) funded by UK Government (Innovate UK) [52], and were carried out in 44 developments located in Wales, Northern Ireland, Scotland and predominantly England. The size of developments ranged from a single dwelling up to over 787 dwellings. The portfolio of domestic buildings can be considered to be exemplary compared with industry averages.

The thermal performance of building fabric analysed in this study are the results of a range of diagnostic field tests carried out during the BPE programme, including *air permeability* test, *thermal transmittance* (U-value) measurements, *whole house heat loss* measurements (co-heating test) and *infra-red thermography*. Air permeability is a measure of the air tightness of the building associated with the uncontrolled infiltration or loss of air through cracks and gaps in the building fabric. It is defined as air leakage rate per hour per square metre of envelope area at a test reference pressure differential across the building envelope of 50 Pa. Accordingly, it is an inherent influencer of heating and cooling energy, and therefore a critical factor to grasp in the design and construction of low energy dwellings. An air permeability test, sometimes referred to as ‘air leakage’ or ‘air pressure testing’, is a recognised method of measuring the extent to which air is lost through leaks in the building fabric. The test, is detailed in ATTMA TSL1 [53] for dwellings. It involves the pressurisation (or depressurisation) of the building by means of variable speed fan(s) installed to a suitable external opening while the remaining openings are closed and vents are shut or sealed. The resulting difference between the external and internal pressure is used to calculate the permeability of the building envelope. Beyond the basic method, the test can be extended to include both pressurisation and depressurisation (in this case the final result is the average of the two values) and smoke test for the identification of air leakage pathways. In England, Wales and Northern Ireland the pressurisation testing of dwellings is a standard requirement of the Building Regulations since 2006 which currently set airtightness limit of $10\,m^3/h/m^2@50\,Pa$, while in 2010 became mandatory also in Scotland.

Thermal transmittance measurements (W/m^2K) assess the effectiveness of specific elements of the building fabric as insulators. In-situ measurements are carried out with heat flux sensors that provide a direct measure of the heat flux from a surface through a construction element. The method, detailed in ISO 9869 [54], can be used to determine the U-value of individual construction materials or the U-value of building elements comprising several layers. Its value lies in providing data that enables investigative examination of a range of heat loss mechanisms and can be particularly useful if undertaken in conjunction with whole house heat loss measurement.

Heat loss in a dwelling is a combination of conduction, convection and radiation through the dwelling fabric (fabric loss) and via air leakage (background ventilation loss). The whole house heat loss test, also called as co-heating test, is a method of measuring heat loss through building fabric and background ventilation of an unoccupied dwelling. The method was developed by Leeds Beckett University [55] and involves heating a dwelling electrically with electric resistance point heaters so as to maintain a constant internal temperature (typically 25 °C) over a specific period of time, typically 1–3 weeks. By measuring the amount of electrical energy required to maintain the internal temperature for each day, the daily heat input (in Watts) to the dwelling can be determined. The heat loss coefficient for the dwelling can then be calculated by plotting the daily heat input against the daily difference in temperature between the inside and outside of the dwelling (ΔT). The resulting slope of the plot gives the Heat Loss Coefficient (HLC – in W/K) of the whole dwelling. In most cases, a correction needs to be applied to account for any solar energy gain during the test. In order to obtain a sufficient ΔT (generally 10 °C or more), the test should be carried out in the winter months and during the post-construction stage.

Whilst the fabric tests detailed above, provide performance measurements, they do not necessarily offer insight into where the performance is being compromised. For this reason, thermal imaging or infrared thermographic surveys have been conducted in the BPE studies. These were carried out internally and externally to the dwellings, using a handheld thermal camera which depicts the intensity of infrared radiation emitted by the surfaces and therefore the heat differential of objects in the view based on the materials emission values. The technique, detailed in BS EN 13,187 [56], is often used as a diagnostic tool to identify anomalies in construction which may be the result of gaps in insulation layers, different insulation characteristics, air movement within the structure, or more usually a combination of all three. It is therefore particularly effective in combination with other techniques, for example during an AP test, by directing the use of smoke test to specific areas of the building, focusing attention on construction details that may be performing poorly, ensuring that U-value measurements are conducted at locations that adequately represent the area to which they relate. The ideal conditions for thermography include an indoor-outdoor temperature difference of at least 10 °C, no precipitation and wind speed of no more than 5 m/s for external surveys.

3.1. Dataset and analysis approach

The database for the meta-study was built using a range of outputs from the BPE programme such as the final report, the SAP[1] and the DomEARM[2] spreadsheets of each study within the programme. SAP, the Standard Assessment Procedure, is the methodology used by the UK Government to assess and compare the energy and environmental performance of dwellings [57]. DomEARM is the energy assessment and reporting methodology for domestic applications developed by Ove Arup and Partners Ltd in collaboration with Oxford Brookes University [58]. The study database comprises fabric performance data of 188 dwellings on air permeability, whole house heat loss, external wall and roof U-values, thermal imaging and contextual data such as floor area, build form, construction system and ventilation strategy.

The gathered data were subjected to quality checks to ensure high fidelity of the developed database which comprised 138 non-Passivhaus (NPH) and 50 Passivhaus (PH) dwellings, including 94 houses, 89 flats and 5 bungalows with floor areas from $37\,m^2$ to $346\,m^2$, designed to diverse standards from Passivhaus and Fabric First approach to Code of Sustainable Homes (CSH 2–6) and Building Regulations. Fig. 1 summarises the percentage distribution of the physical characteristics for the PH and NPH dwellings. The type of construction ranged from structural insulated panels (SIPs), concrete and steel to traditional masonry (73 out of 188, 39%) and timber frames (80 out of 188, 43%) which represent typical construction systems in the UK. In terms of ventilation strategy, natural ventilation (NV) and mechanical extract ventilation (MEV) were adopted in 10% and 5% of the dwellings respectively, whereas the overwhelming majority (85%) used Mechanical Ventilation with Heat Recovery (MVHR) due to the high thermal standards adopted. The most common tenure type across the dwellings was social housing (133 out of 188; i.e. 71%).

The meta-study adopted a statistical approach to assess the difference between as design and as build air permeability, thermal transmittance and whole house heat loss of dwellings from comparable BPE studies (that followed a consistent approach to data collection), thus allowing for conclusions to be applicable to the wider new build population. The quantitative performance data at the dwelling level were analysed by means of the Statistical Package for Social Sciences (SPSS), while the more qualitative thermal imaging data were analysed at the development level. Due to data availability, the respective sample sizes varied between 188 dwellings for air permeability, a subset of 62 dwellings for thermal transmittance and a subset of 29 dwellings for heat loss (Table 2). Each dwelling is represented by a unique ID (e.g. D1, D2, D3, etc.) that is consistent throughout the paper.

Descriptive statistics were analysed for each sample of data, which included the average, minimum and maximum values of the ‘performance gap’ in terms of air permeability, external wall U-values, roof U-values and whole house heat loss for Passivhaus and non Passivhaus dwellings. The analysis of standard deviation was used to identify the

[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.

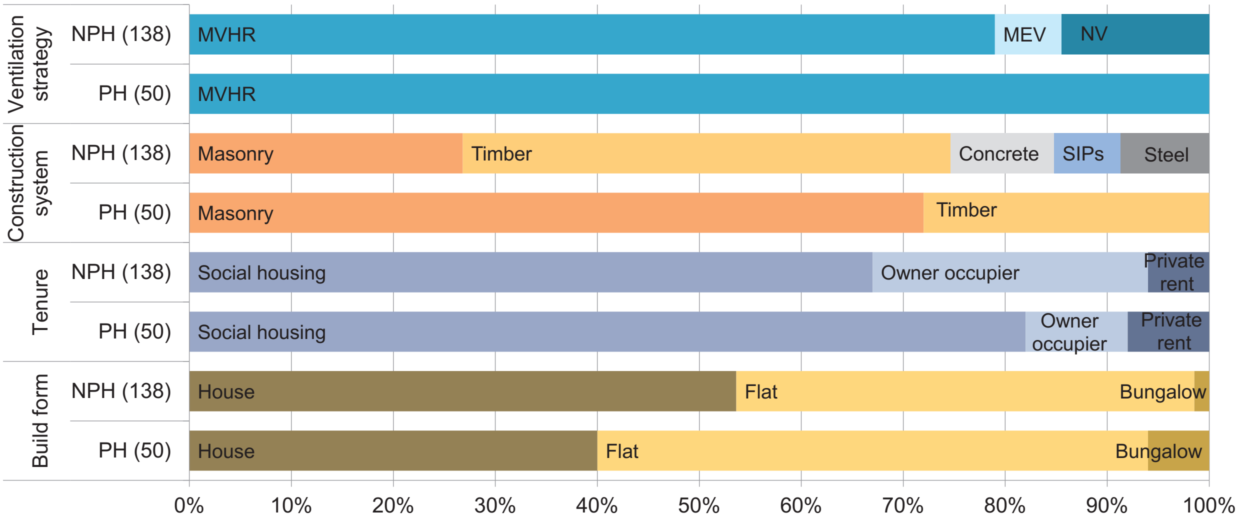

Fig. 1. Build form, tenure type, construction system and ventilation strategy for the 50 Passivhaus (PH) and 138 non-Passivhaus (NPH) dwellings in the study database.

Table 2
Sample size of building performance data analysed.

	Air permeability (N. of dwellings)	External wall U-value (N. of dwellings)	Roof U-value (N. of dwellings)	Whole house heat loss (N. of dwellings)	Thermal imaging (N. of developments)
Passivhaus	50	14	5	6	10
Non-Passivhaus	138	48	15	23	34
Total	188	62	20	29	44

extent of the gap. Regression analyses were applied to investigate correlations between building fabric characteristics and performance gap, so as to identify the cases in which the gap is more likely to occur. 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.

4. Results

4.1. Designed and measured air permeability

Designed and measured air permeability data were reviewed for 188 dwellings in 43 developments. The data were derived from air permeability tests conducted to the ATTMA standard [53], though the test had been extended to include both pressurisation and depressurisation with the final air permeability result represented by the average of the two. The average measured air permeability over the 188 dwellings (3.8 $m^3/h/m^2$@50 Pa) was marginally lower than the respective design value (4.0 $m^3/h/m^2$@50 Pa), however the median values of design and measured air permeability were 3.0 $m^3/h/m^2$@50 Pa and 4.0 $m^3/h/m^2$@50 Pa respectively denoting a performance gap. Surprisingly there was a weak correlation between designed and measured air permeability for PH (R = 0.35), and NPH (R = 0.24) dwellings (Fig. 2a), which is why a large number of dwellings (96 out of 188; 51%) failed to meet the designed air permeability levels (Fig. 3).

The designed air permeability was in the range of 0.4–0.6 $m^3/h/m^2$@50 Pa for PH, while for NPH it ranged from 1.5 $m^3/h/m^2$@50 Pa in a one-off dwelling to 10 $m^3/h/m^2$@50 Pa which is the minimum requirement set in Part L of the Building Regulations. The results from the air permeability tests indicated that over half the PH dwellings (29 out of the 50; i.e. 58%) did not meet the design target, presenting on average 0.5 $m^3/h/m^2$@50 Pa higher air permeability (Table 3). The respective fraction of NPH dwellings was slightly lower (67 out of 138; i.e. 49%), however the average gap was substantially higher at 1.9 $m^3/h/m^2$@50 Pa (Table 3). The maximum deviation from the design target was further representative of the extent of the airtightness performance gap; the widest gap was 1.3 $m^3/h/m^2$@50 Pa among PH dwellings, and considerably higher at 6.3 $m^3/h/m^2$@50 Pa among NPH dwellings.

Further scrutiny of the AP data revealed a strong tendency of NPH envelopes designed to 5 $m^3/h/m^2$@50 Pa or better to demonstrate an air permeability gap. The regression model depicted in Fig. 2b (significant at $p < 0.05$) shows that the lower the designed air permeability, the higher was the difference with the measured air permeability, indicating the importance of workmanship in achieving high levels of airtightness. The regression model indicated that for every 1 $m^3/h/m^2$@50 Pa decrease in design air permeability, the gap between actual and intended AP increased by 0.8 $m^3/h/m^2$@50 Pa, with the cut-off point being at 5 $m^3/h/m^2$@50P.

The analysis of AP data by construction systems for NPH dwellings revealed that concrete and timber-framed constructions performed better than designed, while masonry dwellings underperformed by an average of 1.3 $m^3/h/m^2$@50 Pa demonstrating the need for greater attention to detail (Fig. 4). Interestingly the results for PH dwellings showed minimal deviations from the design target for both masonry and timber constructions, indicating that the quality of detailing and workmanship is more important than the type of construction.

As shown in Fig. 5, when airtightness was analysed by ventilation strategies (centralised MVHR, MEV and NV), the small sample size of dwellings with MEV and NV was seen to perform better than designed. Although dwellings with MVHR systems had considerably lower designed and measured air permeability, by 0.3 $m^3/h/m^2$@50 Pa and 1.8 $m^3/h/m^2$@50 Pa with respect to MEV and NV dwellings respectively, majority of NPH dwellings with MVHR (88 out of the 109, i.e. 81%) had measured AP higher (worse) than 3.0 $m^3/h/m^2$@50P when evidence suggests that the energy required to run the MVHR systems is likely to be greater than the energy saved, resulting in increased energy use overall [59].

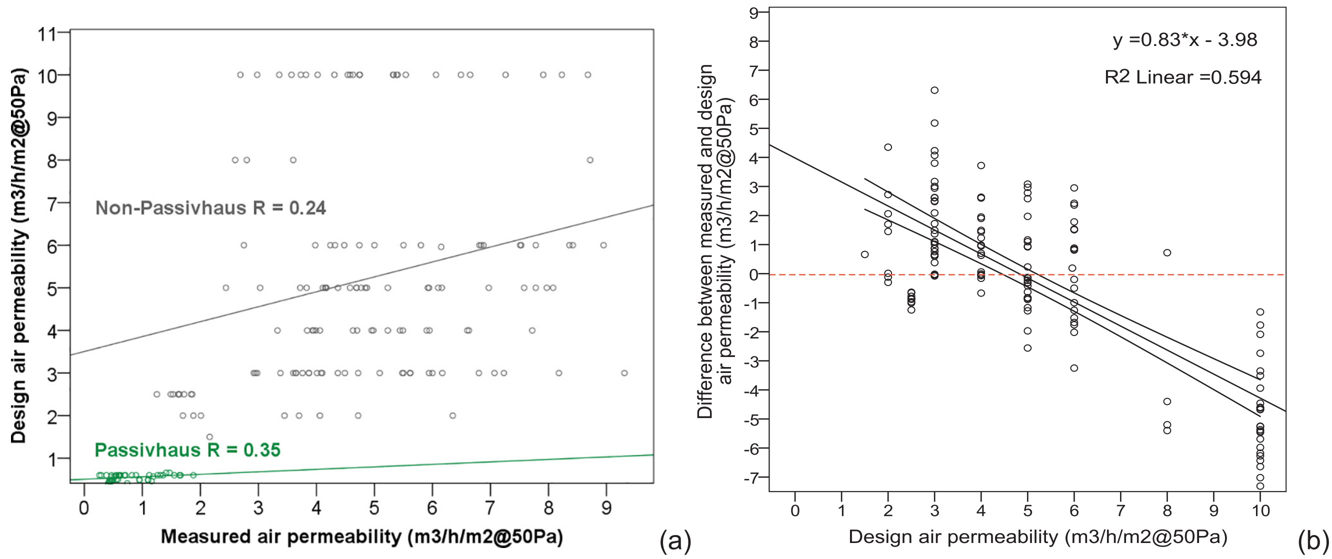

Fig. 2. (a) Relationship between design and measured air permeability for 50 Passivhaus and 138 non-Passivhaus dwellings and (b) rate of change of the difference between measured and design air permeability with changes in the design target for the 138 non-Passivhaus dwellings.

4.2. Thermal transmittance

In assessing fabric performance, in-situ measurements are particularly useful in determining the U-value of elements of the building envelope (walls, roofs) comprising several layers, thus enabling the investigation of a range of heat loss routes. The measurements in the dwellings reviewed were taken by means of heat flux plates positioned on the elements under investigation and were carried out in accordance with ISO 9869 [54]. Design and in-situ external wall U-value data were reviewed for 14 PH and 48 NPH in 37 developments. The mean measured U-value across the 62 dwellings was higher (worse) than the design value by 0.06 W/m^2 K (i.e. 35% higher). The respective difference was only 0.03 W/m^2 K (27% higher) among PH dwellings and wider at 0.07 W/m^2 K (39% higher) among NPH dwellings (Table 4). The in-situ measurements revealed higher values than designed in 37 out of 62 (i.e. 60%) dwellings (8 out of 14 Passivhaus and 29 out of 48 non-Passivhaus) while in 10 cases the measured U-value was beyond the Part L1A limit (Fig. 6a). The average gap derived from the 37 underperforming dwellings was 0.12 W/m^2 K while the corresponding gap in PH and NPH dwellings was at 0.05 W/m^2 K and 0.14 W/m^2 K respectively.

The external wall U-value data were further analysed against the construction system revealing higher mean in-situ U-values for dwellings built with masonry, concrete and SIPs and lower for timber and steel (Fig. 7a). Comparing the two traditional construction systems in the UK, timber frames seem to perform 0.14 W/m^2 K better than masonry construction, which was also found to exhibit the highest difference between design and measured external wall U-value (0.15 W/m^2 K).

Design and in-situ roof U-value data were reviewed for 20 dwellings (5 Passivhaus and 15 non-Passivhaus) in 14 developments. The mean measured U-value was higher than the design value by 0.08 W/m^2 K

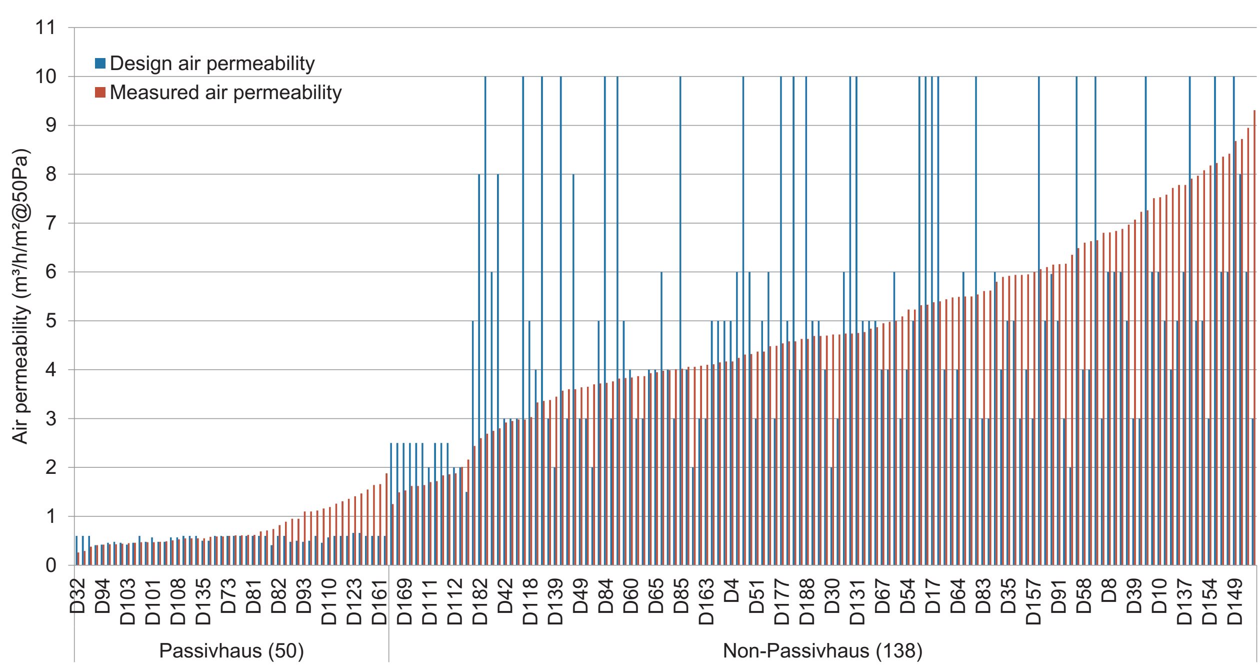

Fig. 3. Design and measured air permeability for 50 Passivhaus and 138 non-Passivhaus dwellings.

Table 3
Descriptive statistics of designed and measured air permeability for PH and NPH dwellings.

		Non-Passivhaus			Passivhaus		
		Total sample (N = 138)	$AP_m > AP_d$ (N = 67)	$AP_m < AP_d$ (N = 71)	Total sample (N = 50)	$AP_m > AP_d$ (N = 29)	$AP_m < AP_d$ (N = 21)
Design air permeability AP_d ($m^3/h/m^2$@50 Pa)	Mean	5.2	3.9	6.5	0.6	0.5	0.5
	Min	1.5	1.5	2	0.4	0.4	0.4
	Max	10	8	10	0.6	0.6	0.6
	SD	2.6	1.4	2.9	0.1	0.1	0.1
Measured air permeability AP_m ($m^3/h/m^2$@50 Pa)	Mean	4.9	5.8	4.1	0.8	1	0.5
	Min	1.3	2	1.3	0.3	0.5	0.3
	Max	9.3	9.3	8.7	1.9	1.9	0.6
	SD	1.9	1.7	1.6	0.4	0.4	0.1
$AP_{mp} = AP_m - AP_d$ ($m^3/h/m^2$@50 Pa)	Mean	−0.3	**1.9**	−2.4	0.2	**0.5**	−0.1
	Min	−7.3	0.01	−7.3	−0.3	0.01	−0.3
	Max	6.3	6.3	−0.01	1.3	1.3	0
	SD	2.8	1.3	2.3	2.8	0.4	2.3

(i.e. 62% higher): the average difference among PH dwellings was 0.04 W/m^2K (44% higher) while for NPH dwellings it was higher, at 0.10 W/m^2K (71% higher) (Table 4). The roof element had failed to perform to its design intention in 15 (4 Passivhaus and 11 non-Passivhaus) out of the 20 dwellings (Fig. 6b) with the average underperformance being 0.12 W/m^2K. Similar to the thermal transmittance of external wall, the roof U-value discrepancies were lower at 0.04 W/m^2K for PH dwellings and higher at 0.15 W/m^2K for NPH dwellings.

4.3. Whole house heat loss

Whole house heat loss data were available for 6 Passivhaus and 23 non-Passivhaus buildings across 21 housing developments. The whole house heat loss (co-heating) tests had mostly been undertaken in accordance with the Leeds Becket University protocol [55]. The predicted heat loss coefficient (HLC) across the 29 dwellings ranged from 36.6 W/K to 337.8 W/K presenting a mean value of 92.6 W/K (Table 4). The majority of dwellings (20 out of 29; i.e. 69%) were seen to underperform showing an average gap of 32.8 W/K, while deviations up to 127 W/K were observed (Fig. 8). About 5 out of 6 PH dwellings and 15 out of 23 NPH dwellings underperformed in terms of whole house heat loss, presenting an average gap of 4.5 W/K and 42.1 W/K respectively.

Overall, however, the mean measured HLC from the 29 dwellings (109.4 W/K) can be considered close to the mean predicted HLC (92.6 W/K) since the average difference, 18%, is close to the generally acceptable discrepancy of up to 15%. The percentage deviation across the total sample of PH dwellings was only 5% but significantly higher at 20% for NPH dwellings (Table 4). Further analysis of the HLC data

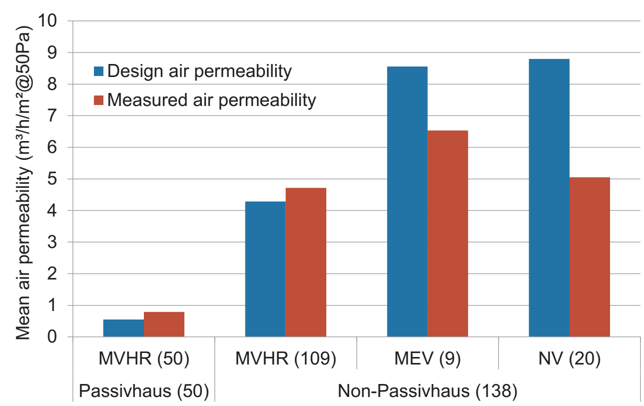

Fig. 5. Designed and measured air permeability by ventilation strategy for 50 PH and 138 NPH dwellings.

revealed that mean in-situ HLC of most construction systems was higher than the respective predicted value (Fig. 7b). The highest performance gap was identified in masonry dwellings (41.1 W/K) which were seen to perform on average 20.4 W/K worse than timber-framed dwellings.

4.4. Infrared thermal imaging

Thermal imaging surveys (internal and external) were conducted across all 44 housing developments to identify the likely reasons for the fabric performance gap. A review of the qualitative data gathered from

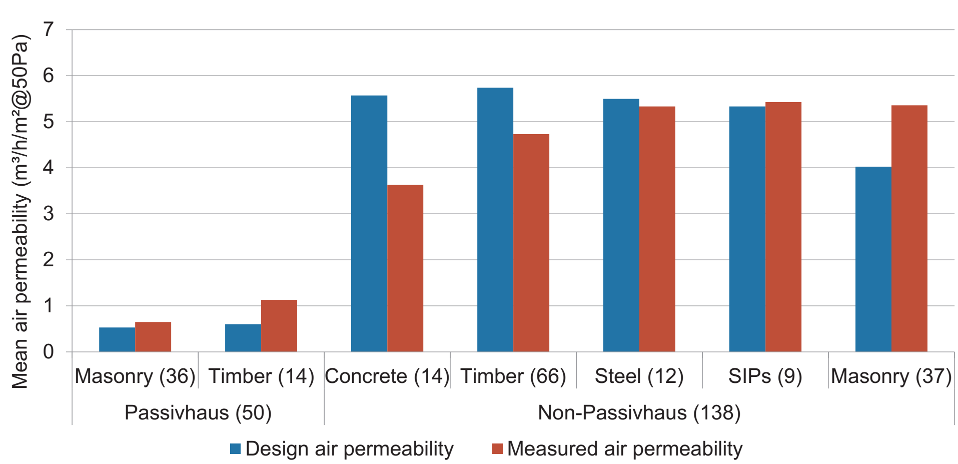

Fig. 4. Mean designed and measured air permeability by construction system for 50 PH and 138 NPH dwellings.

Table 4
Descriptive statistics of designed and measured external wall and roof U-values and heat loss coefficients.

	Design External Wall U-values ($W/m^2 K$)				In-situ External Wall U-values ($W/m^2 K$)			
	Mean	Min	Max	SD	Mean	Min	Max	SD
All dwellings (N = 62)	0.17	0.09	0.27	0.04	0.23	0.09	1.27	0.17
Passivhaus (N = 14)	0.11	0.09	0.15	0.02	0.14	0.10	0.20	0.03
Non-Passivhaus (N = 48)	0.18	0.11	0.27	0.04	0.25	0.09	1.27	0.19
	Design Roof U-values ($W/m^2 K$)				In-situ Roof U-values ($W/m^2 K$)			
	Mean	Min	Max	SD	Mean	Min	Max	SD
All dwellings (N = 20)	0.13	0.09	0.18	0.03	0.21	0.09	0.65	0.17
Passivhaus (N = 5)	0.09	0.09	0.10	0.01	0.13	0.09	0.16	0.03
Non-Passivhaus (N = 15)	0.14	0.10	0.18	0.02	0.24	0.11	0.65	0.18
	Design HLC (W/K)				Measured HLC (W/K)			
	Mean	Min	Max	SD	Mean	Min	Max	SD
All dwellings (N = 29)	92.6	36.6	337.8	58.5	109.4	38.1	245.0	57.1
Passivhaus (N = 6)	46.3	36.6	63.6	11.5	48.8	38.1	60	7.9
Non-Passivhaus (N = 23)	104.6	36.7	337.8	59.9	125.2	39.4	245	53.6

thermal imaging was undertaken at development level and the defects identified were classified according to their location within the building fabric into eight categories, as shown in Table 5. Common 'weak points' identified in nearly half of the case study developments were at the eaves level as well as junctions and joints. The majority of developments (84%) including all PH sites showed heat loss around windows and doors, indicating the need to improve detailing, specification and workmanship. In 25% of the developments, thermal bridging was evident around service penetrations and fittings such as extract fans and MVHR supply vents. Other defects included unregulated heat gain from inadequately insulated pipework.

The examination of the thermographic data against the construction system adopted showed that timber frame dwellings have thermal bridging issues with a frequency of occurrence comparable to masonry dwellings, in spite of the expected advantages in workmanship associated with offsite timber construction (Table 5). Thermal weakness in junctions and joints were found in 8 out of 20 of developments with timber-framed dwellings and in 7 out of 14 of developments with masonry dwellings. A comparison between the NPH (34) and PH (10) developments revealed a significantly lower frequency of defects amongst the latter, highlighting the importance of attention to detail that is integral in a PH approach. Defects associated with roofs, eaves and loft spaces for instance, were revealed in only 2 out of 10 PH developments and in over half (18 out of 34) of the NPH developments. Moreover, thermal deficiencies in junctions and joints were found in over 60% (21 out of 34) of the NPH developments and none in the PH developments (Table 5).

4.5. Cross-analysis of fabric performance data and space heating energy use

Available data from AP tests, thermal transmittance measurements and co-heating tests were cross-analysed for 28 (6 PH and 22 NPH) dwellings (Table 6). Despite the small sample of PH dwellings with a complete set of fabric performance data, it is evident that PH dwellings perform well across all the three in-situ tests, indicating the robustness of the PH standard. On the other hand, 13 out of 22 NPH dwellings showed a gap in fabric performance in two out of the three in-situ tests, indicating that the prevalence of building fabric underperformance (Fig. 9). Interestingly there were a few NPH dwellings (such as D12 and D17 in Table 6) in which the AP gap was very low, but the performance gap in terms of whole house heat loss and/or thermal transmittance was quite high (Fig. 9). This is substantiated by the fact that no significant correlations were found between the results of the three in-situ tests, thereby highlighting the need to combine the various in-situ tests into a comprehensive fabric performance test so as to establish the actual performance of building fabric.

To investigate the impact of fabric thermal performance on space heating, data on the actual (in-use) space heating energy use were assessed with measured AP and HLC values. Fig. 10a indicates that 65% of the variability in space heating can be explained by AP in PH dwellings, whereas there was no relationship observed between the two ($R^2 = 0.07$) for NPH dwellings. These findings imply that high level of airtightness (measured low AP) on its own may not lead to low space heating energy use, since there are other factors such as type of heating system, controls, and occupant behaviour that are also important factors. Conversely, 90% of the variability in space heating energy use can be explained by HLC values albeit for a small sample of nine dwellings (Fig. 10b), indicating that HLC is likely a better determinant of space heating energy air tightness alone.

The cross-analyses does imply that a comprehensive building fabric test would be more effective in assess building fabric performance than just an air permeability test, as currently required by Building Regulations.

4.6. Estimating the probability of a fabric performance gap in the population

The quantity and quality of data on AP performance gap allowed Monte Carlo simulations and probability density function (PDF) analysis to be undertaken to investigate the probability of an AP performance gap occurring in the population of new build housing. The Monte Carlo simulations are used to model the probability of different outcomes in a process that cannot easily be predicted due to the intervention of random variables. PDF is a statistical expression that defines a probability distribution for a continuous random variable. When it is graphically portrayed the area under the curve indicates the interval in which the variable will fall, while the total area in this interval of the graph equals the probability of the continuous random variable occurring. In this application, the input data used in Monte Carlo simulations were the designed (AP_d) and measured (AP_m) air permeability. Firstly, the best fit distributions of design and measured air permeability were identified by means of the Anderson-Darling and Kolmogorov-Smirnov goodness of fit tests. Then the data were used as inputs to the simulation analysis which was conducted separately for PH and NPH dwellings as well as for different NPH sub-datasets shown in Table 7. The simulation plan was as follows: the maximum number of cases to be simulated was set to 100,000 while the stopping criterion was set to 1% of the mean value, meaning that cases were generated until the confidence interval of the mean of the target (i.e. the difference between measured and designed air permeability, AP_{mp}), at the 95% confidence level, was within 1% of the mean value. The number of simulated cases for each sub-dataset is shown in Table 7. The simulated data were subsequently used to determine the probability density function and its graphical illustration and its graphical illustration to evaluate the probability of an air permeability gap. The PDF mathematical expressions are explained in Ref. [60].

The "predicted" mean and median values of AP_{mp} were found to coincide at $-0.9\ m^3/h/m^2$@50 Pa for NPH and $0.3\ m^3/h/m^2$@50 Pa for PH dwellings (Fig. 11). In both cases this was close to the respective average difference between measured and design air permeability over the dwellings reviewed (Table 2). The reference line at the 95% point of

Fig. 6. Design and in-situ U-value of (a) external walls for 62 dwellings and (b) roof for 20 dwellings.

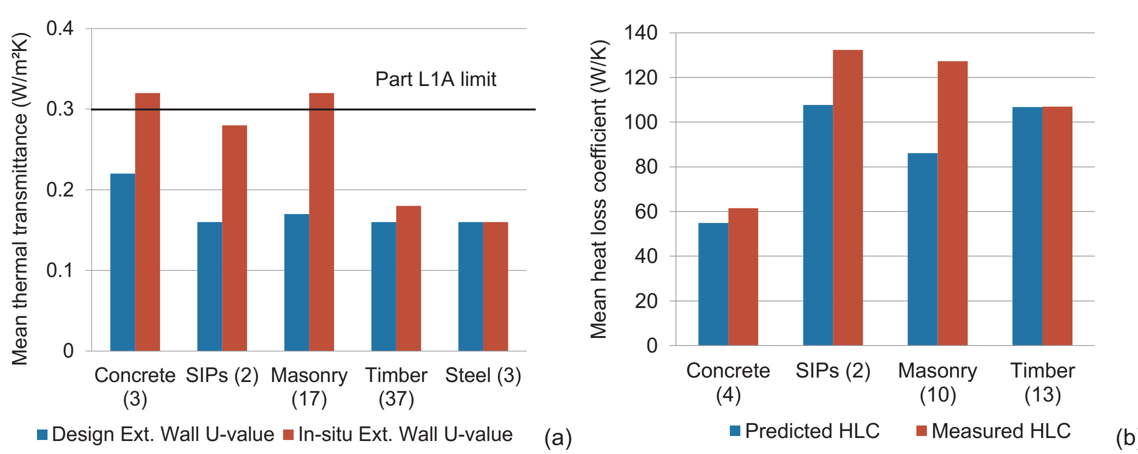

Fig. 7. Design and in-situ (a) external wall U-values for 62 dwellings and (b) HLC for 29 dwellings by construction system.

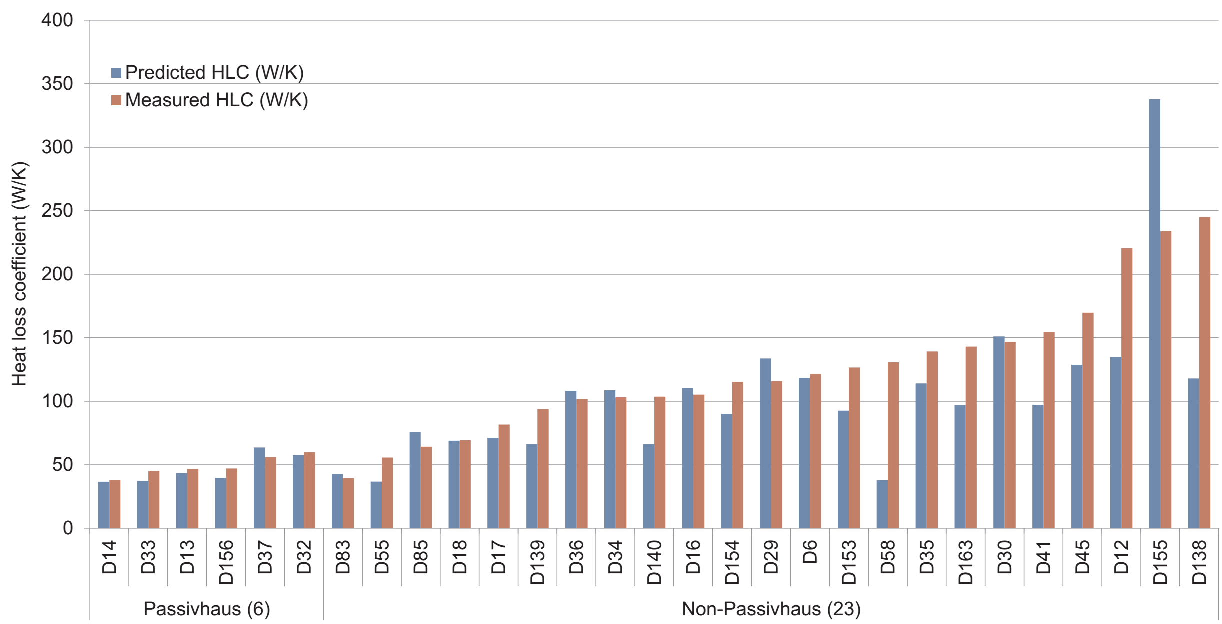

Fig. 8. Predicted and measured heat loss coefficient for 29 dwellings.

Table 5
Fabric related defects and frequency of occurrence from thermographic surveys of 44 developments.

	Roof/Eaves & loft space	Junctions & joints	Walls only	Ceilings only	Windows & doors	Fittings/Service penetrations	Slab/ground level	Other
Overall (44 developments)	20/44	21/44	15/44	11/44	37/44	10/44	4/44	11/44
Passivhaus (10 developments)	2/10	0/10	3/10	3/10	10/10	1/10	0/10	2/10
Non-Passivhaus (34 developments)	18/34	21/34	12/34	8/34	27/34	9/34	4/34	9/34

Table 6
Fabric thermal performance of dwellings with air permeability, HLC and U-value data.

	Dwelling ID	Build form	Floor area (m^2)	Construction system	Ventilation	Air permeability gap[a]	HLC gap[a]	Ext. wall U-value gap[a]	Roof U-value gap[a]
Passivhaus (6)	D14	Bungalow	66	Timber	MVHR	0.7	2	0.00	0.04
	D13	Bungalow	66	Timber	MVHR	0.3	3	0.00	0.04
	D37	House	101	Timber	MVHR	0.1	−8	−0.02	n/a
	D156	House	81	Masonry	MVHR	0.0	8	0.05	−0.01
	D33	House	78	Timber	MVHR	−0.1	8	−0.02	n/a
	D32	House	99	Timber	MVHR	−0.3	2	n/a	n/a
Non-Passivhaus (22)	D153	House	93	Masonry	MVHR	6.3	34	0.13	0.09
	D154	House	93	Masonry	MVHR	5.2	25	n/a	n/a
	D30	House	94	Timber	MVHR	2.7	−4	0.29	n/a
	D83	Flat	43	Concrete	MVHR	2.6	−3	0.21	n/a
	D58	Flat	70	Masonry	MVHR	2.6	93	0.05	n/a
	D138	House	103	Masonry	MEV	2.4	127	1.07	n/a
	D140	House	90	Masonry	MVHR	2.1	37	0.26	n/a
	D29	House	94	Timber	MVHR	1.7	−18	n/a	n/a
	D139	House	90	Masonry	MVHR	1.5	28	n/a	n/a
	D16	House	120	Timber	MEV	1.1	−5	n/a	n/a
	D163	House	90	SIPs	MVHR	1.1	46	0.26	0.01
	D6	House	87	SIPs	MVHR	0.9	3	n/a	n/a
	D35	House	84	Masonry	NV	0.9	25	n/a	n/a
	D45	House	121	Masonry	MVHR	0.9	41	n/a	n/a
	D155	House	329	Timber	MVHR	0.7	−104	−0.01	0.50
	D34	House	82	Timber	NV	0.2	−5	0.02	n/a
	D41	House	107	Timber	MVHR	0.0	57	n/a	n/a
	D36	House	98	Masonry	NV	−0.9	−6	−0.04	0.03
	D12	Bungalow	160	Timber	MVHR	−1.5	86	0.23	0.03
	D17	Flat	49	Concrete	MVHR	−4.6	10	n/a	n/a
	D85	House	107	Timber	NV	−6.0	−12	0.01	n/a
	D18	Flat	83	Concrete	MVHR	−7.3	0	n/a	n/a

[a] Measured minus design value.

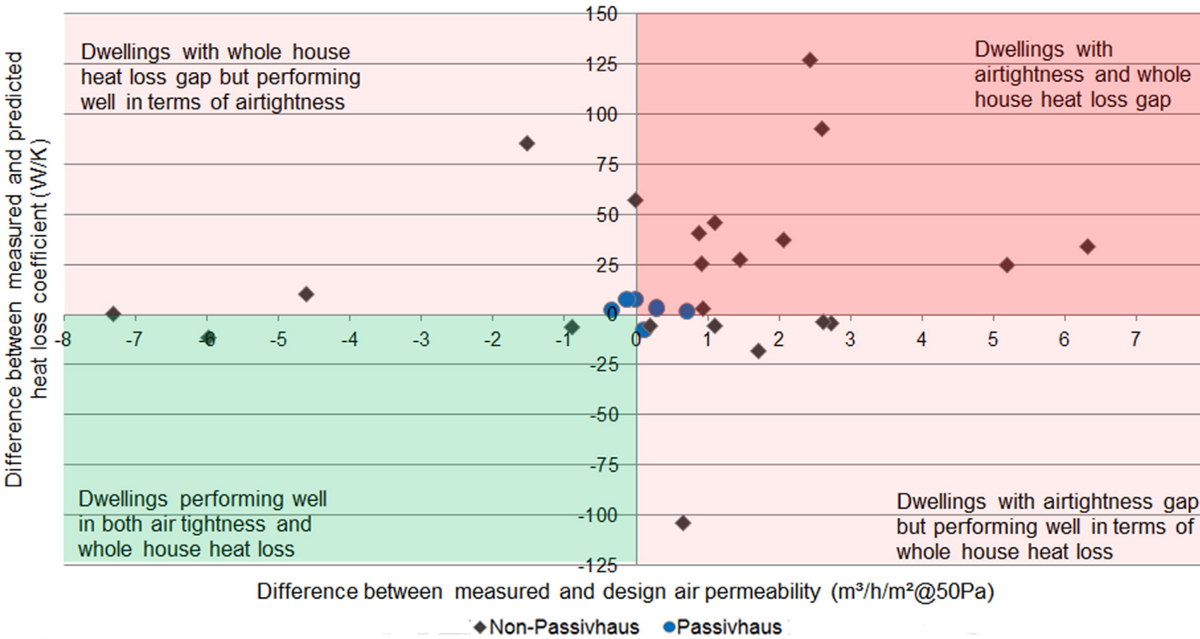

Fig. 9. Cross-analysis of air permeability and whole house heat loss data for 6 PH and 22 NPH dwellings.

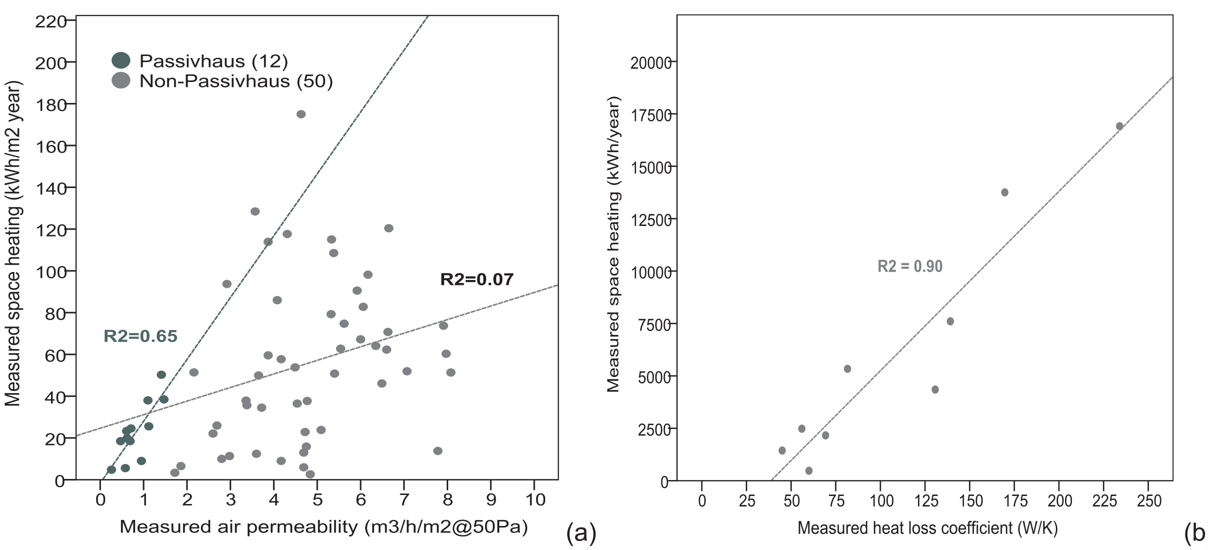

Fig. 10. Relationship between measured space heating energy and measured (a) air permeability for 62 dwellings (12 PH and 50 NPH) and (b) heat loss coefficient for 9 dwellings.

Table 7
Probability of air permeability gap and probability that the gap is within a certain range.

	No. of simulated cases	Air permeability ranges ($m^3/h/m^2$@50 Pa) and probability (%)						Probability of air permeability gap
		< 0	0–1	0–2	0–3	0–4	> 4	
Non-Passivhaus dwellings (N = 138)	100,000	62%	13%	23%	31%	35%	3%	38%
Non-Passivhaus dwellings with design air permeability ≤ 5 $m^3/h/m^2$@50 Pa (N = 90)	63,390	22%	21%	45%	63%	73%	5%	78%
Non-Passivhaus Houses with design air permeability ≤ 5 $m^3/h/m^2$@50 Pa (N = 54)	66,259	23%	21%	44%	61%	71%	6%	77%
Non-Passivhaus Flats with design air permeability ≤ 5 $m^3/h/m^2$@50 Pa (N = 36)	100,000	35%	26%	48%	59%	63%	1%	65%
		Air permeability range ($m^3/h/m^2$@50 Pa) and probability (%)						Probability of air permeability gap
		< 0	0–0.5		0–1	> 1	> 1.5	
Passivhaus dwellings (N = 50)	73,263	30%	44%		67%	4%	0%	70%

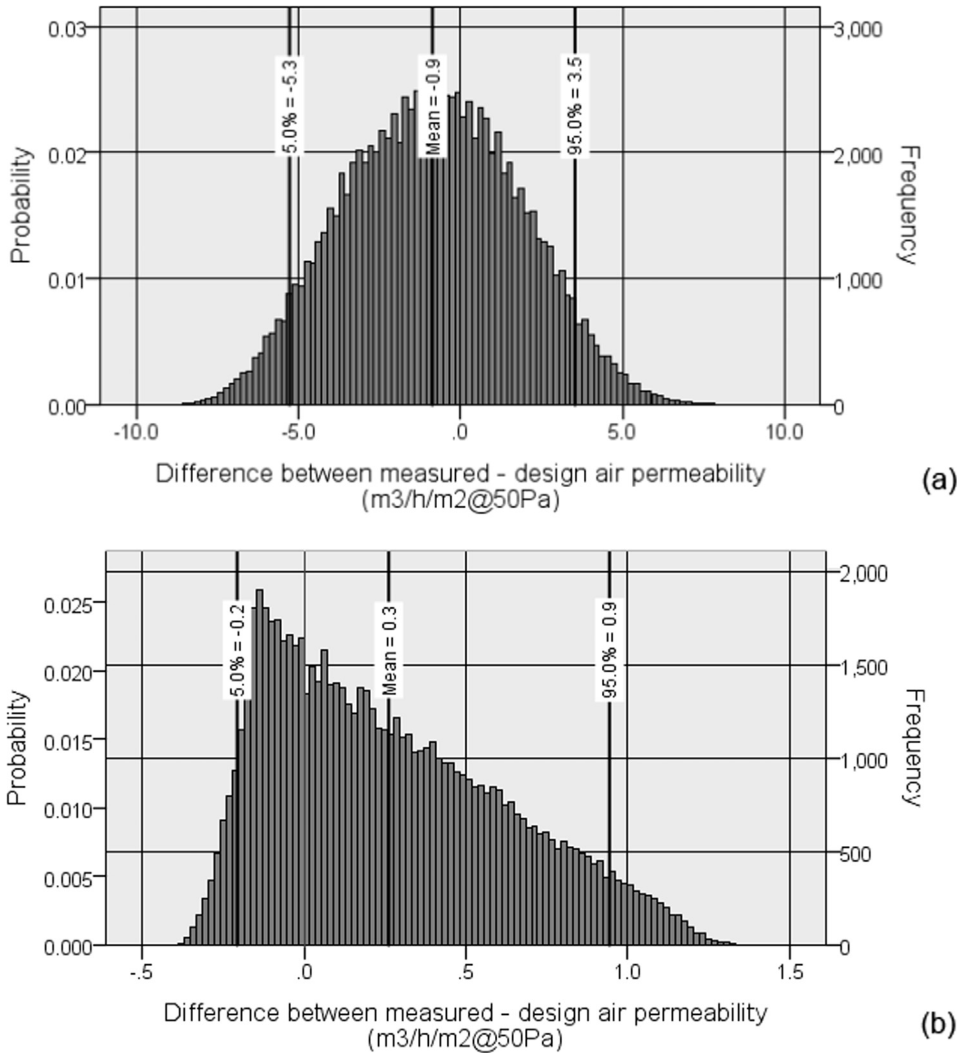

Fig. 11. Probability density function of air permeability performance gap for (a) NPH and (b) PH dwellings.

the probability density charts indicate a 95% probability that AP_{mp} is up to 3.5 $m^3/h/m^2$@50 Pa for NPH and up to 0.9 $m^3/h/m^2$@50 Pa for PH dwellings.

The results revealed that the probability of an air permeability gap is high at 38% for NPH dwellings and considerably higher at 70% for PH dwellings but with a much lower magnitude (Table 3). The probability that NPH dwellings demonstrate an air permeability gap in the range of 0–3 $m^3/h/m^2$@50 Pa is 35%, whereas for PH dwellings there is only 4% probability the gap is wider than 1 $m^3/h/m^2$@50 Pa (Table 7). Moreover, the analysis suggest that the likelihood of an air permeability gap in NPH constructions increases significantly from 38% to 78% for dwellings designed to 5 $m^3/h/m^2$@50 Pa or lower, while further investigation of this sample of dwellings showed that houses are more likely to underperform than flats, with the respective probabilities found at 77% and 65% respectively.

5. Discussion

The presence of significant fabric performance gap in this sample of dwellings that were designed and constructed to low energy standards by expert teams who were also aware of the monitoring and testing regime through the BPE programme, indicates a widespread prevalence of this gap across the population of new-build housing in the UK. The fabric performance gap was more profound in terms airtightness (Table 3) with the probability of an AP performance gap being considerably high (Table 7) across the population of new-build housing. Underperformance in terms of whole house heat loss and thermal transmittance of roof and external wall was of a much smaller magnitude and often within expectations. Despite this windows and doors were identified as weak points in nearly all case study developments, suggesting that thermal weakness around openings is endemic irrespective of the construction system (Table 5). Analysis of the thermal imaging survey data also revealed that thermal defects could occur anywhere within the building fabric, from junctions/joints and roofs to slab/ground level and service penetrations, highlighting the need to improve specification, detailing and workmanship.

The study has also reinforced the need to have updated *as-built* energy models with in-situ performance test data to reduce the performance gap by capturing the impact of design and construction changes on fabric thermal performance. Using statistical analyses, the study has for the first time, provided *adjusting factors* (Table 8) that can be applied to the design values of air permeability and thermal transmittance so as to reduce the magnitude of the performance gap. This will also help to improve the accuracy of energy models for new build dwellings in the UK.

Although a proportionally higher proportion of PH dwellings were found to deviate from the design intent, the magnitude and extent of the gap was small. On the other hand, the fabric performance gap was significant in NPH dwellings. This is why although the probability of underperformance in terms of airtightness was considerably higher for

Table 8
Suggested adjusting factors to be applied to design values (d.v.) for air-permeability and thermal transmittance (U-values).

Fabric performance parameter in models	Adjusting Factors	
	Passivhaus dwellings	Non Passivhaus dwellings
Air permeability	d.v. + 0.05 $m^3/h/m^2$@50 Pa	Masonry dwellings: d.v. + 1.3 $m^3/h/m^2$@50 Pa Other construction types: +0.83 $m^3/h/m^2$@50 Pa for every 1 $m^3/h/m^2$@50 Pa decrease in design air permeability starting from 5 $m^3/h/m^2$@50P
Wall U-value	if timber or steel d.v. + 0.03 W/m^2K if masonry, SIPs or concrete: d.v. + 0.05 W/m^2K	if timber or steel d.v. + 0.07 W/m^2K if masonry, SIPs or concrete: d.v. + 0.14 W/m^2K
Roof U-value	d.v. + 0.04 W/m^2K	d.v. + 0.10 W/m^2K

PH (70%) than NPH (38%) dwellings (Table 7), the measured gap was on average 0.5 $m^3/h/m^2$@50 Pa for PH and nearly four times higher for NPH dwellings (Table 3). Moreover, the average discrepancy between designed and measured performance of walls and roofs was minimal (0.04 W/m^2K) among PH dwellings, whereas it was almost three times higher in underperforming NPH dwellings. Similarly, the percentage deviation of whole house heat loss was only 5% for PH dwellings and four times higher for NPH dwellings. Whether evaluated by means of a single in-situ test (Tables 3 and 5) or by all the three in-situ tests (Table 6), PH dwellings were seen to perform well, indicating that good design, detailing and workmanship are key factors to reducing the fabric thermal performance gap.

The study has also revealed that the fabric performance gap was consistently larger for dwellings with masonry construction which is the most common type of build system in the UK. Compared to their timber counterpart, masonry builds were found to be leakier (Fig. 4) and have higher external wall thermal transmittance and whole house heat loss (Fig. 7). The AP gap of 1.3 $m^3/h/m^2$@50 Pa (Fig. 4) in masonry dwellings can be largely attributed to the common construction practice of plasterboard dry-lining and timber intermediate floors in the UK. Despite the expected link between airtightness and heating energy use, the study found a weak relationship between measured air permeability and space heating energy use in NPH dwellings, suggesting the influence of other factors such as building services, control and occupant behaviour. The strong relationship between whole house heat loss coefficient and space heating energy use, along with the fact that there were cases with minimal air permeability gap but high whole house heat loss or U-value gaps, reinforce the need to carry out a comprehensive fabric performance test rather than the piecemeal AP tests that are currently required for a sample of dwellings in a housing development.

6. Conclusions

The *cross-project* meta-study based approach has statistically assessed the building fabric thermal performance (in terms of measured air permeability, whole house heat loss, thermal transmittance and thermographic survey data) of 188 new build low energy homes (50 PH and 138 NPH dwellings), and revealed widespread deviations from the design intent across the majority of dwellings that were designed to high thermal standards.

The findings show that building to the design intent is not commonplace. The prevalence of the fabric performance gap, more profound in terms of airtightness, and the occurrence of thermal defects across the building fabric has highlighted the need for integrating better detailing and workmanship, and diagnostics to detect any deviation from the design intent. A comprehensive fabric test including air permeability, U-value (heat flux) measurements and thermal imaging survey, of all new build dwellings during the construction and post-construction stages would be more reliable than just an air permeability test that is presently conducted for a sample of dwellings. The results from these in-situ tests can also help to update as-built energy models to produce predictions closer to actual performance. Identifying the underlying causes of the fabric performance gap are relevant to a range of stakeholders (designers, engineers, constructors and policy-makers) involved in the design and delivery of dwellings. Ultimately insights from this study can help to improve the future versions of Building Regulations to require updated as-built models informed by results of in-situ testing, so that dwellings' thermal performance is as intended, thereby contributing to national carbon targets.

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