UK Government

Loughborough University

Building Energy Research Group (BERG)

Project summary and options for future work

Gathering evidence to improve airtightness in the UK housing stock

Research Paper Number 2025/002

September 2025

Authors

Ben M. Roberts, Matthew Li, David Allinson, Chris Gorse, Kostas Mourkos, Vincenzo Rossi, Derek Thomson, and Kevin J. Lomas.

All are part of the School of Architecture, Building and Civil Engineering at Loughborough University, UK.

This report forms the fourth in a series of four produced by Loughborough University on behalf of DESNZ for the project “Gathering evidence to improve airtightness in the UK housing stock”.

Any enquiries regarding this publication should be sent to us at: EnergyResearch@energysecurity.gov.uk

Contents

Executive summary

This report summarises the *Gathering evidence to improve airtightness in the UK housing stock* project and provides options for future research. The project used literature reviews and secondary data analysis to produce four reports. Future work could follow from, and aim to fill, the literature and data gaps that have been highlighted in this project.

Report 1

Report 1 [1] focused on dwelling airtightness at stock level for Great Britain (GB)[1]. A literature review found there is a gap in knowledge regarding the current airtightness of the housing stock. New analysis for this project, using a dataset from low-pressure pulse tests (5,125 dwellings[2]), showed that:

- The mean air permeability of GB dwellings is 8.6 ± 3.3 $m^3/h.m^2$ @ 50 Pa, which is lower (more airtight) than previously thought.
- On average (mean and median), the most airtight GB dwellings were those built between 1965-1980, flats, and those with system-built walls. The least airtight GB dwellings were those built post-1990 (to present), semi-detached houses, and those with solid uninsulated external walls.
- However, large (and overlapping) interquartile ranges indicate that other factors may be influencing airtightness – the literature review suggested these factors could include floor type, degradation over time, weatherstrip detailing, quality of workmanship, and design targets/regulations (in newbuilds only).
- Improving all GB dwellings to have an air permeability of 5 $m^3/h.m^2$ @ 50 Pa or lower would require retrofitting 90% of the stock, but could reduce national heating energy demand by 15.2 TWh (6.9% of total space heating demand of the GB stock), with an average per-treated dwelling saving of 0.61 MWh (equal to 5% of median gas demand[3]), energy costs by £840 million (£33 per treated dwelling per year), and carbon emissions by 2,880 $ktCO_2e$[4].

[1] Insufficient data were available for Northern Ireland, so only GB dwellings were analysed.
[2] This was the largest dataset of airtightness in existing dwellings available to the researchers at the time of the study. The number of dwellings in the sample is almost 10 times greater than previous studies of stock-level airtightness in existing dwellings e.g., [5]. This dataset is also contemporary, with data collected up to October 2023, versus up to 2010 previously. A nationally representative airtightness dataset was produced by weighting a sample of 5,125 dwellings to the GB stock, based on built form, age band, and main wall construction type.
[3] Compared to 2023 data [34].
[4] This is a hypothesised national airtightness improvement scenario. No analysis was done regarding whether airtightness retrofits on this scale would be technically possible or economically viable.

Report 2

Report 2 [2] focused on infiltration estimation methods. The literature suggests that the commonly used infiltration estimation methods are unreliable[5], however most empirical validation studies were based on summertime measurements (small indoor-outdoor temperature differences), and so more research is needed to investigate the reliability of the methods in winter.

Analysis of secondary data to evaluate 12 infiltration estimation methods sourced from the literature revealed that:

- The proposed DESNZ Home Energy Model (HEM)[6] method estimated infiltration with greater accuracy and precision than the eleven other methods.
- The HEM infiltration estimation method was less reliable at low wind speeds because the method does not account for stack-driven infiltration.

This was based on a sample of 15 infiltration tests in one dwelling during summertime; further research would be needed to investigate the performance in winter and in more dwelling types.

A calibrated dynamic thermal model of a single existing[7] dwelling was used to investigate the effect of infiltration on summer overheating and winter heating demand. It showed that:

- If the estimated (higher) infiltration rate was used, the dwelling complied with Part O (overheating) of the Building Regulations.
- However, if the measured (lower) infiltration rate was used, the dwelling did not comply with Part O.
- This meant that a modelled building could pass Part O, but in reality, the building may be susceptible to overheating as the real infiltration rate may be lower, reducing the availability of ventilative cooling.
- Heating demand increased linearly as infiltration rate increased, but the dynamic thermal model was more sensitive to changes in infiltration than the steady-state model.

[5] The literature review did not reveal any prior validation studies of the method used in the Home Energy Model.
[6] Consultation version [33].
[7] Whilst Part O applies only to dwellings submitted to planning after June 2022, an existing dwelling was modelled as it provided the best quality information available at the time of the study to build a calibrated model with accompanying measured indoor temperatures and infiltration rate [8,9].

Report 3

Report 3 [3] focused on construction practices related to airtightness, unintended consequences of more airtight dwellings, and occupant ventilation practices. It showed that:

- There was insufficient evidence to reliably infer typical airtightness failure points by dwelling characteristic, but wet-plastered dwellings are said to be inherently airtight based on several case studies.
- Service penetrations, overreliance on secondary sealing, and poor workmanship are typical airtightness failure points.
- There is no research which links airtightness and build quality.
- The unintended consequences of more airtight construction can be ameliorated with sufficient ventilation, except for fire and smoke transport (which is poorly understood in this context). Further research is likely to impact our confidence in the estimate of the effect and is likely to change the estimate.
- Occupant ventilation practices are driven by responses to indoor and outdoor temperature. Barriers to ventilation use include a lack of knowledge of how to operate ventilation systems, particularly in relation to mechanical ventilation systems.
- Broader, nationally-representative conclusions on ventilation use in UK dwellings cannot be drawn because current studies use small sample sizes, case studies, or unrepresentative surveys.

Analysis of secondary data showed there to be no evidence that in-test, temporary sealing occurs during airtightness testing of existing dwellings, as evidenced by the lack of any clustering of airtightness results around compliance thresholds. Prior research had shown evidence of such a trend existing for newly-built dwellings.

Remaining knowledge gaps

Several knowledge gaps remain:

- What is the airtightness, infiltration, and ventilation rate of the **UK**[8] housing stock (especially in Northern Ireland where little data is available)?
- What other factors influence airtightness in UK dwellings (aside from age, built form, and wall construction type)?
- How can infiltration be reliably calculated from airtightness test results? This includes different dwelling types under a variety of weather conditions.
- How do different construction elements e.g., windows, party walls, vents, and chimneys, contribute to airtightness, infiltration, and ventilation?

[8] New analysis conducted in Report 1 of this project determined the airtightness of the GB housing stock, but there were insufficient data from Northern Ireland to quantify airtightness for the UK stock.

- How can more airtight construction be reliably and repeatably assured?
- How is ventilation[9] used in the UK stock, and how should it be used to minimise wintertime heat loss and summertime overheating while maintaining indoor air quality?

Options for future work

This scoping study for possible future work aims to address the remaining knowledge gaps identified following the research and reviews carried out in Reports 1 to 3. Seven research questions are proposed:

- RQ2.1: What is the airtightness of the UK housing stock?
- RQ2.2: What is the relationship between the blower door test and the low-pressure pulse test?[10]
- RQ2.3: How do the results of pressure tests relate to infiltration under natural indoor-outdoor pressure differences and can infiltration estimation methods be improved?
- RQ2.4: How do different physical construction elements contribute to airtightness, infiltration, and ventilation?
- RQ2.5: How can more airtight dwellings be achieved on-site in newbuild construction and retrofit?
- RQ2.6: What is the ventilation rate of the UK housing stock?
- RQ2.7: How and why is ventilation used in UK dwellings and by whom?

For each research question, a method to answer it is provided along with guidance on the scope, such as the necessary sample size. These are proposals only at this stage, not a commitment from DESNZ to commission research to answer the RQs.

[9] Ventilation refers to purpose-provided openings such as windows, passive vents, trickle vents, and intermittent and continuous mechanical ventilation.

[10] The airtightness datasets analysed in Report 1 and Report 3 were derived from low-pressure pulse tests. Another way of measuring airtightness in buildings is the fan pressurisation ('blower door') test. It was discussed in Report 1 that the DESNZ DEEP project found that inter-dwelling air leakage may be an artefact of the blower door test, rather than the low-pressure pulse test [20]. It will be important to establish if any differences between the two methods exists if the two are being used interchangeably to measure airtightness.

Introduction

In 2023, the Department for Energy Security and Net Zero (DESNZ) commissioned Loughborough University to deliver the *Gathering evidence to improve airtightness in the UK housing stock* project. The project addressed three research gaps:

- Research gap 1: to understand the baseline airtightness of the UK housing stock to inform future retrofit policies that aim to reduce wintertime heat loss and summertime overheating by improving airtightness.
- Research gap 2: to understand the limitations of the infiltration estimation method used in the Standard Assessment Procedure (SAP) to convert airtightness to infiltration[11].
- Research gap 3: to evaluate the effect of construction and operational practices on airtightness, infiltration, and ventilation.

Research gaps were addressed using a desk-based study comprising reviews of the existing literature, analysis of secondary datasets, and a scoping study for possible future work. Three reports have been produced prior to this one. Report 1 [1] addressed the first research gap, Report 2 [2] the second, and Report 3 [3] the third. The findings of each are summarised in this report alongside commentary on how successfully the objectives were achieved, and identification of the research gaps that could be addressed in future research.

The aim of this report is to provide options for the scope of potential future research work. The structure of any such work should be determined and designed using the reviews and analyses of this project to identify remaining evidence gaps.

The options for future research were chosen to address the proposed research questions in a cost-effective and time-efficient manner. For each research question, the study design, test location, sample size, and durations are given. In some cases, a range of sample sizes and a calculation of minimum detectable effect for each sample size is given. Also, in some examples, two different delivery modes (either a research project or a PhD studentship) are offered. This is only done in cases where either delivery mode could be a viable route to answering the research question.

[11] Airtightness differs from infiltration in that airtightness describes the air leakage characteristics of a building and is measured at an artificially induced elevated indoor-outdoor pressure difference. Whereas infiltration is the uncontrolled movement of air into (infiltration) or out of (exfiltration) a building envelope under natural conditions [23].

Summary of the outcomes of Report 1, Report 2, and Report 3

Report 1

Research objectives

- O1.1: Conduct a Rapid Evidence Assessment to investigate what is already known about airtightness, infiltration, and ventilation in the existing UK housing stock.
- O1.2: Calculate the baseline airtightness of the GB[12] housing stock using available data and use these findings to provide insight into how stock-wide changes to dwelling airtightness will impact energy demand, cost, and carbon savings.

Summary

The review of previous studies revealed a paucity of knowledge regarding the current airtightness of the existing UK housing stock. Two studies exist: Stephen [4] and Jones et al. [5]. The former uses a relatively small sample of data collected over 30 years ago. The latter combines the Stephen [4] data with data collected between 2006 and 2010[13] from another relatively small study [6]. Jones et al. [5] also attempted to predict infiltration rate, but the method was unvalidated.

New analysis conducted for this study used a modern[14] and much larger dataset (5,125 dwellings) of measured airtightness to extrapolate to the GB housing stock. This found that the extrapolated mean air permeability of the GB housing stock was 8.6 ± 3.3 m³/h.m² @ 50 Pa, which is lower (more airtight) than previously thought. This analysis also provided new insight regarding airtightness related to built form, age, and construction type.

Using the derived airtightness, it was shown that annual heating energy consumption could be reduced by 15.2 TWh (average 0.61 MWh per dwelling or 6.9% of total GB heating energy consumption)[15] if the airtightness of the entire GB stock was reduced to 5 m³/h.m² @ 50 Pa, which is the specification for the notional dwelling in the Building Regulations for new dwellings. This would require airtightness improvements to the vast majority of the housing stock (90% or 25 million dwellings). This could result in an annual saving on heating costs of £33 per treated dwelling per year (£840 million in the entire stock)[16], with an average per-

[12] There were insufficient data from Northern Ireland to calculate for the UK stock.
[13] Thus, 14 years old at the time of writing this report.
[14] Airtightness tests were conducted between August 2021 and October 2023.
[15] Under the hypothesised national airtightness improvement scenario, these values were calculated by estimating the annual heating energy demand associated with infiltration. Infiltration was estimated using the simple divide-by-20 rule of thumb. Dwelling volume was known from the low-pressure pulse record metadata. Standard heating degree days were used [35]. Total heating energy consumption from Watson et al. [36]. Full details in Roberts et al. [1].
[16] Under the hypothesised national airtightness improvement scenario, these values were calculated by determining main heating fuel of the weighted sample. From this unit costs and emissions factors were sourced from the Government Green Book [37]. Full details in Roberts et al. [1].

treated-dwelling saving of 0.61 MWh (equal to 5% of median gas demand[17]), and reduce carbon emissions by 115 $kgCO_2e$ per treated dwelling per year (2,880 $ktCO_2e$ in the entire stock).

Comparing these findings to other European countries was not possible due to low-quality evidence (quality defined using the GRADE assessment methodology [7]).

Contributions to knowledge

- The most accurate estimation of the mean airtightness of GB dwellings is 8.6 m³/h.m² @ 50 Pa, which is lower (more airtight) than previously thought.
- Prior to this report, a Rapid Evidence Assessment revealed there was low-quality evidence on the airtightness of the existing GB housing stock. The analysis provided new insight using the largest available dataset, giving greater confidence in the findings.
- There remains low-quality evidence of the airtightness of the national stock in other European countries.
- On average (mean and median), the most airtight GB dwellings were those built between 1965-1980, flats, and those with system-built walls. However, large (and overlapping) interquartile ranges indicate that other factors may be influencing airtightness.
- On average (mean and median), the least airtight GB dwellings were those built post-1990, semi-detached houses, and those with solid uninsulated external walls. However, large (and overlapping) interquartile ranges indicate that other factors may be influencing airtightness.
- Improving the airtightness of the GB stock such that all dwellings had an air permeability of 5 m³/h.m² @ 50 Pa or lower would require retrofitting 90% of the stock, but would reduce national heating energy demand by 15.2 TWh, energy costs by £840 million, and carbon emissions by 2,880 $ktCO_2e$.
- A Rapid Evidence Assessment revealed there is low-quality evidence of the infiltration and ventilation of the UK housing stock. This was because studies did not measure infiltration directly or only measured ventilation in a limited number of dwellings.

Remaining knowledge gaps

- What is the airtightness, infiltration, and ventilation rate of the **UK** housing stock?
- What other factors influence airtightness in UK dwellings (aside from age, built form, and wall construction type)?

[17] Compared to 2023 data [34].

Report 2

Research Objectives

- O2.1: Conduct a Rapid Evidence Assessment which describes and critiques the SAP infiltration estimation method.
- O2.2: Validate and compare existing infiltration estimation methods.
- O2.3: Quantify the effect of infiltration on heating energy demand and overheating using a steady-state and dynamic thermal model.

Summary

The Rapid Evidence Assessment described how the divide-by-20 rule of thumb is a leakage-infiltration ratio which converts a pressure test result at 50 Pa to a single heating season average value for infiltration rate. It is the most common method to estimate season-average infiltration rate, and forms the basis for several others. It is not a reliable predictor of a point-in-time infiltration rate, nor is it intended to be. It may not reliably predict heating season average infiltration rate, but more research is needed before solid conclusions can be drawn.

The first research exercise in Report 2 was an empirical validation of 12[18] different infiltration estimation methods. Empirical validation revealed that the Home Energy Model (HEM)[19] infiltration estimation method was the most accurate and precise of 12 tested, with the lowest CVRMSE and NMBE (59 and 24%). The HEM method was less accurate at lower wind speeds which is when stack driven infiltration is expected to dominate. The HEM infiltration estimation method does not include indoor-outdoor temperature as an input. Inclusion of this variable may improve the reliability of the estimated infiltration rate. Infiltration estimation methods which account for wind speed and indoor-outdoor temperature are generally more reliable than those which do not, but more complex methods with a greater number of inputs do not necessarily lead to more accurate estimations.

The second research exercise in Report 2 was to make steady-state and dynamic thermal model[20] predictions for wintertime heating energy demand to quantify how it is influenced by changes in infiltration rate. Both the steady-state and dynamic thermal model predicted that the heating energy demand would increase as infiltration increased; the dynamic thermal model was more sensitive to changes in infiltration rate. but ultimately predicted a lower annual space heating energy demand.

A third research exercise in Report 2 investigated the effect of infiltration on overheating predictions. Overheating predictions were made between May and September using a calibrated dynamic thermal model of an existing English dwelling [8–11]. Infiltration rates were systematically varied in 11 different model variants. The overheating hours were counted according to Part O of the Building Regulations [12] following Criterion A which applies during

[18] Eleven infiltration estimation methods were selected following a review of the literature. A twelfth, the method used in HEM, was added because it was undergoing development by DESNZ at the time of the study.
[19] The consultation version [33] was used in the analysis as this was the version available at the time of study.
[20] Steady-state predictions using SAP and dynamic predictions using EnergyPlus via DesignBuilder.

occupied hours in living rooms and bedrooms (refer to CIBSE TM59 for full details [13]). Varying the infiltration rate of the modelled house revealed that the predicted hours of overheating (Criterion A) were reduced from 5.8 to 2.3% in a bedroom when the value of infiltration was increased from 0.3 to 0.8 ach (the infiltration rate measured vs. estimated by the divide-by-20 method). This means the house would be compliant with Building Regulations on Overheating (Part O) using the estimated (higher) infiltration rate, but not compliant if the real, measured (lower), value for infiltration was used in the model. This is important because infiltration is currently an afterthought for modellers [14] and the methods for calculating it for use in Part O are not tightly prescribed. Yet from this case study[21], it has been shown that varying infiltration rates can cause a typical dwelling to comply, or not, with Building Regulations depending on the allowable choices made on infiltration rates in overheating models. This may lead to dwellings being susceptible to overheating once built, as the real infiltration rate may be lower than the one modelled, reducing the availability of ventilative cooling.

Contributions to knowledge

- A Rapid Evidence Assessment revealed high-quality evidence to suggest that current infiltration estimation methods produce unreliable point-in-time estimates of infiltration rates in English[22] dwellings when validated using point-in-time measurements tested with small indoor-outdoor temperature differences.
- The proposed DESNZ HEM infiltration estimation method estimated infiltration with greater accuracy and precision than the eleven other methods empirically validated. This was based on a sample of 15 infiltration tests in a single dwelling during summer.
- Despite this, the HEM infiltration estimation method is less reliable when measured infiltration rates were lower (when wind speeds were lower), than when measured infiltration was higher (when wind speeds were higher) because the method does not account for stack-driven infiltration.
- The effect of infiltration on overheating was investigated using a calibrated dynamic thermal model of a test house. Comparing the measured infiltration to the estimated infiltration showed that, due to unreliable infiltration estimation, the dwelling complied with Part O overheating Building Regulations with the estimated rate, but did not comply when the real, measured, value for infiltration was used.
- Modelled overheating hours were reduced from 5.8% to 2.3% in a bedroom when infiltration was increased from 0.3 ach to 0.8 (the measured infiltration rate).
- This meant that a modelled building could pass Part O, but in reality the building may be susceptible to overheating.

[21] This is a single case study and further research in a variety of dwelling types would be useful. An existing dwelling was used, but Part O only applies to newbuilds, which are likely to more airtight than the one used in this study.

[22] There were no data for other countries in the UK.

Remaining knowledge gaps

- What is the relationship between airtightness and infiltration?

Report 3

Research objectives

- O3.1: Conduct a Rapid Evidence Assessment to address the six research questions (RQ1: What effect does retrofit have on airtightness? RQ2: What are the typical airtightness failure points by dwelling type, age, or construction? RQ3: What are the typical airtightness failure points in the construction process that can lead to poor airtightness? RQ4: How could typical airtightness failures by addressed by retrofit? RQ5: Is there a relationship between airtightness and build quality? RQ6: Do PAS2035:2023 and PAS2030:2023 contribute to robust airtightness practices?).
- O3.2: Analyse secondary data to investigate airtightness degradation over time.
- O3.3: Analyse secondary data to investigate the presence of in-test sealing in the existing GB housing stock.
- O3.4: Conduct a Rapid Evidence Assessment to investigate what is known about the unintended consequences of more airtight homes and how airtightness affects overheating.
- O3.5: Conduct a Rapid Evidence Assessment to investigate what is known about occupant ventilation practices.

Summary

Following the Rapid Evidence Assessment, it remains unclear what effect specific retrofit measures have on airtightness, and whether this might vary by dwelling type, age, and construction. Most energy efficiency retrofit measures somewhat increase airtightness, providing that close attention is paid to following airtightness design details on-site, and additional penetrations in the primary air barrier are not made. The review found no particular airtightness failure point dependent on dwelling type, age, or construction. Some construction types are inherently more airtight, such as wet-plastered[23] masonry walls. Typical airtightness failure points are service penetrations, overreliance on secondary sealing, and poor workmanship associated with the integrity of the primary air barrier. Window and door seals may deteriorate over time, but these can be remedied with maintenance. There is no strong evidence to suggest that a relationship between airtightness and build quality[24] exists. There

[23] Wet-plastered is distinguished from other methods such as dot-and-dab plasterboard fixing which may allow the movement of air between the plasterboard and external wall surface.

[24] Build quality is considered in Report 3 in a broad sense relating to meticulous planning of airtightness detailing, planning to avoid improvised (on-site) solutions, and ensuring quality workmanship, training, and supervision.

are no studies which evaluate how specific PAS2030 and PAS2035 airtightness practices ultimately influence airtightness.

Unintended consequences of more airtight dwellings include condensation, damp, poor indoor air quality, radon build-up, overheating, and a higher incidence of asthma. Most can be ameliorated with adequate ventilation. Embryonic research suggests that an unintended consequence may exist between airtightness and increased risk of smoke and fire movement in buildings, but more research is needed to establish the effect and extent. There are currently just two studies on the matter, but they highlight the inherent building fabric weaknesses that contribute to building performance compliance for mandatory smoke and fire spread mitigation. Air barriers and fire breaks are commonly bypassed leading to the passage of smoke within and between buildings. These breaches may be introduced during thermal upgrades and retrofits of buildings. Increasing airtightness in buildings may increase the movement of air (and smoke) through any gaps in the building structure.

Contributions to knowledge

- A Rapid Evidence Assessment revealed there is low-quality evidence to quantify the effect of any particular retrofit measure on airtightness. There is insufficient evidence to reliably infer typical airtightness failure points by any particular dwelling characteristic, but wet-plastered dwellings are inherently airtight.
- There is no evidence to suggest that in-test, temporary sealing occurs during airtightness testing of existing dwellings using secondary data analysis. The Rapid Evidence Assessment revealed that such a trend was, however, present in newly-built dwellings.
- There is low-quality evidence to suggest that airtightness can be used as a proxy for build quality. Further research is very likely to have an important impact on our confidence in the estimate of the effect and is likely to change the estimate.
- Unintended consequences of more airtight construction were identified relating to indoor air quality, damp, overheating, and the transport of fire and smoke. These unintended consequences can be ameliorated with sufficient ventilation, except for fire and smoke transport (which is poorly understood in this context). Regarding fire and smoke transport, there exist only two studies on the matter, and as such, further research is likely to impact our understanding.
- Current studies on occupant ventilation practices use small sample sizes, case studies, or unrepresentative surveys which prevent broader, nationally representative, conclusions from being drawn.

Remaining knowledge gaps

- How do different construction elements e.g., windows, party walls, vents, and chimneys, contribute to airtightness, infiltration, and ventilation?
- How can more airtight construction be reliably and repeatably assured to reduce the energy performance gap?

- How do smoke and fire behave in airtight dwellings and how can airtight construction be used to reduce fire transport risks?[25]
- What are the current occupant ventilation[26] practices in the UK stock, and how should they be improved to minimise wintertime heat losses, summertime overheating, whilst maintaining satisfactory indoor air quality?

[25] Research of this nature is out-of-scope for DESNZ, but is currently within the remit of the Health & Safety Executive.

[26] Ventilation refers to purpose-provided openings such as windows, passive vents, trickle vents, and intermittent and continuous mechanical ventilation.

Options for future work

Introduction

This section establishes a rationale for several research questions that could be addressed through future research. The original research questions (RQs) from the Invitation to Quote (ITQ) are presented and discussed, with follow-on RQs suggested, along with methods to answer them. These are proposals only at this stage, not a commitment from DESNZ to commission research to answer the RQs.

Summary of ITQ research questions and suggestions for further work

This section lists all the RQs originally posed by DESNZ in the ITQ, summarises the findings from this project that address them, and provides options to address partially answered or unanswered questions through future research (Table 1).

Table 1: Summary of ITQ RQs, findings from this project, and suggested options for future work.

ITQ RQ	Findings from this project	Options for future work
What is the n/20 rule and how is it used?	Report 2 Rapid Evidence Assessment (REA) showed the “divide-by-20” rule to be one of several infiltration estimation methods based on “pressure test reduction”. It is a simple leakage-infiltration ratio for low-precision estimates of heating season infiltration. It is the most widely used method in the literature.	n/a - answered in Report 2.
What are the limitations with the n/20 rule?	Report 2 REA showed the following limitations: - It provides low-precision estimates of heating season infiltration. - It produced unreliable estimates of infiltration rates in two English two-storey dwellings when validated using point-in-time measurements, tested with small indoor-outdoor temperature differences.	Partially answered in Report 2, with additional research required (see proposed RQ2.3).

ITQ RQ	Findings from this project	Options for future work
How should the SAP methodology for estimating infiltration rates be changed/improved?	Report 2 secondary data analysis revealed that the method should better account for the influential inputs: wind speed and indoor-outdoor temperature difference.	Partially answered in Report 2, with additional research required (see proposed RQ2.3).
What data needs to be collected to support/validate a change/improvement to the way SAP calculates airtightness? E.g. types of tests, numbers of houses that need to be tested, building survey data, costs of tests, time taken to conduct tests, conditions under which tests should be taken etc.	Report 2 revealed that more primary data are needed to validate the infiltration estimation methods, and this report identifies a way to do this.	Answered in Reports 2 and 4, with additional research required (see proposed RQ2.3 and RQ2.4). This report proposes data collection methods for a study with 30 dwellings.
What is the typical airtightness of different house types in the UK? And how does airtightness differ by house type/age/construction type/listed status etc?	Report 1 revealed that the mean airtightness (air permeability) of the existing GB housing stock was 8.6 ± 3.3 m³/h.m² @ 50 Pa, which is lower (more airtight) than previously thought. Differences were identified between dwelling age, built form, and wall construction type – but overlapping interquartile ranges indicated other factors that influence airtightness were present. Insufficient data for Northern Ireland prevented the airtightness of the UK stock being calculated.	Additional research required (see proposed RQ2.1). Report 4 identifies that a field trial could (1) improve the confidence in the results from this project, (2) extend the existing GB study to UK dwellings with the inclusion of Northern Ireland, and (3) examine other categories beyond built form, age band, and wall construction type.
How does the airtightness of UK houses compare to that of houses from other European countries?	Report 1 REA revealed that the airtightness of existing dwellings in other European countries was generally unknown. Only studies from newbuild dwellings exist (e.g. >100,000 new dwellings in France).	Cannot be answered with the currently available literature, and international data collection is beyond the remit of DESNZ-funded research.
What are the typical airtightness failure points by house type/age/construction type etc?	Report 3 REA showed that there is insufficient information to reliably infer typical airtightness failure points by any particular dwelling characteristic, but in general wet-plastered masonry walls are inherently airtight.	Additional research required (see proposed RQ2.4 and RQ2.5).

ITQ RQ	Findings from this project	Options for future work
How could typical failures in airtightness be addressed by retrofit?	This literature gap remains.	Additional research required (see proposed RQ2.5).
What is the potential impact (£ and Carbon savings) of improving airtightness across the UK housing stock? Consider different airtightness retrofit measures.	Report 1 secondary data analysis calculated that improving the airtightness of the GB stock such that all dwellings had an air permeability of 5 m³/h.m² @ 50 Pa or lower would require retrofitting 90% of the stock, but could reduce national heating energy demand by 15.2 TWh, energy costs by £840 million, and carbon emissions by 2,880 $ktCO_2e$.	Answered in Report 1 using air permeability values, e.g., 5 m³/h.m² @ 50 Pa, rather than considering specific retrofit measures. Proposed RQ2.1 could bolster the reliability of these findings.
Is there a relationship between airtightness and build quality?	Report 3 REA showed that build quality can have a direct impact on airtightness. However, there is not strong evidence which shows whether this continues to other aspects of the building, and so more research is needed before airtightness can be used as a proxy for build quality.	Additional research required (see proposed RQ2.5).
What are the typical points of failure in the construction process that can lead to poor airtightness?	Report 3 REA showed that airtightness failure points relate to service penetrations, careless interaction with the primary air barrier, and reliance on secondary seals in place of a robust primary air barrier.	Answered in Report 3.
How do people typically ventilate their buildings?	Report 3 REA revealed that occupant ventilation practices are governed by the available ventilation provision and behavioural drivers (and barriers). Most UK dwellings are naturally ventilated using operable windows, with mechanical ventilation only common in wet rooms (kitchens and bathrooms).	Partially answered in Report 3, from a mostly qualitative perspective. A nationally-representative survey is an option for the future (see proposed RQ2.6).
Do people ventilate their buildings sufficiently or appropriately? Do they know how to?	Report 3 REA showed that people ventilate in response to indoor temperature and air quality – but the body of literature is contradictory. Occupants do not feel they have the knowledge to operate mechanical	Additional research required (see proposed RQ2.7).

ITQ RQ	Findings from this project	Options for future work
	ventilation systems appropriately and often turn them off or do not maintain them.	
What construction and operational practices in relation to airtightness and ventilation need to be considered in the scenario of a warming climate if overheating is to be mitigated?	Report 3 REA showed that the unintended consequences of more airtight dwellings on increased overheating could be mitigated with additional ventilation.	Answered in Report 3.
What might a field study look like in terms of aims/ objectives, method, costs and impact to gather the necessary data?	Report 4 gives full details of such options; including a field trial, laboratory studies, and test house experiments.	Answered in Report 4.

Further work needed

The following evidence gaps remain after this project:

- What is the airtightness, infiltration, and ventilation rate of the **UK** housing stock?
- What other factors influence airtightness in UK dwellings (aside from age, built form, and wall construction type)?
- What is the relationship between airtightness and infiltration?
- How do different construction elements contribute to airtightness, infiltration, and ventilation?
- How can more airtight construction be reliably and repeatably assured?
- How is ventilation[27] used in the UK stock, and how should it be used to prevent wintertime heat loss and summertime overheating while maintaining satisfactory indoor air quality?

Some of these originated in this project, as set out by DESNZ, and cannot be fully answered without additional data collection. Several new research questions have emerged. Any future work should comprise several new studies to supplement those in this project. This section provides details of the proposals with research questions and detailed methods presented.

Proposed future research questions

- RQ2.1: What is the airtightness of the UK[28] housing stock?
- RQ2.2: What is the relationship between the blower door test and the low-pressure pulse test?[29]
- RQ2.3: How do the results of pressure tests relate to infiltration under natural indoor-outdoor pressure differences and can infiltration estimation methods be improved?
- RQ2.4: How do different physical construction elements contribute to airtightness, infiltration, and ventilation?
- RQ2.5: How can more airtight dwellings be achieved on-site in newbuild construction and retrofit?
- RQ2.6: What is the ventilation rate of the UK housing stock?
- RQ2.7: How and why is ventilation used in UK dwellings and by whom?

[27] Ventilation refers to purpose-provided openings such as windows, passive vents, trickle vents, and intermittent and continuous mechanical ventilation.
[28] This project successfully derived an airtightness for the GB stock, but was unable to do so for the UK stock due to insufficient data from Northern Ireland.
[29] The airtightness datasets analysed in Report 1 and Report 3 were derived from low-pressure pulse tests. Another way of measuring airtightness in buildings is the fan pressurisation (or blower door) test. It was discussed in Report 1 that the DESNZ DEEP project found that inter-dwelling air leakage may be an artefact of the blower door test, rather than the low-pressure pulse test [20]. It will be important to establish if any differences between the two methods exists if the two are being used interchangeably to measure airtightness.

Study design for future research

Research question 2.1: What is the airtightness of the UK housing stock?

An extension to the existing field measurements and stock modelling study in this project could be used to (1) improve the confidence in these results, (2) extend the existing GB study to UK dwellings with the inclusion of Northern Ireland, and (3) examine other categories beyond built form, age band, and wall construction type.

Sample size – to compare two groups within categories of an unweighted sample

The required sample size is dictated by the level of accuracy required (minimum detectable effect (MDE)). A larger sample size is needed if a smaller MDE is desired. The size of the MDE should be decided based on the smallest difference between groups that is considered important. In the context of this proposed field study the units of MDE would take the form of "$m^3/h.m^2$ @ 50 Pa". If an MDE of 0.1 $m^3/h.m^2$ @ 50 Pa was required then a much larger sample would be needed than if an MDE of 0.9 $m^3/h.m^2$ @ 50 Pa was required (Table 2). The larger the sample size, the higher accuracy and smaller MDE.

The categories analysed in this project [1] were built form, age band, and wall construction type. This means that, e.g., for built form and a minimum detectable effect of 0.5 $m^3/h.m^2$ @ 50 Pa that the sample should contain 685 flats, 685 terraced houses, 685 semi-detached houses, 685 detached houses, and 685 bungalows – a total of 3,425 dwellings. Other categories that were not investigated here could also be added using the same MDE value. For example, single vs. double glazing would require 685 single glazed dwellings and 685 double glazed dwellings (total 1,370) at a minimum detectable effect of 0.5 $m^3/h.m^2$ @ 50 Pa. If triple glazing was also to be investigated, a sample of 685 triple glazed dwellings should be sampled.

The required sample size was calculated as follows. The statistical significance of differences in mean air permeability for two independent samples (e.g., dwellings of two different built forms) can be assessed using independent t-tests. Given a requisite statistical power and significance level[30], the minimum number of subjects required in each sample is dependent on the desired minimum detectable effect size, i.e., the smallest difference which may be considered important if determined to be significant. Minimum sample sizes have been calculated for conducting independent t-tests at 80% power, 5% significance, and with minimum detectable effect sizes between 0.1–1.0 $m^3/h.m^2$ @ 50 Pa (Table 2).

[30] Statistical power refers to the probability of a "true positive", i.e., correctly rejecting the null hypothesis that there is no difference between two means; meanwhile, significance level refers to the probability of a "false positive", i.e., incorrectly rejecting the null hypothesis.

Table 2: Sample sizes required for comparing mean air permeability (m³/h.m² @ 50 Pa) calculated for two independent samples via independent t-tests, at 80% power, 5% significance level and with varying minimum detectable effect size between 0.1–1.0 m³/h.m². (Expected population standard deviation 3.3 m³/h.m² @ 50 Pa derived from [1]).

Minimum detectable effect (m³/h.m² @ 50 Pa)	**1.0**	**0.9**	**0.8**	**0.7**	**0.6**	**0.5**	**0.4**	**0.3**	**0.2**	**0.1**
Sample size required (per sample)	172	213	269	350	476	685	1,070	1,901	4,275	17,096

Further data collection could be used to increase the sample size by adding to the existing dataset used in this work. Table 3 to Table 6 present the size of the additional sample required to enable comparison between mean air permeabilities between any two dwelling samples categorised by country of the UK, built form, age band or main wall construction type, based on adding these to the number of dwellings of each type in the current sample.

Table 3: The additional sample required in each country for independent t-tests comparing mean air permeabilities between dwelling samples categorised by region (at 80% power, 5% significance, expected population standard deviation 3.3).

Country	**Sample size from this project**	**Additional dwellings required to allow testing with specified minimum detectable effect size E m³/h.m² @ 50 Pa**									
		E=1.0	**0.9**	**0.8**	**0.7**	**0.6**	**0.5**	**0.4**	**0.3**	**0.2**	**0.1**
England	4,744	0	0	0	0	0	0	0	0	0	12,352
Wales	263	0	0	6	87	213	422	807	1,638	4,012	16,833
Scotland	118	54	95	151	232	358	567	952	1,783	4,157	16,978
Northern Ireland	0	172	213	269	350	476	685	1,070	1,901	4,275	17,096

Table 4: The additional sample required in each built form for independent t-tests comparing mean air permeabilities between dwelling samples categorised by built form (at 80% power, 5% significance, expected population standard deviation 3.3).

Built form	**Sample size from this project**	**Additional dwellings required to allow testing with specified minimum detectable effect size E m³/h.m² @ 50 Pa**									
		E=1.0	**0.9**	**0.8**	**0.7**	**0.6**	**0.5**	**0.4**	**0.3**	**0.2**	**0.1**
Flat	797	0	0	0	0	0	0	273	1,104	3,478	16,299

Terrace	1,571	0	0	0	0	0	0	0	330	2,704	15,525
Semi-detached	1,516	0	0	0	0	0	0	0	385	2,759	15,580
Detached	358	0	0	0	0	118	327	712	1,543	3,917	16,738
Bungalow	883	0	0	0	0	0	0	187	1,018	3,392	16,213

Table 5: The additional sample required in each dwelling age band for independent t-tests comparing mean air permeabilities between dwelling samples categorised by age band (at 80% power, 5% significance, expected population standard deviation 3.3).

Dwelling age band	Sample size from this project	Additional dwellings required to allow testing with specified minimum detectable effect size E m^3/h.m^2 @ 50 Pa									
		E=1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
Pre 1919	1,435	0	0	0	0	0	0	0	466	2,840	15,661
1919-1944	961	0	0	0	0	0	0	109	940	3,314	16,135
1945-1964	1,359	0	0	0	0	0	0	0	542	2,916	15,737
1965-1980	949	0	0	0	0	0	0	121	952	3,326	16,147
1981-1990	167	5	46	102	183	309	518	903	1,734	4,108	16,929
Post 1990	254	0	0	15	96	222	431	816	1,647	4,021	16,842

Table 6: The additional sample required in each main wall construction type required for independent t-tests comparing mean air permeabilities between dwelling samples categorised by main wall construction type (at 80% power, 5% significance, expected population standard deviation 3.3).

Main wall construction type	Sample size from this project	Additional dwellings required to allow testing with specified minimum detectable effect size E m^3/h.m^2 @ 50 Pa									
		E=1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
Cavity uninsulated	660	0	0	0	0	0	25	410	1,241	3,615	16,436
Cavity with insulation	2,010	0	0	0	0	0	0	0	0	2,265	15,086
Solid uninsulated	1,397	0	0	0	0	0	0	0	504	2,878	15,699
Solid with insulation	427	0	0	0	0	49	258	643	1,474	3,848	16,669
Other	631	0	0	0	0	0	54	439	1,270	3,644	16,465

Sample size – including Northern Ireland to enable analysis of the UK stock

Northern Irish (NI) dwellings comprise 2.8% of the total UK dwelling stock [15]. This would require 146 pressure tests from Northern Ireland for this be a representative proportion in the current GB dataset of 5,125 dwellings [1]. This is less than the 172 needed to make comparison between NI and other UK countries in the unweighted sample with an MDE of 1 m³/h.m² @ 50 Pa (Table 3). It is suggested that the minimum number for the selected unweighted sample MDE is used[31] to form the sample of and then scaled to the national level using weightings to achieve the required counts. This would follow the same method as this project [1], i.e., using national housing surveys (in this case the Northern Ireland House Condition Survey (NIHCS)). Independent samples z-tests can be used to ensure a representative sample is chosen with which to derive a reliable weighting.

Estimated duration

A field trial to gather additional pressure test data is estimated to take 1.5 years, although this ultimately depends on the number of tests conducted. Given that approximately 130,000 pressure tests are lodged annually in newly built dwellings [16] there is capacity within the UK industry to perform a large number of tests[32]. The majority of these tests are conducted in as-yet unoccupied dwellings, however, and securing existing dwellings for testing is more challenging. Historically, large field trials have used incentive payments to encourage participation [17,18] and recruitment companies to source participants [18]. These add costs which vary with sample size. Accuracy and a smaller MDE can be traded against a faster and cheaper field trial. For example, an MDE of 0.6 m³/h.m² @ 50 Pa across built form could be achieved by adding 118 detached dwellings to the existing dataset Whereas achieving an only slightly lower MDE of 0.4 m³/h.m² @ 50 Pa would require 1,172 in pressure tests (273 flats + 712 detached houses + 187 bungalows = 1,172 dwellings).

Research question 2.2: What is the relationship between the blower door test and the low-pressure pulse test?

The required sample size for assessing the degree of agreement between air permeability values (m³/h.m² @ 50 Pa) derived from blower door and low-pressure pulse tests varies according to desired margin of error for the mean difference between the two, and the expected standard deviation of the differences. Bland & Altman [19] formulate a 95% confidence interval for the mean difference between two measurement methods as $\bar{d} \pm t\sqrt{s^2/n}$, where $\bar{d}$ is the mean difference between methods, s the standard deviation of differences, n the sample size, and t the critical t-value for a 2-tailed test at 95% significance with $n-1$ degrees of freedom. The margin of error is then $t\sqrt{s^2/n}$; that is, half the width of the confidence interval.

Table 7 presents the minimum sample sizes required to produce 95% confidence intervals with varying margins of error, assuming that the standard deviation of per-dwelling differences is 3.24 m³/h.m² @ 50 Pa. The standard deviation assumed here is derived from a sample of 79

[31] Which is 172 dwellings.
[32] As these are in newly built dwellings, many tests will be done on similar dwellings on the same estate, allowing for efficient and economical delivery. The time and costs will be higher with tests done in the existing stock.

dwellings (50 from the DEEP project [20]; 17 tested by BTS [21]; 12 from Retrofit Revisit [22]) with results from both blower door and low-pressure pulse tests, for which the mean difference (low-pressure pulse minus blower door test) was 0.16 m³/h.m² @ 50 Pa, with standard deviation 3.24 m³/h.m². As the standard deviation of differences increases, so too does the minimum sample size required: for example, with standard deviation 5 m³/h.m² @ 50 Pa, a sample size of at least 387 would be required for a margin of error of 0.5 m³/h.m² @ 50 Pa; conversely, for a standard deviation of 1 m³/h.m² @ 50 Pa, only 18 dwellings would be required.

Table 7: Minimum sample sizes (number of dwellings) required to produce 95% confidence intervals for the mean difference between blower door and low-pressure pulse test air permeability values with given margins of error, assuming the standard deviation of per-dwelling differences is 3.24 m³/h.m². (Margin of error = half the width of the confidence interval.)

Required margin of error (m³/h.m²)	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
Minimum sample size required	43	53	66	85	115	164	255	451	1011	4036

Estimated duration

The field trial could be shared with RQ2.1 if combining the test visits. Otherwise, the duration is estimated to be one year, although is dependent on the sample size chosen.

Research question 2.3: How do the results of pressure tests relate to infiltration under natural indoor-outdoor pressure differences and can infiltration estimation methods be improved?

Further research could answer RQ2.3 by collecting high-quality data to validate (or not) existing infiltration estimation methods and develop new relationships between AP_{50}, AP_4, and infiltration. Previous studies have focused on 15 tests in one dwelling [23] or one test in 30 dwellings [24], so future work should go beyond this by doing multiple tests in several dwellings using fan pressurisation, low-pressure pulse, and tracer gas in combination. Data could be generated from repeated tests under a variety of weather conditions in a selection of unoccupied test houses that can be visited and tested at regular intervals. Relationships could be developed to understand the influence of indoor-outdoor temperature difference, and wind speed/direction on infiltration. These new air tightness-infiltration relationships could be validated using a larger field trial of a minimum of 43 real dwellings and combined with the work done to address RQ2.2. The field trial would measure AP_{50} (via blower door tests), AP_4 (via low-pressure pulse tests), infiltration (tracer gas), indoor temperature, and local weather in a variety of dwellings, multiple times, in the winter heating season.

The relationship between airtightness and infiltration may be affected by the methods used to measured airtightness. One method, the blower door test, which measures airtightness at a reference pressure of 50 Pa may increase party wall airflow. It has been suggested that this is an artefact of the blower door test [20]. It should be established whether this is true and if it also occurs with the low-pressure pulse test and under natural pressure differences (i.e. infiltration). The study should detect the presence of party wall air flow, quantify the direction and flow rate, and determine an in-test correction method or a post-test correction factor. If party wall air leakage is found to be present, and can be quantified according to dwelling characteristics, this could be incorporated into the infiltration estimation methods that underpin SAP and HEM.

Airtightness may vary seasonally due to expansion/contraction of the building fabric and multiple pressure tests across various seasons will enable a new understanding of seasonal variation in airtightness. Matched pairs of test houses and groups of test flats could be used to investigate these effects utilising the guarded zone method [25].

Test location

Unoccupied test houses for relationship testing of various ages and construction types.

Sample size

Six dwellings for detailed testing and development. A minimum of 43 additional dwellings to be sought for validation with repeated tests in each.

Estimated duration

This could be funded as a PhD project over three years. The host university would offer two academic supervisors to hold weekly meetings with the students. DESNZ could offer a supervisor to attend meetings once per month.

- Year 1: Develop and instrument the test houses (or multi-room test cells) with equipment to measure pressure on different facades and indoors, infiltration rate (tracer gas), indoor temperature, and on-site weather. Conduct a detailed literature review.
- Year 2: Measure infiltration (tracer gas) and airtightness at least 24 times (twice per month) over one year using the decay method and also for three consecutive days at least twice per year using the constant concentration method. Airtightness testing to include both blower door (fan pressurisation) and low-pressure pulse with and without co-pressurisation alongside measurement of on-site weather.
- Year 3: Use the data gathered to develop new leakage-infiltration ratios (or relationships as suggested by Jones et al. [25]) and quantify the effect of seasonal variation and party wall air leakage. Test this in a sample of at least 43 real dwellings of various ages, built forms, and construction types to validate the revised leakage-infiltration ratio comparing AP_{50} (blower door test), AP_4 (low-pressure pulse test), and infiltration (tracer gas).

Research question 2.4: How do different construction elements contribute to airtightness, infiltration, and ventilation?

A reductive sealing approach [26] could be taken to establish how different construction elements, e.g., windows, party walls, vents, and chimneys, contribute to airtightness. Reductive sealing involves several pressure tests being conducted on the same building, each with a different construction element sealed.

This method should be used to establish a baseline of data to feed into RQ2.3 regarding whether purpose-provided continuous ventilation openings [27,28] should be sealed when estimating infiltration from pressure tests. It has been suggested in BS EN 40101 [29] guidance that the usual ventilation sealing for compliance testing should not be done when performing pressure tests to estimate infiltration.

A pair of climate chambers, such as a hygrothermal test facility, could be among the most robust ways to test the performance of individual building elements, window sealing approaches, and vents.

Test location

Unoccupied test houses, a test chamber, and real dwellings.

Sample size

Two test houses to develop the method. One test chamber. A minimum of 30 real dwellings to gather data[33].

Estimated duration

This could be funded as a research project either affiliated or sharing data and dwellings with the RQ2.3 PhD project. The project would last 1 year.

Research question 2.5: How can more airtight dwellings be achieved on-site in newbuild construction and retrofit?

Research problem

In mainstream low-density housing, site operatives may not consider airtightness in their work [30,31].

Study design

The proposed study will determine the value propositions that must be offered to the site operative by either the production system within which they work, the importance of airtightness itself in terms of societal need for energy-efficient housing, or the operative's understanding of "good" work against which they judge their own performance, or other, as yet unknown, constructs. Once identified, methods of communicating, rewarding, understanding, and so forth can be proposed via dissemination to relevant communities to address the issues

[33] These could be shared with those used in RQ2.1 to reduce recruitment and travel costs.

they create for the site operative: designers and specifiers; site agents; work gang leaders ("gaffers"); builders' merchants, manufacturers, suppliers of relevant materials; and so on.

The study unit of analysis could be the individual operative within representative mainstream (i.e. using traditional superstructure construction trades, methods and materials) housebuilding sites as its unit of analysis. A sample of at least three retrofit/renovation/refurbishment projects and three new-build projects should be secured.

Having established access to these sites via client and/or site management, considerable effort should be taken to create an open environment for observation by building relationships with the site management and site operatives. This could comprise a simple, sustained presence on site and exploratory, informal and undocumented conversations (e.g. during the typical 10:00 site "breakfast") to introduce the work and open discussions to build trust and openness. This may take some time and will not generate research data but is imperative to create the opportunities to access representative data.

Data gathering could adopt two strategies. First, short periods of intense visual ethnography should occur during focused periods of site activity during which the airtightness membrane should be a matter of concern to site management and operatives. During the observation window for each site, observed activities could include: builder's work associated with services penetrations through membranes; taping of junctions between wall/roof/floor membranes; and first and second fix plumber work and/or electrical work. Then, observations could be elucidated through individual or group interviews to identify the enablers and barriers associated with the practices observed. These should identify the materiality of airtightness to site operatives and either their frustration or satisfaction with their ability to achieve it, and the enablers and barriers that need to be overcome through actions associated with work organisation, communication of design intent, training, payment/reward mechanisms etc. Operatives should be paid to engage with this data gathering to ensure that financial loss would not dissuade them from doing do. To ensure ethical soundness, payment will be at a level equivalent to operative's hourly pay rate, making them indifferent to participation from a financial perspective.

Test location

Housing construction sites and on-site retrofit schemes.

Sample size

Three newbuild housing construction sites and three retrofit schemes.

Estimated duration

The project should take 24 months, organised as follows:

- 3 months initialisation and project identification.
- 3 to 6 months project introductions, relationship building, and trust/familiarity building with site operatives.

- 12 months of data gathering via visual ethnography and group interviews (see above). Data gathering will not be continuous during this period, but will instead be focused on occurrences of activities associated with airtightness across the six observed sites.
- 9 months dissemination of practice recommendations to industry via focused campaigns.
- 3 months dissemination of findings to relevant organisations via publications in a variety of formats to suit the audience.

With the above performed concurrently during a 24-month study duration.

The intensity of the work and need for coordination will require 15% of the associated investigator's time.

An experienced post-doctoral researcher will be required as the work is not appropriate to the active training of PhD study. The researcher could either be an experienced ethnographer, able to rapidly acclimatise to the construction site environment and culture, or a construction researcher familiar with site culture and able to perform ethnographic work with supervision.

Research question 2.6: What is the ventilation rate of the UK housing stock?

This research question could be answered with measurement of ventilation rate during different seasons in 100 to 500 nationally-representative dwellings. Prior to measurement in real homes, there needs to be development and validation of a ventilation measurement method suitable for occupied homes. This method development could be done in test houses[34]. High-quality measurement equipment is required to sense tracer gases, monitor window operation, use of other ventilation, and occupancy.

Test location

Test dwellings for ventilation measurement method validation; real occupied dwellings for measurement.

Sample size

The required sample size for such a field trial was determined by Kukadia & White [32] using winter ventilation data from 33 dwellings. They used a confidence interval approach to determine the sample size based on desired level of precision. A sample of 100 dwellings would provide a high level of precision and 500 dwellings a very high level of precision. This sample size could answer the question: "what is the mean ventilation rate of the UK dwelling stock?".

A representative sample should select for both dwelling and occupancy categories.

[34] Both single-storey and two-storey test houses should be used to account for stack ventilation.

Estimated duration

The duration of study has been estimated as 1.5 years assuming the field trial contains 100 dwellings or 3 years assuming 500 dwellings, which depends on the desired level of precision.

Research question 2.7: How and why is ventilation used in UK dwellings and by whom?

A nationally-representative survey, validated by dwelling visits, and in-depth monitoring in a sub-sample of dwellings could elucidate how, when, and why ventilation is operated. It is assumed that this will run alongside the activities to answer RQ2.6 and use a subsample of those field trial dwellings.

Test location

Real occupied dwellings.

Sample size

Drawing on a nationally-representative sub-sample of that identified in RQ2.6 activities.

Estimated duration

There are two options for carrying out this work: Option A is via a PhD student and Option B is via a funded research project. Option A would likely be lower cost, but with a longer duration (3 years) than Option B (1 year).

Report conclusions

To understand what is currently known, what can be discovered by analysing existing datasets, and to scope additional studies, DESNZ commissioned Loughborough University to undertake the *Gathering evidence to improve airtightness in the UK housing stock* project in 2023. This is Report 4, in a series of four reports, which summarises the previous three reports and includes the scoping study for further work required to address the research questions, and any other important research questions that arose during the project.

Report 1 [1] focused on dwelling airtightness at stock level. The results showed that GB dwellings are more airtight than previously thought. Although dwellings built between 1965-1980, flats, and system-built homes were found to be more airtight than others, other yet-to-be-identified factors are likely to influence airtightness at stock level. Modelling demonstrated the effect of improving airtightness on heating energy demand, energy costs, and carbon emissions [1].

Report 2 [2] focused on infiltration estimation methods and showed these to be unreliable in limited tests in two-storey English dwellings during spring and summer weather conditions. More research is needed to assess the accuracy and precision during the winter heating season in a variety of dwelling types. The proposed Home Energy Model (HEM) infiltration estimation method (consultation version [33]) was validated (using summer data) against eleven other methods sourced from the literature, including that used in the Standard Assessment Procedure (SAP). The HEM method was the most accurate and precise, but was less accurate at lower wind speeds [2].

Report 3 [3] focused on construction and retrofit practices relating to airtightness, unintended consequences of more airtight dwellings, and occupant ventilation practices. The findings revealed that there is limited evidence on the effect of specific retrofit measures on airtightness, but that wet-plastered dwellings are thought to be more airtight. Secondary data analysis revealed there to be no evidence of intentional secondary sealing during airtightness testing in existing homes, while the literature shows this occurs in newly built dwellings. Concerning occupant ventilation practices, the current studies are limited and not nationally representative, and so it is not possible to draw any general conclusions [3].

Overall, the project successfully answered the research questions set out in the original ITQ and identified where further research was needed. This report compiled the research gaps and proposed seven new research questions that could be investigated through further work. Methods were developed to answer each new question. Sample size analysis was conducted which allowed for a range of options depending on the level of precision required.

References

[1] B.M. Roberts, M. Li, D. Allinson, K.J. Lomas, Baseline airtightness of the GB housing stock, Department for Energy Security & Net Zero (2025).

[2] B.M. Roberts, K. Mourkos, K.J. Lomas, Evidence to support an update to the methodology for estimating infiltration rates in SAP, Department for Energy Security & Net Zero (2025).

[3] B.M. Roberts, V. Rossi, C. Gorse, M. Li, K.J. Lomas, Airtightness retrofit and construction practices, unintended consequences, and ventilation practices, Department for Energy Security & Net Zero (2025).

[4] R.K. Stephen, Airtightness in UK dwellings: BRE's test results and their significance, Building Research Establishment. (1998).

[5] B. Jones, P. Das, Z. Chalabi, M. Davies, I. Hamilton, R. Lowe, A. Mavrogianni, D. Robinson, J. Taylor, Assessing uncertainty in housing stock infiltration rates and associated heat loss: English and UK case studies, Build Environ 92 (2015) 644–656. https://doi.org/10.1016/j.buildenv.2015.05.033.

[6] W. Pan, Relationships between air-tightness and its influencing factors of post-2006 new-build dwellings in the UK, Build Environ 45 (2010) 2387–2399. https://doi.org/10.1016/j.buildenv.2010.04.011.

[7] G.H. Guyatt, A.D. Oxman, G.E. Vist, R. Kunz, Y. Falck-Ytter, P. Alonso-Coello, H.J. Schünemann, GRADE: An emerging consensus on rating quality of evidence and strength of recommendations, BMJ 336 (2008) 924–926. https://doi.org/10.1136/bmj.39489.470347.ad.

[8] B.M. Roberts, D. Allinson, K. Lomas, Prediction of overheating in synthetically occupied UK homes: dataset for validating dynamic thermal models of buildings, Figshare Dataset (2019). https://doi.org/10.17028/rd.lboro.8094575.

[9] B.M. Roberts, D. Allinson, B. Abel, K. Lomas, Measured indoor temperature, weather, infiltration, and ventilation in synthetically occupied test houses: summer 2021, UK, Figshare Dataset (2022). https://doi.org/10.17028/rd.lboro.19308299.

[10] B.M. Roberts, D. Allinson, K.J. Lomas, A matched pair of test houses with synthetic occupants to investigate summertime overheating, Journal of Sustainable Design & Applied Research 6 (2018) 29–38. https://doi.org/10.21427/D70N8S.

[11] B.M. Roberts, B. Abel, D. Allinson, J. Crowley, T. Rashid, B. Salehi, K.J. Lomas, A dataset from synthetically occupied test houses for validating model predictions of overheating, in: CIBSE Technical Symposium, London, UK, 2022: pp. 1–23. https://hdl.handle.net/2134/19412207 (accessed April 7, 2022).

[12] HMG, The Building Regulations 2010 - Approved Document O: Overheating, (2021).

[13] CIBSE, Design Methodology for the Assessment of Overheating Risk in Homes, TM59 (2017). https://doi.org/10.1093/oxfordjournals.aje.a009805.

[14] B.M. Roberts, D. Allinson, S. Diamond, B. Abel, C.D. Bhaumik, N. Khatami, K.J. Lomas, Predictions of summertime overheating: Comparison of dynamic thermal models and measurements in synthetically occupied test houses, Building Services Engineering Research and Technology 40 (2019) 512–552. https://doi.org/10.1177/0143624419847349.

[15] J. Piddington, S. Nicol, H. Garrett, M. Custard, The Housing Stock of The United Kingdom, 2020. www.bretrust.org.uk.

[16] J. Crawley, P. Biddulph, J. Wingfield, M. Ashdown, R. Lowe, C. Elwell, Inferring the as-built air permeability of new UK dwellings, International Journal of Building Pathology and Adaptation 38 (2020) 3–19. https://doi.org/10.1108/IJBPA-02-2019-0018.

[17] D. Allinson, B. Roberts, K. Lomas, D. Loveday, D. Johnston, D. Glew, K. Rakhshanbabanari, F. Fylan, D. Farmer, C. Elwell, J. Crawley, F. Hollick, J. Wingfield Halton Housing, G. Roberts, L. Reevell, Technical Evaluation of SMETER Technologies (TEST) Project, 2022. https://assets.publishing.service.gov.uk/media/61f2cc6ee90e0768a90f1f9b/smeter-innovation-competition-report.pdf (accessed February 25, 2022).

[18] K.J. Lomas, D. Allinson, S. Watson, A. Beizaee, V.J. Haines, M. Li, Energy savings from domestic zonal heating controls: Robust evidence from a controlled field trial, Energy Build 254 (2022) 111572.

[19] J.M. Bland, D.G. Altman, Statistical methods for assessing agreement between two methods of clinical measurement, Int J Nurs Stud 47 (2010) 931–936.

[20] D. Glew, M. Collett, M. Fletcher, A. Hardy, D. Miles-Shenton, K. Morland, J. Parker, K. Rakhshanbabanari, F. Thomas, D. Allinson, D. Farmer, DEEP Report 1: Synthesis - Demonstration of Energy Efficiency Potential, 2024. https://www.gov.uk/government/publications/demonstration-of-energy-efficiency-potential-deep (accessed June 20, 2024).

[21] L. Smith, A. Moring, R. Jack, Low pressure pulse test - Field trial report, 2018.

[22] J. Godefroy, M. Baeli, Retrofit Revisit: 10 case studies, 2024. https://www.cibse.org/knowledge-research/knowledge-portal/retrofit-revisit-2024 (accessed July 30, 2024).

[23] B.M. Roberts, D. Allinson, K.J. Lomas, Evaluating methods for estimating whole house air infiltration rates in summer: implications for overheating and indoor air quality, International Journal of Building Pathology and Adaptation 41 (2023) 45–72. https://doi.org/10.1108/IJBPA-06-2021-0085.

[24] A.V. Pasos, X. Zheng, L. Smith, C. Wood, Estimation of the infiltration rate of UK homes with the divide-by-20 rule and its comparison with site measurements, Build Environ 185 (2020). https://doi.org/10.1016/j.buildenv.2020.107275.

[25] B. Jones, A. Persily, M. Sherman, The origin and application of leakage-infiltration ratios, in: AIVC Conference, 2016.

[26] D. Johnston, R.J. Lowe, Improving the airtightness of existing plasterboard-lined load-bearing masonry dwellings, Building Services Engineering Research and Technology 27 (2006) 1–10. https://doi.org/10.1191/0143624406bt135oa.

[27] ATTMA, Measuring air permeability in the envelopes of dwellings. Technical Standard L1, 2016.

[28] ASTM, Standard Test Methods for Determining Airtightness of Buildings Using an Orifice Blower Door E1827-11, (2007). https://doi.org/10.1520/E1827-11.

[29] BSI, BS 40101-2022 Building performance evaluation of occupied and operational buildings (using data gathered from tests, measurements, observation and user experience) — Specification, BSI British Standard Publication (2022) 1–106.

[30] C. Hobart, D.S. Thomson, A.R.J. Dainty, S. Fernie, D. Dewniak, Closing the energy performance gap in zero carbon homes - pro-active identification, prioritisation and mitigation of causes using FMEA., in: Proceedings 31st Annual ARCOM Conference, 2016: pp. 307–316. http://www.arcom.ac.uk/-docs/proceedings/3f85e692df147656ee6e2b09f2d83ded.pdf.

[31] A. Dainty, D. Thomson, S. Fernie, Closing the performance gap in the delivery of zero-carbon homes: A collaborative approach, in: Construction and Housing in the 21st Century, Faculty of Architecture, HKU, Hong Kong, 2013.

[32] V. Kukadia, M. White, Monitoring ventilation in homes built before 1995: A pilot study, 2006. www.bre.co.uk.

[33] DESNZ, Modelling ventilation and infiltration within the Home Energy Model: A technical explanation of the methodology (HEM-TP-06 v1.0), 2023. https://assets.publishing.service.gov.uk/media/65783edb095987001295de83/hem-tp-06-infiltration-and-ventilation-heat-loss.pdf (accessed February 13, 2024).

[34] Department of Energy Security & Net Zero, National Energy Efficiency Data Framework (NEED) report: summary of analysis 2023, 2023. https://www.gov.uk/government/statistics/national-energy-efficiency-data-framework-need-report-summary-of-analysis-2023 (accessed March 20, 2024).

[35] CIBSE, Energy benchmarks TM46, London, 2008.

[36] S.D. Watson, K.J. Lomas, R.A. Buswell, Decarbonising domestic heating: What is the peak GB demand?, Energy Policy 126 (2019) 533–544. https://doi.org/10.1016/j.enpol.2018.11.001.

[37] DESNZ, Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal, 2023. https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal (accessed February 2, 2024).

This publication is available from: https://www.gov.uk/government/collections/buildings-energy-efficiency-technical-research