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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

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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-