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Building Energy Research Group (BERG)

Baseline airtightness of the GB housing stock

Gathering evidence to improve airtightness in the UK housing stock

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This report forms the first 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".

Contents

Executive summary

This study shows that British (GB) dwellings are more airtight than previously thought with a mean air permeability of 8.6 m³/h.m² @ 50 Pa. Previous studies were based on smaller, older samples, so this report provides valuable new evidence.

Research purpose

Gather evidence of the airtightness of the UK housing stock to better target retrofit policy.

Research methodology

Firstly, a Rapid Evidence Assessment screened 1,203 documents for relevance and quality. Seventy-seven documents were ultimately selected for inclusion in the review.

Secondly, secondary data analysis revealed the airtightness of the GB housing stock. A total of 12,277 airtightness test results gathered using the low-pressure pulse method across 8,933 unique addresses were cleaned and extrapolated to the GB housing stock to produce a weighted sample of 5,125 dwellings. These data were used as they covered a wide range of new and existing homes. Each sample airtightness measurement was associated with an Energy Performance Certificate, which enabled weightings to be applied from national housing surveys to investigate the influence of built form, age, and construction type on airtightness.

Research findings

The Rapid Evidence Assessment revealed low-quality evidence on the airtightness of the existing UK housing stock exists, and similarly for the existing housing stock in other countries in Europe. Pre-1994 and pre-2010 data suggested a stock mean airtightness of 11.5 and 8.9-9.0 m³/h.m² @ 50 Pa respectively. Existing research on the factors which influence airtightness in existing UK homes is limited and based on studies that are outdated or limited in scope.

Secondary data analysis showed that the GB housing stock has a mean air permeability of 8.6 ± 3.3 m³/h.m² @ 50 Pa (median 8.1 m³/h.m² @ 50 Pa). This indicates that GB dwellings are more airtight than previous studies suggest. Dwellings built between 1965-1980, flats, and system-built walls are the characteristics of the most airtight dwellings in the GB stock. Those built post-1990, semi-detached houses, and those with solid uninsulated walls are the least airtight in the GB stock, but there is large variation within categories. Improving the airtightness of the GB stock such that all dwellings had an air permeability of 5 m³/h.m² @ 50 Pa or below (the notional newbuild dwelling in the Building Regulations) would require retrofitting 25 million dwellings (90% of stock) but would reduce annual national heating energy demand by 15.2 TWh, annual heating energy costs by £840 million (mean £33 per treated dwelling), and annual carbon emissions by 2,880 ktCO_2e (mean 115 kgCO_2e per treated dwelling).

Introduction

Background and context

En route to a net zero emissions economy, residential buildings must be energy efficient, future-proofed to cope with future climate risks such as overheating, and have decarbonised heating systems. Making buildings more airtight is a potential energy efficiency measure which will lower heating energy demand, improve national energy security, and reduce greenhouse gas emissions. Demand reduction is vital at peak times to reduce the load on strained electricity networks. Peak demand reduction initiatives can be more readily exploited in energy efficient, airtight homes [1]. Reducing energy costs for households is important, especially for the 3.3 million households that are currently in fuel poverty [2], and lower energy demands reduce fuel price shocks which affect the entire economy.

Buildings that are more airtight are also more comfortable through reduced draughts in winter [3] and unwanted heat gains in summer [4]. Furthermore, more airtight buildings may improve indoor air quality by allowing closer control over the air that enters. Airtight construction is essential for the effective operation of domestic mechanical ventilation systems and the filtration of air [5]. This control is particularly valuable in areas that are highly polluted with airborne particulates from surface transport or industry [6]. Net zero homes should be built with precision and reliability, allowing for a long and maintainable airtightness service life.

UK Building Regulations are driving requirements for increasing airtightness in newbuild dwellings [7–10] and for continuous mechanical extract ventilation in very airtight buildings, to ensure satisfactory indoor air quality is maintained, as described in Approved Document F [11]. Airtight buildings have other benefits, particularly related to reducing fire risk across party walls and floors. Such fire bypasses are mitigated in new buildings through building regulations concerned with firebreaks [12], but in existing buildings the risk can be ameliorated with improved airtightness detail within and between dwellings [13]. The long-range transmission of airborne pathogens between dwellings is also reduced when bypasses are removed [14].

It is important to quantify the current airtightness of the UK housing stock to enable policymakers to identify the attributes of the leakiest dwellings and to design policy to make useful energy efficiency improvements at a national scale. This will also allow benchmarking of current airtightness to indicate the scale of improvements to be made and the potential benefits this will have regarding reductions in carbon emissions, heating energy demands, and costs to householders.

Airtightness in dwellings is usually measured in one of two ways [15]. The first is the fan pressurisation test, alternatively called the blower door test. The second is the low-pressure pulse test. Both methods artificially induce a pressure difference across the building envelope during the test. In contrast, infiltration and ventilation is usually measured via tracer gas, doing so at natural indoor-outdoor pressure differences.

Key terms

Air leakage

The flow of air through the envelope of a building when subject to a pressure differential [15]. Often expressed as an air leakage rate, commonly “air change rate” (normalised by building volume) or “air permeability” (normalised by building envelope surface area) both expressed at a reference pressure according to the testing method [15]. The reference pressure depends on the airtightness test: 50 Pa for the fan pressurisation (blower door) test and 4 Pa for the low-pressure pulse test.

Air change rate

The air leakage per internal volume across the building envelope [16] at a specified internal-external pressure difference [15], often reported as N_{50} (where the reference pressure is 50 Pa), with the units “h^{-1}”, “ach” or “1/h” at the test reference pressure.

Air permeability

In BS EN 9972, air permeability is the volumetric air leakage rate per square metre of envelope area [16]. Reported as AP_x [15] with the units $m^3/h.m^2$ @ x Pa, with x being the test reference pressure (e.g., 4 or 50 Pa).

Air permeability is the air leakage parameter adopted for building regulations compliance purposes in England, Scotland, Wales, and Northern Ireland [15].

Airtightness

Defined according to CIBSE TM23, airtightness describes the air leakage characteristics of a building. The smaller the air leakage for a given pressure difference across a building, the more airtight the building envelope [15].

Infiltration

Infiltration is the uncontrolled fortuitous movement of air into (infiltration) or out of (exfiltration) a building envelope under natural conditions [15]. The units are “h^{-1}”, “ach”, or “1/h”.

Aims and objectives

The aim of this report is to gather evidence on the baseline airtightness of the UK housing stock. This will ultimately allow better targeting of retrofit policy. The aim will be addressed via the following 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[1] 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.

Research questions

The following research questions will be addressed in this report:

- RQ1: What is the airtightness, infiltration, and ventilation of existing dwellings in the UK?
- RQ2: How does the airtightness of UK dwellings compare to that of dwellings from other European countries and countries with a similar climate?
- RQ3: How does airtightness differ in existing UK dwellings with respect to built form, age, construction, and listed status?
- RQ4: What is the potential impact on energy, cost, and carbon emission reductions of improving airtightness in the UK housing stock?

Research questions RQ1, RQ3, and RQ4 will be addressed by the Rapid Evidence Assessment and by analysis of secondary data. RQ2 will be addressed by the Rapid Evidence Assessment only.

Report structure

The first section provides details of a Rapid Evidence Assessment of the currently available literature. The second section gathers and analyses secondary quantitative evidence of the airtightness of the GB housing stock. The final section draws together the findings from the literature and the new analyses conducted to address the research questions.

[1] The secondary data analysis focuses on Great Britain (GB) only as data from Northern Ireland were unavailable.

Rapid Evidence Assessment

Introduction

This Rapid Evidence Assessment will review what the current literature says about the airtightness, infiltration, and ventilation of the existing UK housing stock and identify gaps in the evidence base. It will specifically:

- Review studies which measure and extrapolate or model the airtightness of the existing UK housing stock and compare these to studies from other countries in Europe.
- Identify factors influencing airtightness such as built form (dwelling type), age, construction, listed status, etc.

Methodology

Overview of methodology

Rapid Evidence Assessments are rigorous and timely reviews of the literature in order to make evidence-based recommendations [17]. The review process was adapted from Drury [18] following the order:

1. Define research questions.
2. Develop search terms.
3. Develop literature screening criteria.
4. Identify databases and information sources.
5. Conduct literature searches.
6. Combine results and remove duplicates.
7. Screen documents for relevance based on title and abstract.
8. Screen documents for relevance based on full document.
9. Screen documents for eligibility based on quality.
10. Extract data.
11. Synthesise findings of remaining literature.
12. Classify quality of evidence based on Grading of Recommendations, Assessment, Development, and Evaluation (GRADE) system.

A full methodology is provided in Appendix A.

Findings from the literature

The statement of included studies following screening for relevance and quality is reported following the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) methodology [19] (Figure 1).

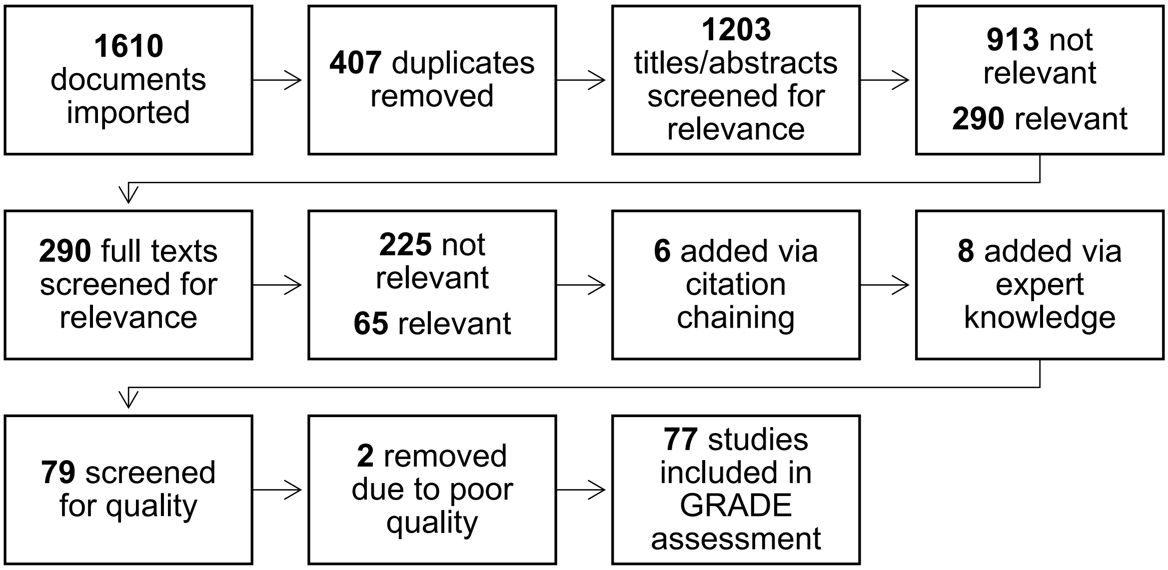


Figure 1: PRISMA diagram, after [19]**.**

RQ1: What is the airtightness, infiltration, and ventilation of existing dwellings in the UK?

Key findings:

There was only one published study in the last decade that reported on the airtightness and infiltration of the existing UK housing stock. It used secondary airtightness test data from 384 dwellings built pre-1994 and 287 dwellings built 2006-2010. The airtightness was quantified as 8.9-9.0 $m^3/h.m^2$ @ 50 Pa with a mean heating season infiltration rate of 0.32-0.44 h^{-1}. The infiltration model used to convert from airtightness to infiltration requires further validation.

There was no evidence for the ventilation rate of the existing UK housing stock.

GRADE quality assessment rating:

There is low-quality evidence of the airtightness of the existing UK housing stock.

There is very low-quality evidence of the infiltration of the existing UK housing stock.

There is very low-quality evidence of the ventilation rate of the existing UK housing stock.

Of the 77 studies subject to GRADE quality assessment, there is one study which estimates the airtightness and infiltration of the English and UK existing housing stock [20] (Table 1). Jones et al. [20] state that there are "no known large-scale measurements… of heating season infiltration rates in English dwellings and so a modelling approach is proposed". Air permeability values were required for the model and these were sourced from the combination of two datasets of English housing airtightness tests conducted prior to 2000 (from Stephen [21]) and post-2006 (from Pan [22]). Geometric, physical, and environmental information were sourced from the English Housing Survey. The study makes two separate assumptions about party wall air permeability. The first is that party walls are permeable; the second is that they are not. The infiltration rate was predicted using the DOMVENT3D model [23,24]. The study highlights several limitations with the methodology and availability of information. Firstly, it is impossible to state with any certainty the most likely known party wall permeability assumption applicable to UK houses. The study points to a small number of guarded zone tests (co-pressurisation tests) but calls for a field trial in the UK to further investigate the matter. Secondly, the accuracy of the predictions could be improved with more robust distributions of airtightness by dwelling age and type as the two datasets used were reasonably small. Thirdly, the modelling approach to calculate infiltration (DOMVENT3D) requires further validation, having only been validated in one small study of three dwellings to date, which showed the model predictions differing by 34-107% when compared to a blower door test and 43-64% when compared to a low-pressure pulse test [25].

Stephen [21] is the oft-cited source of airtightness in the existing UK housing stock, despite the study making no claim to be representative of the stock. Furthermore, although it is commonly cited today, it was published 26 years ago and so does not capture more recently built dwellings (post-1992). It contains a sample of 471 dwellings for which air leakage rate (N_{50}) was derived and 384 for which air permeability was reported (AP_{50}). Results for a sample containing some of the same dwellings was reported earlier [26]. The reported air permeability was higher than that of Jones et al. [20] perhaps because it does not include the post-2006 dwellings in Pan [22] (Table 1).

Twenty studies describe the airtightness of several homes, without being a sufficiently large or diverse sample with which to make generalisations to the whole dwelling stock (Table 1). The largest of these are for newbuild homes [27–30]. Stephen [32] contains combined data from Stephen [21] and Cornish et al. [32] which reported results for a sample of 87 Large Panel System flats which make up less than 1% of the UK housing stock and so are not nationally representative. Etheridge et al. [33] reported data from 217 dwellings from four counties in England that were constructed prior to 1987. The DESNZ DEEP study only contained dwellings with solid walls or masonry cavity walls[2] located in the North and Midlands of England [34]. Semi-detached houses in a limited geographical area formed the majority of some samples (e.g., Allinson et al. [35] and Pasos et al. [36]). Stephen et al. [37] measured the airtightness of 40 dwellings in Southampton, half with MVHR and half with natural ventilation. Johnston and Lowe [38] tested masonry dwellings built in 1970s in County Durham. Several studies of fewer than 35 dwellings also exist (Table 1).

As there are so few studies of airtightness at stock level in the UK, and airtightness is comparatively easy to measure compared to infiltration and ventilation, it is unsurprising that there are no measurements of ventilation and infiltration at stock level. Only case studies of a statistically insignificant sample of homes have measured infiltration and ventilation (Table 1). This part of the Rapid Evidence Assessment is restricted to UK studies. However, an extensive review and summary of tracer gas infiltration and ventilation studies conducted worldwide between 1980 and 2019 is presented in Roberts [39]. A focused review of the drivers and barriers of ventilation operation in UK dwellings is provided in Report 3 of this series [40].

[2] Airtightness tests were successful in 146 of an original sample of 160 dwellings. Of the 160 dwellings, there were 77 solid walled dwellings (10 with internal wall insulation, 13 with external wall insulation, one with both, 53 were uninsulated); 75 cavity walled homes (55 insulated, 20 uninsulated); eight homes with a mixed or unrecorded construction.

Table 1: Summary of literature on airtightness, infiltration, and ventilation of the UK housing stock.

Study	Year	No. dwell-ings	Meth-od	Average			
				Airtightness		Infiltration (h^{-1})	Ventilation (h^{-1})
				AP_{50}	N_{50}		
Warren and Webb [41]	1980	19	BD, TG	22.1	13.4	0.7	0.73 *
Everett [42]	1985	1	TG		8.9	0.41	
Courtney [43]	1986	26-100 †	BD, TG		11.5		0.7
Etheridge et al. [33]	1987	217	BD				
Cornish et al. [32]	1989	87	BD		7.3		
Galbraith et al. [44]	1989	32	BD		18.4		
Perera and Parkins [26]	1992	385	BD		13.0		
Stephen et al. [37]	1997	40	BD		16.6		
Stephen [21]	1998	384	BD	11.5			
Stephen [21]	1998	471	BD		13.1		
Crump et al. (2005) [45]; Dimitroulopoulou et al. [46] (winter)	2005; 2005	37	BD, TG		12.9		0.44
Crump et al. (2005) [45]; Dimitroulopoulou et al. [46] (summer)	2005; 2005	37	BD, TG		13.9		0.62
Johnston and Lowe [38] pre-retrofit	2006	12	BD	25.0			
Johnston and Miles-Shenton (2009) [47]	2009	7	BD	6.9			
Pan [22]	2010	287	BD	6.0			
Hubbard [48]	2011	5	BD	11.6	13.3		

Study	Year	No. dwell-ings	Meth-od	Average			
				Airtightness		Infiltration (h^{-1})	Ventilation (h^{-1})
				AP_{50}	N_{50}		
Guerra-Santin et al. [49]	2013	2	BD, TG	0.4	0.41		
Jones et al. [20] with permeable party walls	2015	671	BD, M	9.0		0.32	
Jones et al. [20] with impermeable party walls	2015	671	BD, M	8.9		0.44	
Johnston and Stafford [50]	2016	4	TG, M	6.2	6.0	0.3	
Love et al. [27]; Crawley et al. [28,29]	2017; 2019; 2020	144,024	BD				
Ashdown et al. [30]	2020	901	BD				
Pasos et al. [36]	2020	21	BD, TG, M	7.92			
Roberts [39]	2020	1 ‡	TG				0.8-3.3
Allinson et al. [35]	2022	30	BD; LPP				
Roberts et al. [51]	2022	1 ‡	TG			0.25	0.8-3.7
Roberts et al. [4]	2023	1 §	BD, TG, M	14.7	15.3	0.25	0.37
Glew et al. (2024) [34]	2024	146	BD; LPP	11.0			
Godefroy and Baeli [52]	2024	10	BD; LPP	2.54			

Key to methods: BD = Blower Door test; TG = tracer gas test; M = modelling; LPP = low-pressure pulse.

* 290 individual rooms.

† N_{50} = 100 dwellings, ventilation = 430 samples in 26 dwellings.

‡ Three separate rooms, not whole house. 79 tests.

§ 42 blower door and 19 tracer gas tests in one dwelling.

RQ2: How does the airtightness of existing UK dwellings compare to that of existing dwellings in other European countries and countries with a similar climate?

Key findings:

No studies report on the airtightness, infiltration, or ventilation of the existing dwelling stock in European countries and countries with a similar climate. Two recent studies report on large samples (>100,000) of new dwellings in France.

GRADE quality assessment rating:

There is very low-quality evidence of the airtightness, infiltration, and ventilation of the existing housing stock of Europe and countries with a similar climate to the UK.

As with the UK, there is scarce evidence for the airtightness of the housing stock of other European countries, or those with a similar climate. France, like the UK, has large (219,000 and 406,717) datasets (Table 2) of newly built dwellings only which therefore do not represent the national stock of existing dwellings. In the French newbuild airtightness dataset there is evidence for “last minute correction” – also known as in-test sealing [53] which reduces the reliability of this information as an indication of how the stock will perform once occupied. This has similarly been found in the UK dataset [29].

Small samples that are not representative of national stocks dominate the available data from Europe and other countries with a similar climate (Table 2). These could perhaps be amalgamated to produce a combined dataset that is diverse enough to be extrapolated to a representation of a national stock, as Jones et al. [20] did for the UK. France and Spain are the two countries most likely to be able to achieve this, but neither have yet done so.

Comparison between countries is also made difficult as many use different measurement protocols and testing methods. For example, some envelope components are sealed prior to testing in France but not in the UK [53,54] according to Method 3 of EN ISO 9972 [16]. Some countries use other metrics for airtightness such as air change rate, whereas air permeability is required in the UK Building Regulations [8]. Various reference pressures are used. In the UK it is 50 Pa, whereas France and Switzerland use 4 Pa [7–10,15].

Table 2: Summary of literature on airtightness and infiltration in European and New Zealand dwellings.

Study	Year	Country	Number of dwellings	Average		
				Airtightness		Infiltration (h^{-1})
				AP_{50}	N_{50}	
Bassett [55]	1984	New Zealand	40		9.0-19.0	
Boman and Lyberg [56]	1986	Sweden	500			0.17-0.78
Stymne et al. [62]	1994	Sweden	1,500			<0.5
Kauppinen [57]	2001	Finland	171		5.9	
Sfakianaki et al. [58]	2008	Greece	20		7	0.6
Hens [59]	2011	Belgium	15	9.3		
Ramos et al. [60]	2015	Portugal	49		6.8-8.9 *	
Kalamees [61]	2007	Estonia	32	4.2	4.9	
Montoya et al. [62]	2011	Spain				0.2
Pinto et al. [63]	2011	Portugal	5	6.1		
Alfano et al. [64]	2012	Italy	20			
Sinnott and Dyer [65]	2012	Ireland	28	9.1	9.6	
Tiberio and Branchi [66]	2013	Spain	25		3.4	
Villi et al. [67]	2013	Italy	5		3.4	
Górzeński et al. [68]	2014	Poland	10		3.6	
Laverge et al. [69]	2014	Belgium	44		6	
Meiss and Feijó-Muñoz [70]	2015	Spain	13	4.4	6.3	
Bramiana et al. [71]	2016	Netherlands	320	2.0		
Fernández-Agüera et al. [72]	2016	Spain	45	5.7		
Šadauskiene et al. [73]	2016	Lithuania	27	6.0		
Sinnott [74]	2016	Ireland	9	10.7		
Broderick et al. [75]	2017	Ireland	15	7.6	7.1	
Salehi et al. [76]	2016	Portugal	4	5.48-9.63		
Berthault et al. [77]	2019	France	117		0.44-13.7	
Domínguez-Amarillo et al. [78]	2019	Spain	21	25.6	7.5	

Study	Year	Country	Number of dwellings	Average		
				Airtightness		Infiltration (h^{-1})
				AP_{50}	N_{50}	
Fernández-Agüera et al. (2019) [79]	2019	Spain			7.0	
Feijó-Muñoz et al. [80]	2019	Spain	129	5.4 (houses) 6.8 (flats)	6.1 (houses) 7.1 (flats)	
Feijó-Muñoz et al. [81]	2019	Spain and Canary Islands	225	6.6	8.4	
Mélois et al. [53]	2019	France	129,000			
Martín-Garín et al. [82]	2020	Spain	37		9.03	
Böhm et al. [83]	2021	Czech Republic	558		1.03	
Poza-Casado et al. [84]	2021	Spain	400		7.52	
Birchmore et al. [85]	2023	New Zealand	2		9.74	
González-Lezcano et al. [86]	2023	Spain	151	5.8		
Hallik et al. [87] – pre-2008 dwellings	2023	Estonia	539	6.9		
Hallik et al. [87] – post-2008 dwellings	2023	Estonia	539	1.6		
Moujalled et al. [88]	2023	France	406,717 †		1.70 and 1.43 ‡	

* In renovated versus non-renovated dwellings [60].

† Moujalled et al. [88] reported a sample size of 406,717, but 10,603 of these were non-residential buildings and distinctions between the airtightness of the sample is not obvious, so the whole sample was reported.

‡ The two N_{50} values are reported for single-family and multi-family dwellings respectively.

RQ3: How does airtightness or infiltration differ in existing dwellings with respect to the characteristics of the dwellings?

Key findings (UK dwellings):

There is no single study which provides conclusive evidence of the influence of dwelling characteristics on airtightness or infiltration in existing UK dwellings at stock level. Smaller sample, “case study” evidence is largely relied upon.

Several influential factors were identified:

- Built form
- Construction age (confounded by several variables)
- Floor type
- Short- and long-term degradation (and variation)
- Weatherstrip detailing
- Quality of workmanship
- Design targets and regulations (in newbuilds)

Several uninfluential factors were identified:

- Dwelling volume and/or surface area
- Listed status
- Roof type
- Ventilation type in newbuilds (there is evidence for this being influential in France, however)

Several factors were inconclusive, unknown, or contradictory:

- External wall type (due to changing construction practices)
- Inter-dwelling air leakage effects
- Window type
- Presence of chimneys (due to sealing during airtightness tests in some cases)

GRADE quality assessment rating:

There is low-quality evidence that the airtightness and infiltration of the existing UK housing stock is influenced by any single factor or combination of factors.

A prior review of the factors influencing airtightness in dwellings across multiple countries identified as influential factors: dwelling geometry, construction materials, technology (heating and ventilation) and guidance (design targets and workmanship) [89], with the significant factors listed in Table 3. Contradictory information has emerged since the Prignon and Van Moeseke [89] review was published. For example, this review found, with evidence in the following sections, that ventilation system type is not a significant factor influencing airtightness in new UK, French, or Czech[3] dwellings.

Table 3: Significant and not significant factors influencing airtightness identified by Prignon and Van Moeseke [89]**.**

Significant	Not significant
Envelope structure	Roof type
Building method	Heating system
Ventilation system	Window material
Design target	Floor structure
Supervision and workmanship	Climate variation and surroundings

Among the most important papers about the influence of building characteristics on airtightness in existing UK dwellings is Stephen [21] and in new dwellings is Pan [22]. Pan takes a particularly rigorous approach to exploring the relationship between airtightness and an individual factor, using statistical tests to determine the interaction between them [22]. However, the sample is small (n = 287) and restricted to dwellings built between 2006-2010. The findings are noted in the following sections.

The DESNZ DEEP project was unable to identify a relationship between airtightness and characteristics such as wall type, floor type, and EPC rating [34]. Indeed, the authors report that it was not possible to identify which dwellings would have excessive air leakage prior to testing. It should be noted, however, that the project did not collect data from a statistically significant sample of the UK stock.

Built form (dwelling type)

In a study of 287 UK new dwellings (110 houses and 117 flats) built post-2006, it was shown that the air permeability of flats is statistically significantly lower than that of houses (Table 4) [22]. Breaking this down further, mid-floor flats had the lowest air permeability, followed by

[3] Applies to non-Passivhaus dwellings only.

ground-floor flats, top-floor flats, mid-terrace houses, detached houses, end-terrace houses, and finally semi-detached houses.

Table 4: Air permeability of different built forms (post-2006 dwellings) (Pan [22]**).**

Dwelling type	Dwelling sub-type	Air permeability ($m^3/h.m^2$ @ 50 Pa)
Houses	All	7.14
	End-terrace	7.17
	Mid-terrace	7.07
	Detached	7.12
	Semi-detached	7.83
Flats	All	5.25
	Ground-floor	5.41
	Mid-floor	4.50
	Top-floor	5.94

The differences between the dwelling types was only statistically significant between the mid-floor flat and each of the four house types, and between the ground-floor flats and semi-detached houses [22]. This finding is supported in a study of 37 dwellings built 1995-2005 where flats were most airtight and mid-terrace and semi-detached houses the least [46].

Stephen [21] does not attempt to distinguish between the airtightness of houses and flats. It is assumed this is because the flats in the dataset are mostly constructed of precast concrete panels, which are inherently airtight, and so no useful distinction between built form and airtightness can be made. The report does, however, note that the number of storeys in a dwelling does not significantly influence airtightness. In contrast, a study of 32 new dwellings in Estonia found that two-storey dwellings were less airtight than one-storey dwellings [61].

Drawing on the literature from other European countries, the difference in airtightness between flats and houses is contradictory. In Finland, it was found in a sample of 56 flats and 170 houses that flats were more airtight [90], whereas in a study of 129 dwellings in continental Spain, houses were found to be more airtight than flats[4] (apartments) [80]. In tests on 40 pre-fabricated timber dwellings in Poland, there was no correlation between the length of party wall and airtightness [91]. Finally, in Portugal, geometry is reported to be a more important modifier of airtightness than dwelling type (house or flat), but the sample size is small, just four dwellings [76]. Yet, in 117 French dwellings built before 2005, apartments were more airtight than houses (4.9 vs. 7.2 h^{-1} @ 50 Pa) [77].

[4] The air permeabilities and airtightness of houses was 5.4 and 6.1 $m^3/h.m^2$ @ 50 Pa versus flats at 6.8 and 7.1 h^{-1} @ 50 Pa [80].

Age

Overall, UK dwellings built pre-1919 and post-1980 are more airtight (less leaky) than those built in the middle of the century, whereas in Europe and New Zealand there is a trend for increasing airtightness (less leaky) in newer dwellings, as discussed in the following paragraphs. A strength of existing UK research is a range of dwellings being sampled across age bands (although only up to 1994), whereas non-UK studies tend to be more limited in the age ranges sampled.

There is no evidence to suggest that older UK dwellings are less airtight according to analysis of 421 UK dwellings built prior to 1994 [21]. The trend is for the oldest dwellings (those built pre-1900 to 1919) and the youngest (those built 1980-1994) to be the most airtight (less leaky). Those built 1930-1959 and 1970-1979 were the least airtight (leakiest). The authors attribute this to other factors related to construction type including claims that the move to cavity walls after the 1920s may have decreased airtightness, and this is supported by further analysis of the dataset with respect to wall type. Dwellings built post-1980 were more airtight than average [21]. The authors state this could be due to fewer chimneys in newer dwellings, the introduction of sealed boiler flues, and adoption of other energy efficiency measures. There is a contradiction, however, concerning chimneys. The study states that chimneys were sealed during the tests and so their contribution would not be accounted for, and this is likely to be a large air leakage path during normal operation. The absence of air leakage via chimneys is important and affects the reliability of the results when using these data to convert to infiltration if this air leakage path is not accounted for in the model. Despite this, Johnston argues to the contrary, i.e., that there is a relationship between age and airtightness [92]. The DESNZ DEEP project indicates that the English houses built after 2000 were more airtight from an overall sample of 160 houses [34].

Bramiana et al. [71] warn against characterising airtightness by age due to the interrelationship between age and several other factors. Age is linked to degradation over time, seasonal variation, construction types, ventilation systems, design standards, and regulations. Even so, the authors report that old buildings are leakier than new in a study of 320 Dutch dwellings. A New Zealand study of 40 timber-framed houses supports this saying that whilst there was no significant increase in airtightness in dwellings 0-20 years old, those older than 20 were less airtight [55].

Blower door tests conducted between 2003 and 2022 on 539 detached houses and apartments built between 1810 and 2022 in Estonia revealed that newer dwellings were significantly more airtight [87]. This is due to Estonian building performance regulations being introduced in 2008. The variation in airtightness was greater in older buildings; up to 35 $m^3/h.m^2$ @ 50 Pa compared to 6.6 $m^3/h.m^2$ @ 50 Pa in newer buildings.

Infiltration measurements in 1,500 dwellings in Sweden found that those constructed pre-1940 and 1941-1960 had higher infiltration rates than newer dwellings [93].

In Ireland, the notion that new dwellings cannot be automatically assumed more airtight is supported by a field study of dwellings built from 1941 to 2008, as even the newest dwellings had high air permeability in excess of 10 m³/h.m² @ 50 Pa [65]. The study showed that dwellings built pre-1975 had a mean air permeability of 7.5 m³/h.m² @ 50 Pa.

In 558 new (2006-2019) low energy and Passivhaus dwellings in the Czech Republic, airtightness increased with every year of construction, probably driven by mandatory standards and government subsidies [83].

In a study of 16 dwellings in Denmark, the houses built between 1963 and 1974 were the least airtight, but the study highlights that the other dwellings in the study had been retrofitted and so it was not possible to relate building age to airtightness [94].

A survey of 219,000 predominantly newbuild French dwellings showed that median airtightness increased in dwellings built post-2007 due to the introduction of new requirements. Since then, the median air leakage has remained stable as the test has become mandatory for all new dwellings [53]. The key drawback of this dataset is that it is not representative of existing dwellings.

External wall type (construction)

Etheridge et al. [33] found from a sample of 217 English dwellings that those of timber-framed construction were on average half as leaky as the traditional dwellings with the same volume. In a sub-sample of only traditional dwellings, those with solid or filled cavities were more airtight than those with empty cavities. However, the wall construction (e.g., masonry or timber-framed), had a greater influence on airtightness than whether it was insulated.

In a sample of 433 UK dwellings[5], Stephen [21] reported that cavity masonry walls were the least airtight (around 14 1/h @ 50 Pa), then solid masonry (~ 13 h^{-1} @ 50 Pa), timber-frame (~ 8 h^{-1} @ 50 Pa), and finally precast concrete (~ 7 h^{-1} @ 50 Pa). The study states that precast concrete panels are inherently airtight compared to masonry (or block concrete) walls where air leaks through numerous mortar joints, and wall-floor junctions. The finding is confounded by the fact that the sample of dwellings with precast concrete panels are exclusively high-rise flats, which may affect the airtightness. Further confounding factors relate to age – the timber-framed dwellings tend to be built post-1980 – an age band associated with more airtight dwellings. The report concludes that building with a particular wall construction does not guarantee a particular level of airtightness [21]. Elsewhere, it has been claimed that masonry walls are 60% more airtight than timber-framed walls [95]. In a study of 10 Polish dwellings built between 1900-2012, those with masonry brick walls with inner plaster were more airtight than timber-framed dwellings [68].

The internal finish of the external wall is also likely to be influential on airtightness. Plasterboard wall linings can result in poor airtightness [38], and Lowe et al. [96] have demonstrated that wet plastered masonry can make the walls significantly more airtight.

The DESNZ DEEP project did not find a correlation between airtightness and wall material, although it is noted that most houses in the sample were of masonry construction and none were timber-framed [34]. Johnston et al. [92] found that steel framed dwellings were only

[5] Note that this is smaller than the sample listed in Table 1 because the authors selected a sub-sample.

slightly less airtight than dry lined walls and could have been improved with a clearly defined and well-constructed airtightness barrier.

Turning now to newbuild UK dwellings, it was shown that dwellings built with precast concrete panels were significantly more airtight than those built using a timber frame (2.21 vs. 6.04 $m^3/h.m^2$ @ 50 Pa) – yet those constructed with masonry and reinforced concrete[6] were the least airtight of all (6.51 and 6.64 $m^3/h.m^2$ @ 50 Pa respectively) [22].

In a study of 901 new build homes from a single English housing developer, it was found that reinforced concrete and dry-lined masonry construction were more airtight than timber-frame and considerably more airtight than steel frame construction [30]. The study highlights the improvements brought to dry-lined masonry walls which were previously being thought of as a less airtight construction, e.g. [38,96,97]. Others have similarly shown UK dwellings built of steel frames to be significantly less airtight than, for example, wet plastered masonry – which achieved high airtightness without specific consideration for the matter, unlike timber- and steel-frame which require careful consideration and design [47,92].

Elsewhere in Europe, the database of 219,000 newbuild French dwellings has shown that timber-framed walls are less airtight than concrete or brick – but the difference is small [53]. The study also shows that external wall insulation makes multi-family buildings (apartments) more airtight, although the same trend was not present for single-family houses [53]. In 539 Estonian detached houses and apartments, timber-based construction had significantly higher air leakage than precast concrete, block, and brick dwellings [87]. External render onto masonry was found to significantly increase airtightness in 129 Spanish dwellings [80]. But there was no correlation between wall or roof construction on airtightness in 40 Polish pre-fabricated wooden framed buildings [91].

Change over medium- and long-term (degradation)

The National House Building Council (NHBC) conducted fan pressurisation tests on 23 dwellings (all <4 $m^3/h.m^2$ @ 50 Pa) at the time of construction and again one to three years later. Most of the sample was detached houses (61%) or flats (39%) but there were no semi-detached or terraced houses. Most had masonry dry-lined walls (74%), but some had masonry plastered walls (13%), or a timber frame (13%). Fifteen (65%) of the dwellings became less airtight, on average by 1.5 $m^3/h.m^2$ @ 50 Pa but some by 5.91 $m^3/h.m^2$ @ 50 Pa. Eight of the dwellings (35%) became more airtight, on average by 0.63 $m^3/h.m^2$ @ 50 Pa. Generally detached houses had the greatest reduction in airtightness, as did timber-framed dwellings. Plastered masonry dwellings showed the smallest change [98].

Most changes to airtightness appear to occur in the first few years after construction [99]. In measurements of airtightness in 60 new timber-framed and masonry cavity wall dwellings one month after occupation and again after one year, it was found that the timber-framed dwellings became 10% less airtight and the masonry cavity dwellings 14.2% less airtight [21].

[6] This construction type differs from precast concrete panels.

Ten retrofitted UK dwellings were tested for airtightness once after retrofit and again ten years later[7] [52]. On average the air permeability increased over ten years by 0.56 m³/h.m² @ 50 Pa (from 1.98 to 2.54 m³/h.m² @ 50 Pa). The greatest increase in air permeability (i.e., a dwelling becoming less airtight) was 2.58 m³/h.m² @ 50 Pa. Two dwellings, however, became more airtight. One of the main issues identified was failing door and window seals which were not replaced over the ten years in all but one house [52].

In two adjoining semi-detached UK houses that were built in the 1930s, airtightness tests were conducted in 2017 and again in 2022. No changes or retrofits had been made to the houses during that time. The results revealed that the houses' air permeability increased from 14.7 and 14.9 m³/h.m² @ 50 Pa to 18.5 and 17.5 m³/h.m² @ 50 Pa – an increase of 26% in one house and 17.5% in the other [100,101]. Being a masonry cavity house, it was hypothesised that structural cracking in the thermal envelope of these 80+ year old dwellings led to a decrease in airtightness following observations and a structural engineers report.

Plasterboard-lined masonry dwellings are likely to become less airtight over time due to wear-and-tear of the plasterboard lining around the edges of doors, windows, and behind kitchen units [38]. In a French study of 61 timber-frame houses, airtightness was found to deteriorate in the first year after construction (by 18% on average) and then stabilise. Then between three and 10 years, airtightness decreased again by 20% on average [102].

In 41 low energy Belgian dwellings, it was shown that airtightness changes over time – on average being 38% less airtight between tests at 6 months and 12 years. There was a positive correlation between the number of days between measurements and the decrease in airtightness. In 29 of the dwellings, airtightness decreased by up to 200% (to 1.36 h^{-1}@ 50 Pa). In four of the dwellings there was an increase in airtightness, of up to 1.19 h^{-1} @ 50 Pa [103]. Similarly, Bracke et al. [104] demonstrated up to 200% decreases in airtightness after construction, but they note that in the very airtight dwellings studied, the absolute increase was quite small.

In contrast, Wolfgang Feist, co-creator of the Passivhaus concept, reports that Passivhaus dwellings remain stable in their airtightness over more than 25 years due to the durability of all building fabric components [105].

Seasonal variation in airtightness

Airtightness tests conducted in four different seasons on 287 different dwellings showed a pattern of increasing airtightness from summer (6.27 m³/h.m² @ 50 Pa) to winter (5.21 m³/h.m² @ 50 Pa), but not a difference that was found to be statistically significant at the 95% level [22].

Dimitroulopoulou et al. [46] found that in 37 UK dwellings built between 1995 and 2005 the airtightness was 1 h^{-1} @ 50 Pa higher in summer than in winter (13.9 vs. 12.9 h^{-1} @ 50 Pa).

[7] In the intervening period, only one home had additional retrofit carried out (the original test was conducted in the middle of a staged retrofit), beyond the adjustment (but not replacement) of door seals.

In the UK, 34 airtightness tests were conducted on a single house built in the 1930s on 13 different winter days between January and March [106]. The air permeability varied by 1.12 $m^3/h.m^2$ @ 50 Pa but there was no correlation with wind speed, wind direction, or indoor-outdoor temperature difference. The house had a masonry cavity wall construction so was perhaps less susceptible to changes in airtightness than, e.g., a timber-framed dwelling. Additionally, the tests were only conducted in winter so did not capture the full range of seasonal variation.

In a wooden house in Sweden, airtightness was reported to be 58% lower when the indoor relative humidity was lower (RH 25%). When relative humidity was high (90%) internal timber expanded which closed adventitious openings in the building fabric [107]. This indicates that seasonal variation is both dependent on the construction type as well as the climate.

A survey of 219,000 predominantly newbuild French dwellings showed no evidence of seasonal variation in airtightness in continental and oceanic climates – the measured variation was 5% [53].

Kim and Shaw [108] reported a 20% difference in airtightness in two houses measured in different seasons.

Volume and surface area

No correlation was observed between air permeability and floor area and only a weak correlation with envelope area in a survey of 287 newbuild UK dwellings [22]. However, in a survey of older English dwellings it was found that airtightness decreases with dwelling volume, although the correlation was not quantified [33]. Prignon and Van Moeseke [89] say this is because increasing volume multiplies the leakage paths.

In contrast, tests on 40 pre-fabricated timber-framed dwellings in Poland, revealed no correlation between volume or surface area and airtightness [91]. Similarly, in a Czech study, there was no correlation between volume and airtightness in low energy and Passivhaus new build dwellings [83].

Taking the English, UK, and European studies together, a trend may be apparent whereby the airtightness of less airtight dwellings are more influenced by dwelling volume and surface area than more airtight dwellings, but further research is required to firmly establish such a relationship.

Inter-dwelling air leakage

Air leakage across party walls, floors, or ceilings may occur between dwellings. Whilst this tends to be between two conditioned spaces, thus not increasing energy demand, it is undesirable for reasons of fire spread and air quality [21]. In the UK, it was found that inter-dwelling air leakage occurs in adjoining houses and contributes between 2 and 27% of the total air leakage [21]. In nine adjoining flats across seven floors, air leakage was found to occur between floors, but not between walls and contributes 12 to 34% of the total air leakage [32].

More recently, in dwellings in the North and Midlands of England, the DESNZ DEEP project found that the effects of inter-dwelling air leakage may be an artefact of the blower door testing method, but that more testing is required to generate conclusive results. It also says that the low-pressure pulse test results may not be as affected by inter-dwelling air exchange, but more investigations are needed [34].

The views from other European countries on inter-dwelling air leakage are conflicting. In three apartments in Sweden, it was reported that 12 to 36% of the total air leakage was attributed to internal partitions with other apartments [109]. In Germany, co-pressurisation tests using between two and eight blower door fans in eight multi-family buildings revealed that air leakage through internal partitions accounts for 27 to 32% of dwelling air leakage [110]. However, in 45 Spanish apartments built post-2000, no party wall air leakage was found [72]. Similarly, in tests on 40 pre-fabricated timber dwellings in Poland, there was no correlation between length of party wall and airtightness [91]. Perhaps the confusion arises because the guarded zone method, one of the methods to detect inter-dwelling air leakage, gives inconsistent results [111]. Stephen [21], however, describes three methods which could be used and these could potentially provide more accurate results.

Ground floor type

In a sample of 391 existing UK dwellings, it was shown that suspended timber floors are on average around 5 h^{-1} @ 50 Pa leakier than solid concrete floors (~11 h^{-1} @ 50 Pa vs. ~16 h^{-1} @ 50 Pa) [21]. It is noted, however, that suspended timber floors with tongue and groove floorboards the air leakage is limited to the perimeter of the floor. McGrath & McManus [112] provide further evidence for suspended floor air leakage and estimate that five million UK dwellings have a basement or timber sub-floor, presenting a significant source of air infiltration in UK dwellings. Their experiment demonstrates that air moves from the basement or sub-floor into the room, but air does not flow in the opposite direction. Thus, a source of unconditioned air is always moving into the room from below. Lowe et al. [96] similarly support the notion that suspended timber floors do not permit airtight construction. In a study of eight heritage buildings in Spain, four of which were dwellings built between 1893 and 1919, it was found that where an original timber floor had been replaced with reinforced concrete, airtightness was improved [82].

In contrast to previous studies, the DESNZ DEEP project's survey of 160 English homes reported only marginally worse airtightness in the homes with a suspended timber floor [34]. The authors state that any of the floor types in the sample could have a low airtightness and 70% of dwellings had air leakage at the ground floor-wall junction regardless or floor type.

Listed status

There are no studies which specifically examine the influence of listed status on airtightness.

Window number, size, and type

In existing UK dwellings, window type does not have a significant influence on airtightness because the effect is confounded by other factors [21]. However, other studies have attempted to quantify the effect of window type on airtightness. Pre- and post-retrofit of windows in 10

English dwellings showed that new windows increase airtightness (reduced air leakage) by 4.6 h^{-1} @ 50 Pa [113]; by 7 h^{-1} @ 50 Pa in another English dwelling [114]; and by 6.1 $m^3/h.m^2$ @ 50 Pa in an English semi-detached dwelling [106].

In a statistically representative sample of 225 dwellings from Spain and the Canary Islands, dwellings with aluminium windows were found to be more airtight than dwellings with wooden windows [81].

In 69 new UK dwellings, the number of "significant penetrations" which included windows and doors, showed a weakly positive correlation to air permeability [22]. Conversely, in 40 pre-fabricated timber dwellings in Poland, there was no correlation between the number of window openings and airtightness [91].

In 20 Greek dwellings, a correlation was noted between airtightness and window frame length in dwellings of low airtightness, but the small sample size prevents firm conclusions from being drawn [58]

Roof type

Exposed wood frame timber roofs become less airtight over time as joints between the wooden beams and plasterboard expand when the wood shrinks [102]. In a study of 10 Polish dwellings built between 1900-2012 it was noted that wooden pitched roofs were the least airtight of all areas of the building [68]. The study found that flat roofs of timber or concrete construction were more airtight.

Presence of air barriers and weatherstripping

In a subsample of 217 dwellings containing only those of traditional construction, it was found that "weather-stripped" dwellings are more airtight than dwellings without weather stripping, but the effect is small compared to that of construction type [33].

Timber-framed houses with a vapour barrier in France tended to become more airtight over time as the wood expands with humidity. Houses without vapour barriers became less airtight as leakage pathways appeared at junctions between wood and plasterboard as the mastic shrank over time [102].

A survey of 219,000 predominantly newbuild French dwellings states that incorrect fitting of vapour barriers in wooden buildings has led to this construction type being slightly less airtight than others [53].

Norwegian houses have been shown to be most airtight with an airtight wind-barrier installed [115]. The presence of a vapour barrier can increase airtightness, but the installation process is more labour-intensive than installing gypsum boards, which were found to be the least airtight air barrier. A vapour permeable barrier on a sample of 558 Czech low energy dwellings was more airtight than a polyethylene one [83].

Presence of chimneys

Both Stephen [21] and the DESNZ DEEP project [34] highlight that chimneys are sealed during airtightness tests, but usually open whilst the dwelling is in use. Thus, dwellings with chimneys will be less airtight in-use than during an airtightness test, although neither of the aforementioned authors quantify the effect of this. The effect is likely to be significant though. For example, in Norway, considerable air leakages from dwellings are associated with lightweight aggregate concrete chimneys – with the air leaks both via the chimney and the interface between the chimney and the roof [116]. The effect is even apparent in low energy dwellings. A survey of 558 dwellings in the Czech Republic found low energy dwellings with a chimney were slightly less airtight (0.98 vs. 0.84 h^{-1} @ 50 Pa) [83]. In 20 Italian dwellings, chimneys were found to be a considerable source of air leakage [64].

Ventilation type

Ventilation type was found to make very little difference to airtightness in a national survey of new UK homes[8] [28]. Mechanically ventilated new dwellings had only 0.46 m³/h.m² @ 50 Pa lower air permeability than naturally ventilated dwellings. The study highlights the disconnect between airtightness and ventilation in UK Building Regulations.

In 37 UK dwellings, all of which were naturally ventilated and built between 1995 and 2005, there was no relationship between airtightness and ventilation rates [46]. Likewise, there was no relationship between ventilation type and airtightness in 140,542 French newbuild single-family houses. However, there was a relationship in 70,632 multi-family dwellings, with those with balanced ventilation systems (e.g. MVHR[9]) being more airtight [53].

In 558 dwellings built between 2006 and 2019 in the Czech Republic, there was no difference in airtightness between naturally- and mechanically-ventilated low energy dwellings (1.03 and 1.07 h^{-1} @ 50 Pa respectively), but Passivhaus dwellings (all with mechanical ventilation and heat recovery) were more airtight (0.44 h^{-1} @ 50 Pa) [83].

Workmanship and build quality

In a study of 287 UK dwellings built after 2006, dwellings built by three different companies were compared. There was a statistically significantly difference between the airtightness achieved by two of the companies [22]. This may indicate that one building company had different built quality standards or construction management approaches. Evidence from four timber-framed dwellings in England also indicates that the quality of workmanship and the level of site supervision can influence airtightness [47]. Wingfield et al. [97] similarly link good airtightness to good build quality.

In Belgium, 14 dwellings showed significant variations in airtightness which was attributed to poor workmanship [59]. Also in Belgium, Laverge et al. [69] highlight that a sample of 161 privately-built homes with attention to airtightness details are twice as airtight as a randomly selected sample of 44 dwellings. Sinnott and Dyer [65] state that quality workmanship is

[8] Data were collected using Method B of BS EN 9972 [16] which excludes purpose-provided ventilation by temporarily sealing for the duration of the test.
[9] Mechanical ventilation with heat recovery.

essential for making airtight homes in Ireland, which is supported by a study of 32 dwellings in Estonia [61].

Design targets and regulations

In 287 newbuild UK dwellings, design targets have been shown to positively correlate with airtightness [22]. Similarly, a large dataset of 144,024 new UK dwellings has shown that air permeabilities are clustered close to design targets, e.g. 5 $m^3/h.m^2$ @ 50 Pa as a result of in-test sealing of construction elements to “achieve” a particular target or comply with regulations [27]. The authors highlight the potential role of the test and lodgement procedure in distorting the test results and state that secondary sealing should be discouraged, with a focus instead on the primary air barrier. In a separate paper, the same authors demonstrate that modal air permeability has improved by 3.6 $m^3/h.m^2$ @ 50 Pa since testing became mandatory, but they also estimate that 39% of dwellings have sealing interventions at the point of pressure testing [29]. Similarly, “last minute correction” has also been found in a large airtightness dataset of new French dwellings [53]. In contrast, however, a Spanish study of 129 dwellings found no relationship between regulations and increased airtightness [80].

Summary

There is no single study which provides conclusive evidence of the influence of dwelling characteristics on airtightness or infiltration in existing UK dwellings at stock level. Smaller sample, “case study” evidence is largely relied upon. **Flats** are more airtight than houses (dwellings built 1995-2005 and 2006-2010). Old (pre-1919) and newly built dwellings are the most airtight – but **age** is a factor confounded by several variables including wall type. There is contradictory evidence relating to **external wall type** and airtightness – particularly as construction practices have changed over time (improvements to timber-frame sealing and the use of wet plaster). Dwelling airtightness may **degrade** rapidly in the first year after construction yet may be stable over longer timescales. Short-term changes in airtightness (**seasonal variation**) may occur in some dwellings, particularly timber-frame construction. There is no correlation between **volume**, **surface area**, and airtightness. There is contradictory evidence regarding the occurrence of **inter-dwelling air leakage**. Suspended timber **floors** are found to be less airtight than solid concrete floors in older studies, but recent evidence states the effect is only marginal. There is no evidence regarding **listed status** and airtightness. There is contradictory evidence regarding the effect of **windows** on airtightness, perhaps due to confounding factors. There is no evidence from the UK on the effect of **roof type**. **Weatherstrip** details may increase airtightness but the effect is small compared to construction type, and the sample is small and old. **Chimneys** are often sealed during airtightness tests, so the in-use effect is unknown. There is no relationship between **ventilation type** and airtightness (in new dwellings) or ventilation rate (existing). The quality of **workmanship** is influential. In new homes, **design targets and regulations** influence airtightness.

RQ4: What is the potential impact on energy, cost, and carbon emission reductions of improving airtightness in the UK housing stock?

Key findings:

There was only one published study in the last decade that reported the impact of infiltration on energy and carbon emissions, but not cost. The study relies on an unvalidated model to predict the stock infiltration rate from airtightness and so calculate energy and carbon emissions. The report does not determine the potential effect of possible further airtightness improvements.

GRADE quality assessment rating:

There is low-quality evidence of the energy and carbon emissions associated with current housing stock level infiltration.

There is very low-quality evidence of the effect of improving airtightness across the UK housing stock on energy, cost, and carbon emissions.

Reporting at UK stock level, only one paper was found which reported on the contribution of wintertime infiltration[10] to heating energy demand [20]. The study found that infiltration was responsible for 3-5% of total UK energy heating demand, 11-15% of UK housing stock energy demand, and 10-14% of UK housing stock carbon emissions. The study also reports on the relationship between infiltration and indoor air quality, stating that up to 79% of the current English housing stock could require additional purpose-provided ventilation to limit the negative health effects of exposure to poor indoor air quality. The study does not consider the effect of improving airtightness and how this might affect energy, cost, and carbon emissions. The study relies on an unvalidated infiltration estimation model[11] to convert airtightness tests to an infiltration rate.

[10] Converted from airtightness measurements, not measured directly.
[11] Only very limited prior validation had taken place prior (three dwellings).

Summary, quality of evidence, and identification of research gaps

The Rapid Evidence Assessment has gathered the available literature and screened it for relevance and quality. Using the GRADE system to assess the quality of evidence:

- There is low-quality evidence about the airtightness of the existing UK housing stock. Further research is warranted as the available information is either outdated or based on small samples.
- Moderate quality evidence is available for the airtightness of the newly built UK stock, yet these data may be unreliable representations of true airtightness due to in-test sealing to achieve regulatory compliance. This limits the utility of these data for converting airtightness to in-use infiltration rates.
- There is very low-quality evidence for the infiltration rate of the UK housing stock. The stock level infiltration has been estimated using models based on the available airtightness data, but the models are not validated. There are no measurements of infiltration in sufficient quantities to be extrapolated to the UK stock.
- There is very low-quality evidence about the ventilation rates of the UK housing stock. Only limited case studies exist. This is unsurprising as testing is expensive and ventilation rates in buildings change over very short timescales.
- There is low or very low-quality evidence about the current airtightness of existing dwellings in other countries included in the review. Moderate quality evidence for the airtightness of the newbuild French housing stock is available, yet these are likely to contain similar in-test air sealing errors to those seen in the UK dataset.
- There is low-quality evidence for the factors which influence airtightness and infiltration in existing UK homes. Studies which do exist focus on small, homogeneous samples or case studies.
- There is low-quality evidence of the energy and carbon emissions associated with infiltration in the current UK housing stock and very low-quality evidence of the effect of improving airtightness on stock level energy, cost, and carbon emissions.

Calculating the baseline airtightness of the GB housing stock

This section addresses Objective 1.2: *Calculate the baseline airtightness of the GB 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*.

Methodology

The airtightness measurement datasets, identified from the Rapid Evidence Assessment, were evaluated to identify the most appropriate data for representing the housing stock. These data were cleaned, the characteristics of the GB[12] housing stock were assessed, and then a weighting factor was calculated for each dwelling measurement so that the dataset could be scaled to represent the GB housing stock. The resulting nationally representative airtightness data were analysed to understand the distributions across the housing stock, and by age band, main wall construction type, and built form. Further analysis was carried out to quantify the energy, cost, and carbon saving potential from retrofitting the housing stock to improve airtightness. This section presents an abridged description of the methodology, which is presented in full in Appendix B.

Availability of stock level airtightness data for UK dwellings

The UK airtightness datasets of existing homes identified in the Rapid Evidence Assessment (Table 1) were out of date or from small studies. The 130,000 results lodged with the Air Tightness Testing and Measurement Association (ATTMA) database annually [29] for newly constructed dwellings do not represent the existing UK stock, may be unreliable representations of airtightness due to “in-test” sealing [27], and are not publicly available or available for this project.

The only available dataset of airtightness results and dwellings metadata that is large and diverse enough to be extrapolated to the existing stock of UK homes was that owned by BTS (Build Test Solutions Ltd.). These data are not publicly available but were provided by BTS for use in this study. All air permeability[13] results in the BTS dataset were collected using the low-pressure pulse method [15] between August 2021 and October 2023. EPC-reported age bands for the dwellings in the dataset covered every age band from pre-1900 to 2007 onwards. Extrapolated AP_{50} values[14] provided in the dataset were calculated as $AP_{50} = 5.2540 \times AP_4{}^{0.9241}$, where AP_4 is the measured airtightness at 4 Pa in accordance with CIBSE TM23 [15], which is the procedure referred to in Part L of the English and Welsh Building Regulations

[12] The subsequent data cleaning process identified insufficient data from Northern Ireland to enable analysis of the UK stock, so only data for Great Britain (GB) were analysed.
[13] Air permeability (AP_x) is the measure of airtightness used in the Building Regulations [7,8].
[14] AP_{50} is the extrapolated air permeability (AP_{50}) at 50 Pa (m³/h.m²) in accordance with CIBSE TM23 [15]; similarly, AP_4 is that measured at 4 Pa.

[7,8]. The indoor-outdoor pressure difference of 4 Pa is that exerted across the building envelope during the low-pressure pulse test [117].

Dataset cleaning

The dataset comprised 12,277 test results gathered from 8,933 unique addresses. These data were submitted to four data cleaning phases, as described below. The cleaning process derived 5,125 unique results.

1. Initial filtering on test validity, geography, and property type, which reduced the dataset to 8,465 test results associated with 6,627 unique addresses located in Great Britain. (3,812 results removed.)
2. Matching of test results with dwelling Energy Performance Certificates (EPCs) available in national EPC registers, which reduced the dataset to 6,133 results associated with 5,083 unique addresses. (2,332 results removed).
3. Elimination of repeat test results associated with the same dwelling, which reduced the dataset to 5,334 results, each matched with a unique EPC, across 5,083 unique addresses[15]. (799 results removed).
4. Removal of dwellings lacking sufficient metadata for weighting, which reduced the dataset to 5,125 results. The variables required for weighting were built form, age band, and main wall construction type. Most of the removals here were due to EPCs providing a U-value for the main wall construction, rather than a description of the construction. (209 results removed).

Dataset corrections

Dataset corrections were considered to account for inter-dwelling air leakage across party walls and changing performance over time. However, no alterations were applied as there was insufficient robust evidence to support this at this time.

Assessing the characteristics of the GB domestic stock

Data describing the characteristics of the GB domestic stock were collated from national housing condition datasets accessed through the UK Data Service[16]. Nationally-weighted dwelling counts were summed across these datasets to determine the number of GB dwellings falling into different categories for each of the following dwelling characteristics:

- Built form (flat, terrace, semi-detached, detached, bungalow).

[15] Where multiple results were associated with the same address, these corresponded to pre- and post-retrofit tests, matched against pre- and post-retrofit EPCs. For this study, the pre- and post-retrofit dwellings were treated as two distinct dwellings.

[16] Data were sourced from: The English Housing Survey (EHS), 2017: Housing Stock Data [129]; The Scottish House Condition Survey (SHCS), 2012–2019 [130]; and The Welsh Housing Conditions Survey (WHCS), 2017–2018 [131]. Data from 2017 (and 2017–2018 for Wales) were used, as this was the most recent year for which data were available for all three countries (with the most recent national housing stock data releases for England, Scotland, and Wales having been for 2020, 2021, and 2017–2018, respectively.)

- Construction age band (pre-1919, 1919–1944, 1945–1964, 1965–1980, 1981–1990, post-1990).
- Main wall construction type (cavity with insulation, cavity uninsulated, solid with insulation, solid uninsulated, other).

Sample distributions of the examined dwelling characteristics were found to be inconsistent with those reported for the GB stock; therefore, weighting of the sample was deemed necessary to produce a nationally representative dataset.

Calculating weighting factors

Weighting factors for the airtightness test results were calculated using a Random Iterative Method (RIM), based on main wall construction type, built form and age band, using target proportions derived for the GB stock. Weights were then calculated by scaling to the size of the GB stock (N=27,755,120). The weighting efficiency was 51%, compared with 84%, 80%, and 71% respectively when weighting on each of construction type, built form, and age band alone.

Analysis of the nationally representative airtightness dataset

The nationally representative airtightness dataset was analysed as follows:

- Descriptive statistics were calculated for airtightness values (extrapolated AP_{50}) for the weighted, nationally representative airtightness dataset, categorised according to built form, age band, and construction.
- Distributions of airtightness among different dwelling categories were visualised and compared using boxplots and histograms.

Quantifying the impact of airtightness improvements

To assess the potential impact of stock-wide airtightness improvements, per-dwelling annual heating energy demand associated with infiltrative losses was estimated across the study sample (Appendix B). This was done using both the measurement-derived airtightness values, and following hypothesised airtightness improvements applied to achieve prescribed minimum levels of airtightness across the whole sample. These heating energy demands were then scaled up to GB stock level by summing across the GB stock-weighted sample, and the impact of the airtightness improvements quantified through comparison of energy demands calculated before and after their implementation. Using a national average unit fuel cost (0.0551 GBP/kWh) and emissions factor (0.190 kgCO_2e/kWh)[17], associated annual energy costs and greenhouse gas emissions were calculated similarly.

[17] A national average unit fuel cost and emissions factor were used due to the weighted sample's poor representation of the national distribution of main heating fuels used. The values used are weighted averages derived from unit costs and emissions factors provided in Government Green Book supplementary guidance on value of energy use and greenhouse gas emissions [133], weighted according to the distribution of main heating fuels reported for the GB stock.

Under the hypothesised national airtightness improvement scenarios, all dwellings with measurement-derived air permeability AP_{50} exceeding a prescribed maximum value AP_{max} (m³/h.m² @ 50 Pa) were assumed to have been treated to bring their air permeability down to AP_{max} (while those with $AP_{50} \leq AP_{max}$ were unaltered). Annual stock-level energy demands, costs and emissions were re-calculated for 6 scenarios, with $AP_{max} = 10, 9, 8, 7, 6, 5$ m³/h.m² @ 50 Pa, and the results compared against those produced for the current GB stock.

Note: Energy demands, costs, and emissions calculated for this study did not account for any efficiency losses. Calculated energy demands (and associated costs and emissions) pertain only to energy converted to heat within dwellings, rather than the total input heating fuel energy demands. This produces results that are heating system agnostic.

Results

Analysis of the nationally representative airtightness dataset

The 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 (see Table 5 for unweighted and weighted sample counts). A low-pressure pulse airtightness test result — which characterised dwelling air permeability (m³/h.m²) at a 4 Pa pressure difference — was available for each dwelling in the sample. These air permeability values were extrapolated to a 50 Pa pressure difference, denoted AP_{50}.

Table 5: Unweighted and GB stock weighted sample sizes.

Dwelling characteristic		Sample sizes			
		Unweighted sample		GB stock weighted sample ‡	
		Count	Proportion	Count	Proportion
All dwellings		5,125	100%	27,755,120	100%
Built form	Flat	797	16%	5,905,383	21%
	Terrace	1,571	31%	7,608,892	27%
	Semi-Detached	1,516	30%	6,949,774	25%
	Detached	358	7%	4,942,383	18%
	Bungalow	883	17%	2,348,688	8%
Age band	Pre 1919	1,435	28%	5,789,978	21%
	1919-1944	961	19%	4,216,435	15%
	1945-1964	1,359	27%	5,345,930	19%
	1965-1980	949	19%	5,508,388	20%
	1981-1990	167	3%	2,199,673	8%
	Post 1990	254	5%	4,694,715	17%
Main wall construction type	Cavity uninsulated	660	13%	5,997,448	22%
	Cavity with insulation	2,010	39%	13,155,709	47%
	Solid uninsulated	1,397	27%	7,121,560	26%
	Solid with insulation	427	8%	863,688	3%
	Other	631	12%	616,714	2%

‡ Following weighting, weighted sample counts and proportions correspond to those found in the GB stock.

Calculation of descriptive statistics produced for the nationally representative dataset (Table 6) determined that:

- The mean air permeability of GB dwellings was 8.6 ± 3.3 m³/h.m² @ 50 Pa (median 8.1 m³/h.m² @ 50 Pa).

- While the air permeability of GB dwellings ranges between 0.6 [18] and 46.2 m³/h.m² @ 50 Pa, the central 50% of dwellings (bounded by the lower and upper quartiles) have air permeability between 6.5 to 10.2 m³/h.m².

Table 6: Descriptive statistics for air permeability of the GB stock (m³/h.m² @ 50 Pa). (Sample N = 5,125, weighted N = 27,755,120).

Dwelling characteristic		Per-dwelling air permeability (m³/h.m² @ 50 Pa)						
		Mean	SD	Min	Q1	Median	Q3	Max
All dwellings		8.6	3.3	0.6	6.5	8.1	10.2	46.2
Built form	Flat	7.3	3.5	0.6	5.0	6.8	9.2	23.7
	Terrace	9.1	3.0	1.6	7.0	8.6	10.6	36.5
	Semi-Detached	9.2	3.2	1.8	7.1	8.6	10.8	46.2
	Detached	8.7	3.2	1.7	6.7	8.2	10.2	29.6
	Bungalow	7.6	3.4	1.6	5.4	7.0	9.3	44.0
Age band	Pre 1919	8.9	3.2	1.8	6.8	8.3	10.5	46.2
	1919-1944	8.7	2.8	2.0	6.9	8.3	10.2	27.8
	1945-1964	8.1	3.6	0.8	5.7	7.7	9.9	36.5
	1965-1980	7.9	3.3	0.6	5.9	7.7	9.9	44.0
	1981-1990	8.6	2.6	4.1	7.0	8.0	9.8	17.8
	Post 1990	9.3	3.5	1.6	6.7	8.5	11.1	21.5
Main wall construction type	Cavity uninsulated	8.2	3.9	0.6	5.8	7.8	10.3	36.5
	Cavity with insulation	8.6	3.1	1.3	6.5	8.1	10.2	28.3
	Solid uninsulated	8.9	3.1	2.0	6.9	8.4	10.4	46.2
	Solid with insulation	8.2	3.4	1.8	5.9	7.5	9.6	27.8
	Other	7.9	3.4	1.0	5.8	7.7	9.6	44.0

Visualising the distribution of extrapolated AP_{50} results in histogram form (Figure 2) indicates an approximately symmetric distribution centred roughly around the mean, with positive skew[19] resulting from a small proportion of values exceeding 20 m³/h.m². There is no evidence of bunching around design targets, with frequency dropping off steadily after a single peak.

[18] For comparison, Crawley et al. [28] equate the Passivhaus target of 0.6 h^{-1} @ 50 Pa to 0.5 m³/h.m² @ 50 Pa for a mid-terrace dwelling.
[19] Skewness describes the level of asymmetry in a distribution: a positively skewed distribution is one whose values are mainly clustered around the lower end of the distribution, with a small proportion of high values appearing as a 'tail' on the right-hand side of the distribution.

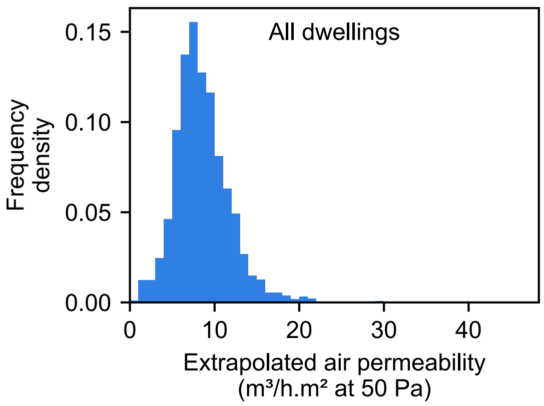
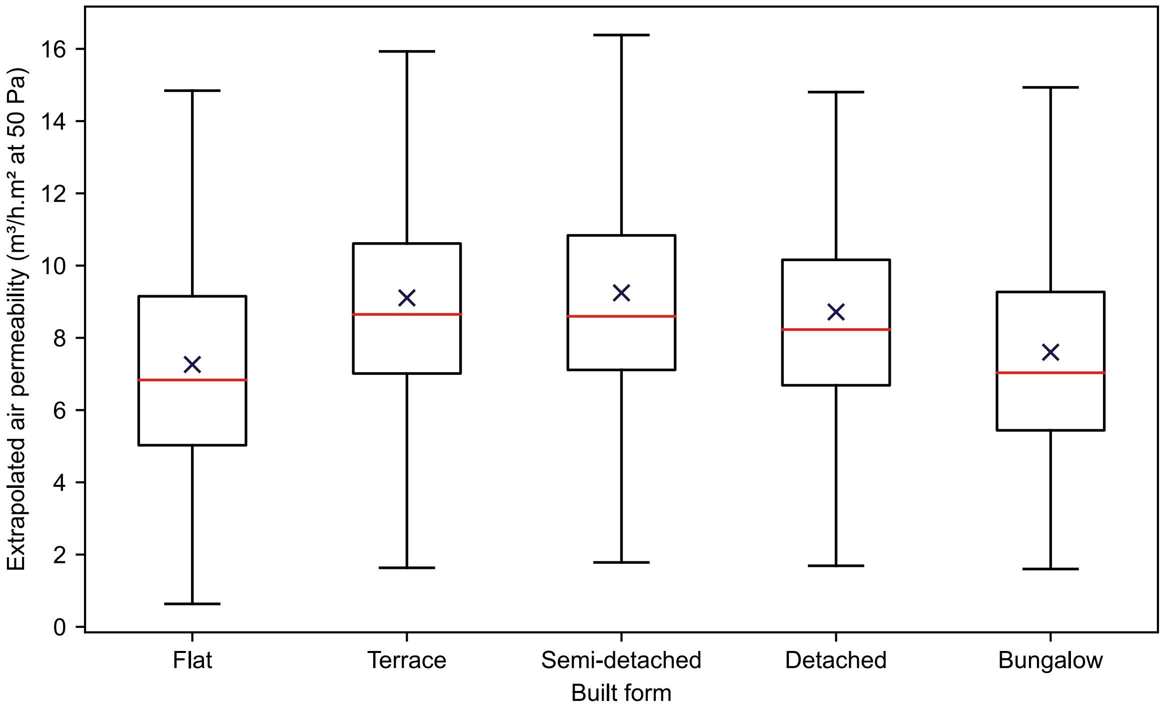


Figure 2: Distribution of per-dwelling AP_{50} air permeability results, weighted to GB stock.

Comparing the distributions of extrapolated AP_{50} values for dwellings categorised by built form (Figures 3 and 4):

- On average, flats and bungalows are the most airtight dwelling types, with mean air permeabilities of 7.3 and 7.6 m³/h.m² @ 50 Pa, respectively.
- On average, terraced and semi-detached dwellings are the least airtight, with mean air permeabilities of 9.1 and 9.2 m³/h.m² @ 50 Pa, respectively.
- Air permeabilities are distributed with slight positive skew for all dwelling types.
- There is little evidence of any bunching around individual values.



Box bounds indicate lower and upper quartiles (Q1 & Q3), red line indicates median, × indicates mean, tails indicate minimum and maximum values not including outliers. (Outliers defined as values lying outside of the range $[Q1 - 1.5 \times IQR, Q3 + 1.5 \times IQR]$, where $IQR = Q3 - Q1$.)

Figure 3: Boxplot representation of distribution of per-dwelling AP_{50} air permeability results categorised by dwelling built form, weighted to GB stock.

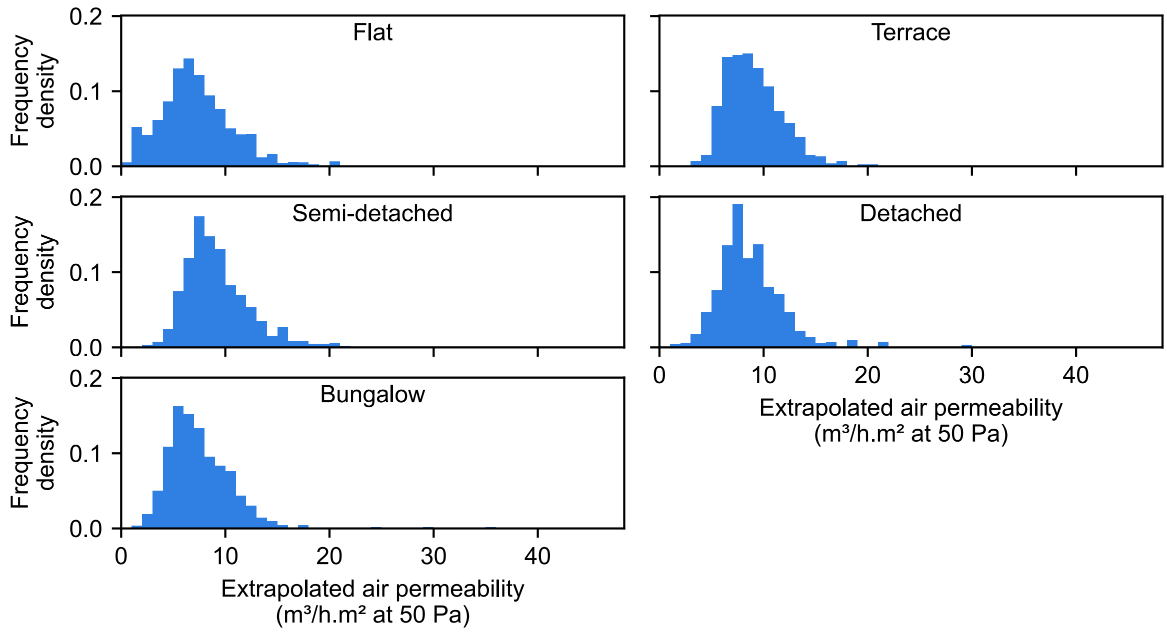
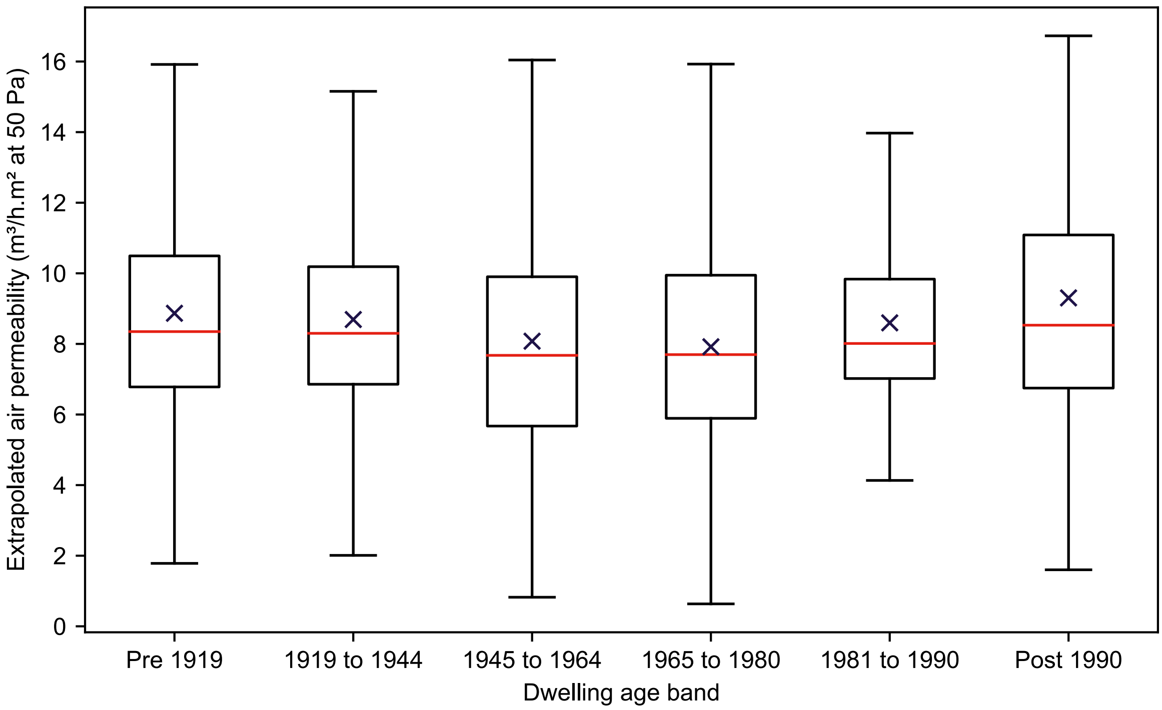


Figure 4: Histogram representation of distribution of per-dwelling AP_{50} air permeability results categorised by dwelling built form, weighted to GB stock.

Comparing the distributions of extrapolated AP_{50} values for dwellings categorised by age band (Figures 5 and 6):

- Mean air permeability decreases moving from the pre-1919 age band through to 1965–1980, falling from 8.9 to 7.9 m³/h.m² @ 50 Pa.
- After 1980, mean air permeability increases to 8.6 m³/h.m² @ 50 Pa in the 1981–1990 age band, before rising to 9.3 m³/h.m² @ 50 Pa for dwellings built from 1991 onwards.
- Air permeabilities are distributed with positive skew for all age bands.
- There is little evidence of any bunching around individual values.



Box bounds indicate lower and upper quartiles (Q1 & Q3), red line indicates median, × indicates mean, tails indicate minimum and maximum values not including outliers. (Outliers defined as values lying outside of the range $[Q1 - 1.5 \times IQR, Q3 + 1.5 \times IQR]$, where $IQR = Q3 - Q1$.)

Figure 5: Boxplot representation of distribution of per-dwelling AP_{50} air permeability results categorised by dwelling age band, weighted to GB stock.

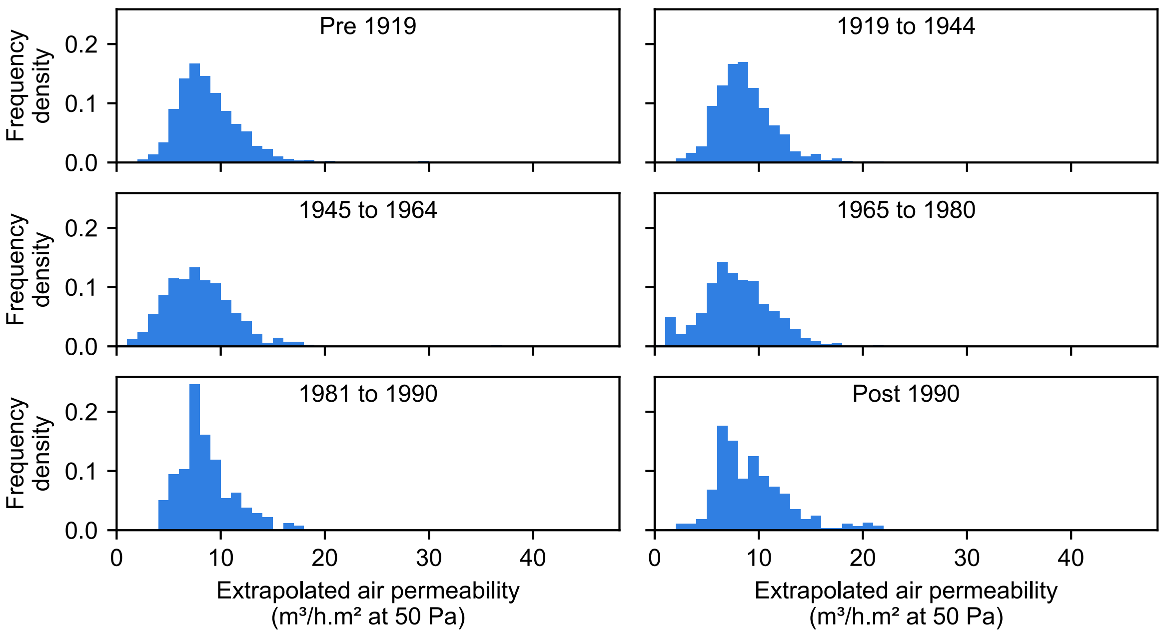
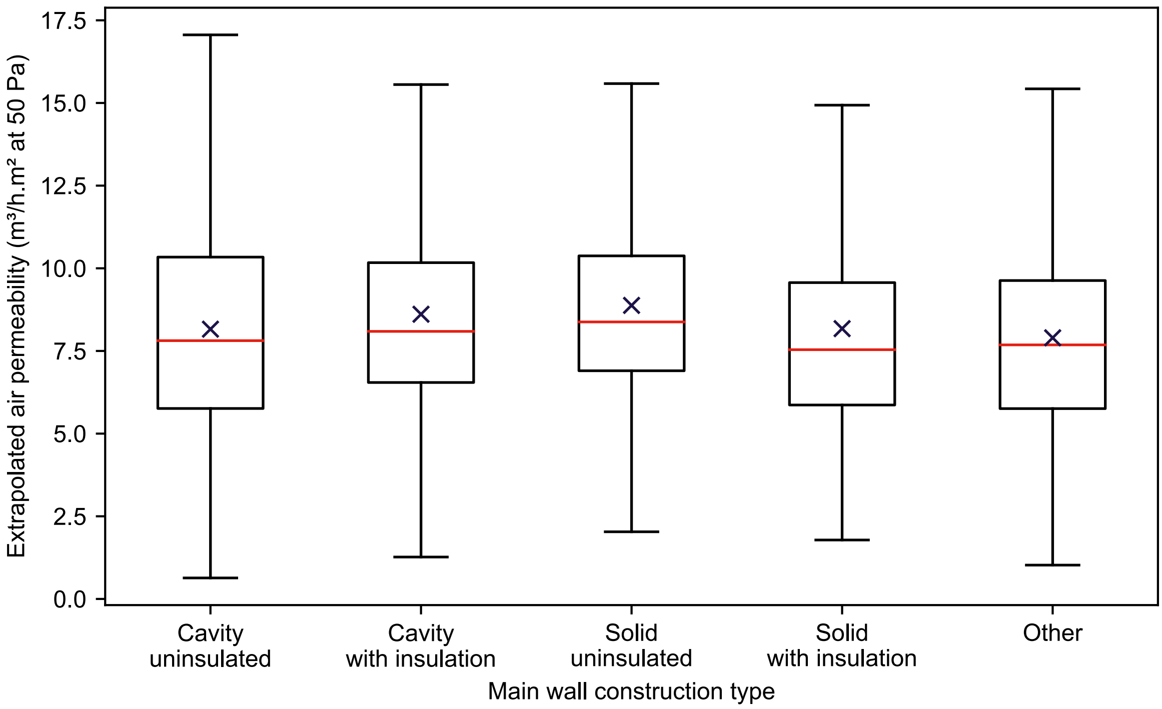


Figure 6: Histogram representation of distribution of per-dwelling AP_{50} air permeability results categorised by dwelling age band, weighted to GB stock.

Comparing the distributions of extrapolated AP_{50} values for dwellings categorised by main wall construction type (Figures 7 and 8):

- There is little clear distinction between the distributions exhibited for cavity and solid wall constructions, or indeed other wall construction types (comprising system built, timber frame and park home constructions).
- Dwellings with uninsulated cavity wall construction (mean air permeability 8.2 m³/h.m² @ 50 Pa) were on average slightly more airtight than those with insulated cavity wall construction (mean air permeability 8.6 m³/h.m² @ 50 Pa).
- Dwellings with insulated solid wall construction (mean air permeability 8.2 m³/h.m² @ 50 Pa) were on average more airtight than those with uninsulated solid wall construction (mean air permeability 8.9 m³/h.m² @ 50 Pa).
- For dwellings with insulated solid wall construction, there appears to be some bunching around values up to 10 m³/h.m² @ 50 Pa.



Box bounds indicate lower and upper quartiles (Q1 & Q3), red line indicates median, × indicates mean, tails indicate minimum and maximum values not including outliers. (Outliers defined as values lying outside of the range $[Q1 - 1.5 \times IQR, Q3 + 1.5 \times IQR]$, where $IQR = Q3 - Q1$.)

Figure 7: Boxplot representation of distribution of per-dwelling AP_{50} air permeability results categorised by main wall construction type, weighted to GB stock.

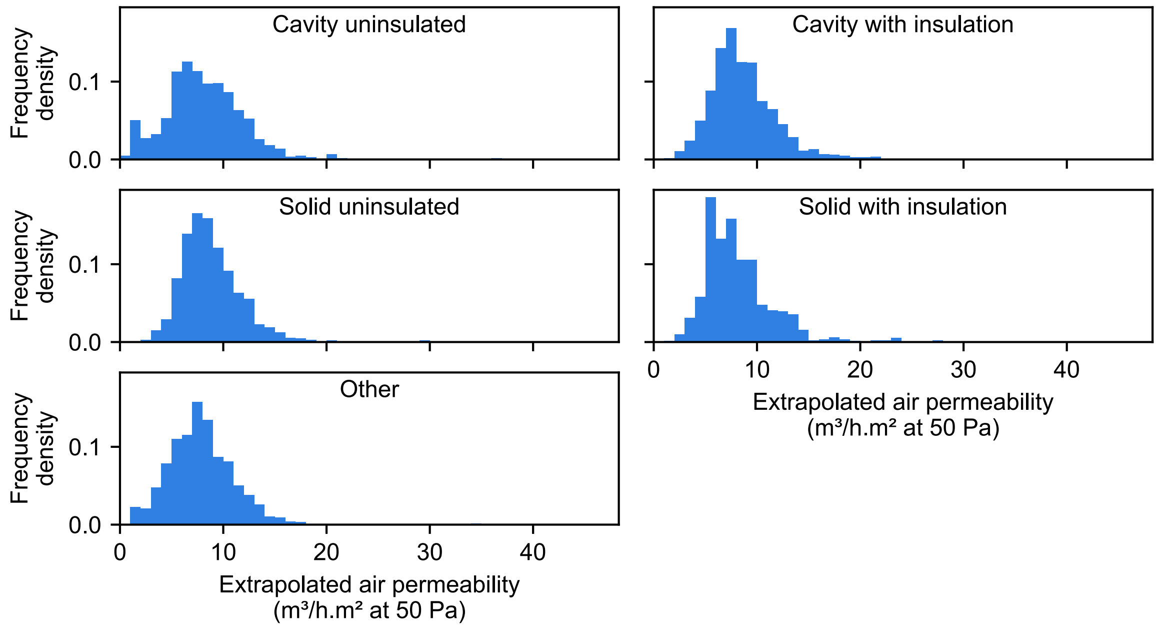


Figure 8: Histogram representation of distribution of per-dwelling AP_{50} air permeability results categorised by main wall construction type, weighted to GB stock.

Quantifying the impact of airtightness improvements

The estimated annual GB heating energy demand associated with infiltrative heat losses was 36 TWh, corresponding to a per-dwelling average of 1.3 MWh; this represents 16% of the GB domestic space heating demand for a normal year (221 TWh as estimated by Watson et al. [118]). The potential impacts of stock-wide airtightness improvements were estimated by recalculating the heating demand associated with infiltration after reducing air permeability to maximum values of 10, 9, 8, 7, 6, 5 m³/h.m² @ 50 Pa in those dwellings whose measured air permeability exceeded the target value. Comparison of energy demands calculated before and after airtightness improvements (Table 7) showed that:

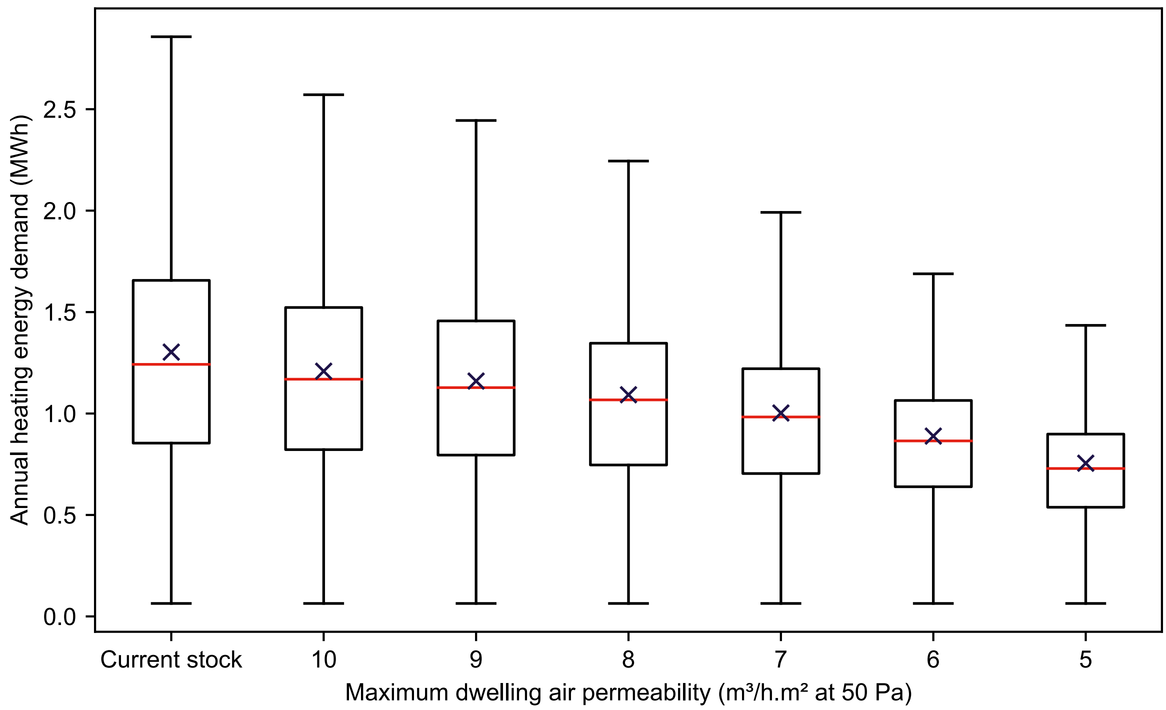
- Applying airtightness improvements to the 7.5 million dwellings (27% of the GB stock) with measured permeability exceeding 10 m³/h.m² @ 50 Pa, such that their air permeability is reduced to 10 m³/h.m² @ 50 Pa, would reduce the annual GB heating energy demand by an estimated 2.61 TWh — an average saving of 0.35 MWh[20] per treated dwelling, or 1.2% of total space heating demand for the GB housing stock.
- Achieving a national maximum air permeability of 5 m³/h.m² @ 50 Pa would require treatment of 25 million dwellings, representing 90% of the GB stock. The annual GB heating energy demand reduction associated with achieving this level of airtightness is estimated at 15.2 TWh relative to the current stock — an average of 0.61 MWh[21] per treated dwelling, or 6.9% of total space heating demand for the GB housing stock.

[20] This is equal to 3% of the median household gas demand of English and Welsh dwellings. In comparison, median gas savings for energy efficiency measures installed in 2021 are estimated at 14% for solid wall insulation, 10% for cavity wall insulation, and 3% for loft insulation [119].
[21] This is equal to 5% of the median household gas demand of English and Welsh dwellings.

Table 7: Estimated annual GB domestic heating energy demand associated with infiltrative heat losses, following airtightness improvements to achieve specified maximum dwelling air permeability levels, weighted to GB stock.

Maximum dwelling air permeability (m³/h.m² @ 50 Pa)	Number of dwellings treated (1000s) [% of stock]	Heating energy demand due to infiltrative losses		Energy savings relative to current stock		
		GB total (TWh)	Per dwelling mean (MWh)	GB total (TWh)	Per dwelling mean (MWh) *	Per treated dwelling mean (MWh) †
Current stock	0	36.16	1.30	—	—	—
10	7,543 [27%]	33.55	1.21	2.61	0.09	0.35
9	10,774 [39%]	32.19	1.16	3.96	0.14	0.37
8	14,305 [52%]	30.32	1.09	5.84	0.21	0.41
7	18,617 [67%]	27.83	1.00	8.33	0.30	0.45
6	22,430 [81%]	24.67	0.89	11.49	0.41	0.51
5	25,082 [90%]	20.96	0.76	15.20	0.55	0.61

* The GB total energy savings divided by total number of dwellings in the GB stock. † The GB total energy savings divided by the number of dwellings in the GB stock that received airtightness improvements.



Box bounds indicate lower and upper quartiles (Q1 & Q3), red line indicates median, × indicates mean, tails indicate minimum and maximum values not including outliers. (Outliers defined as values lying outside of the range $[Q1 - 1.5 \times IQR, Q3 + 1.5 \times IQR]$, where $IQR = Q3 - Q1$.)

Figure 9: Boxplot representation of distribution of per-dwelling annual heating energy demand associated with infiltrative heat losses, following airtightness improvements to achieve the indicated maximum dwelling air permeability levels, weighted to GB stock.

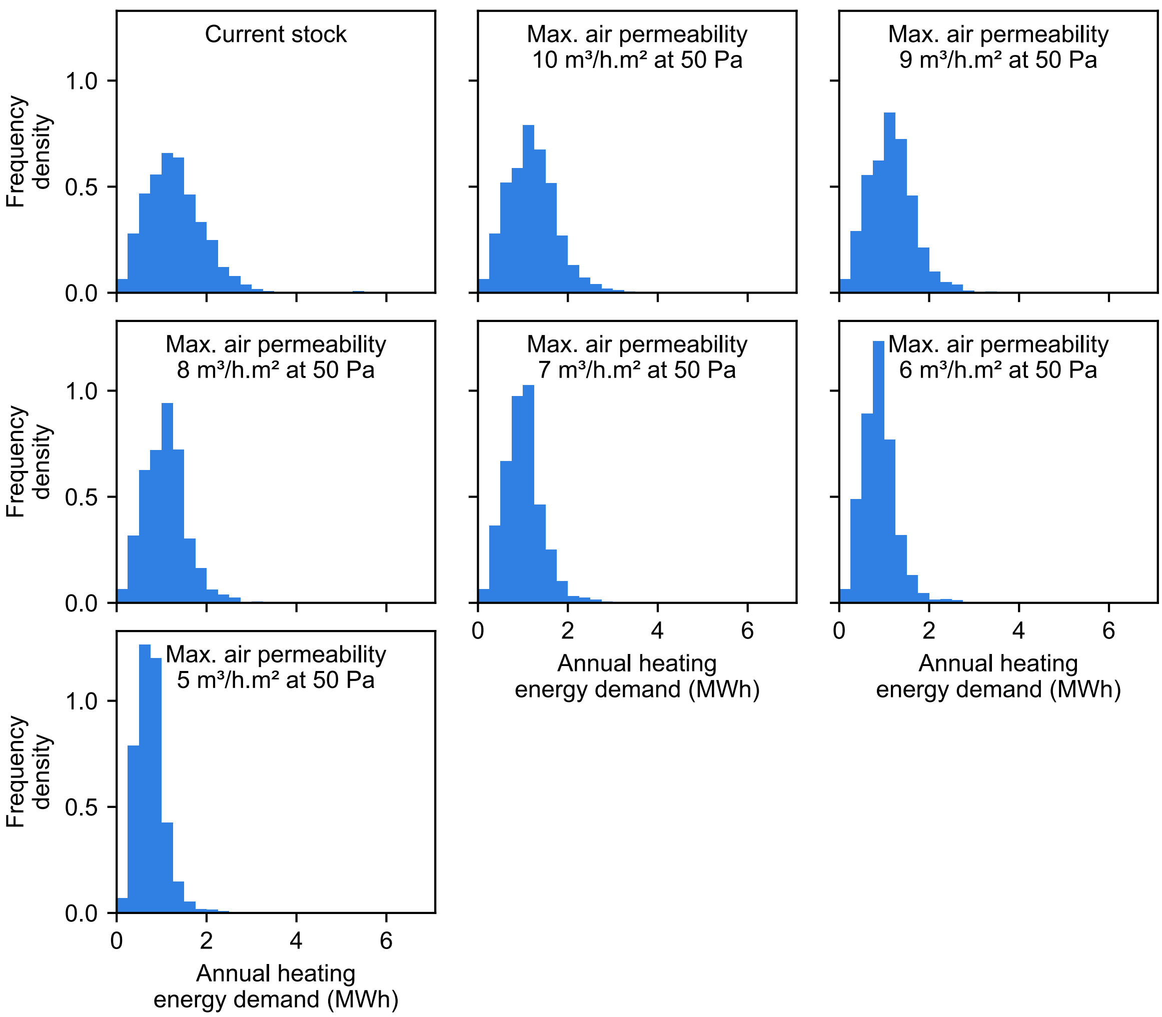


Figure 10: Histogram representation of distribution of per-dwelling annual heating energy demand associated with infiltrative heat losses, following airtightness improvements to achieve the indicated maximum dwelling air permeability levels, weighted to GB stock.

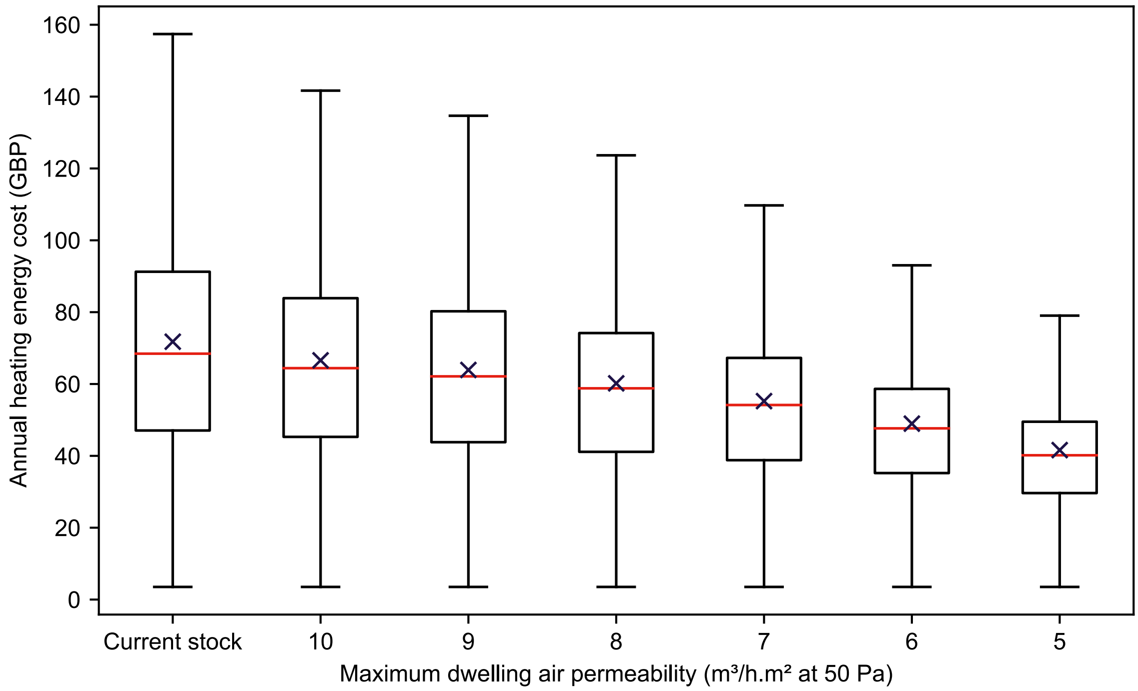
Comparison of annual GB heating energy costs associated with infiltrative losses, calculated before and after airtightness improvements (Table 8), showed that:

- The annual heating energy cost reduction associated with achieving GB-wide maximum air permeability of 10 m³/h.m² @ 50 Pa is estimated at 140 million GBP — an average annual saving of 19 GBP per treated dwelling.
- The annual heating energy cost reduction associated with achieving GB-wide maximum air permeability of 5 m³/h.m² @ 50 Pa is estimated at 840 million GBP — an average annual saving of 33 GBP per treated dwelling.

Table 8: Estimated domestic heating energy costs associated with infiltrative heat losses, following airtightness improvements to achieve specified maximum dwelling air permeability levels, weighted to GB stock.

Maximum dwelling air permeability ($m^3/h.m^2$ @ 50 Pa)	Number of dwellings treated (1000s)	Heating energy cost due to ventilative losses		Cost savings relative to current stock		
		GB total (bn GBP)	Per dwelling mean (GBP)	GB total (bn GBP)	Per dwelling mean (GBP) *	Per treated dwelling mean (GBP) †
Current stock	0	1.99	71.78	—	—	—
10	7,543 [27%]	1.85	66.59	0.14	5.19	19.08
9	10,774 [39%]	1.77	63.91	0.22	7.87	20.27
8	14,305 [52%]	1.67	60.19	0.32	11.59	22.48
7	18,617 [67%]	1.53	55.24	0.46	16.54	24.66
6	22,430 [81%]	1.36	48.96	0.63	22.81	28.23
5	25,082 [90%]	1.15	41.60	0.84	30.18	33.39

* The GB total cost savings divided by total number of dwellings in the GB stock. † The GB total cost savings divided by the number of dwellings in the GB stock that received airtightness improvements.



Box bounds indicate lower and upper quartiles (Q1 & Q3), red line indicates median, × indicates mean, tails indicate minimum and maximum values not including outliers. (Outliers defined as values lying outside of the range $[Q1 - 1.5 \times IQR, Q3 + 1.5 \times IQR]$, where $IQR = Q3 - Q1$.)

Figure 11: Boxplot representation of distribution of per-dwelling annual heating energy demand associated with infiltrative heat losses, following airtightness improvements to achieve the indicated maximum dwelling air permeability levels, weighted to GB stock.

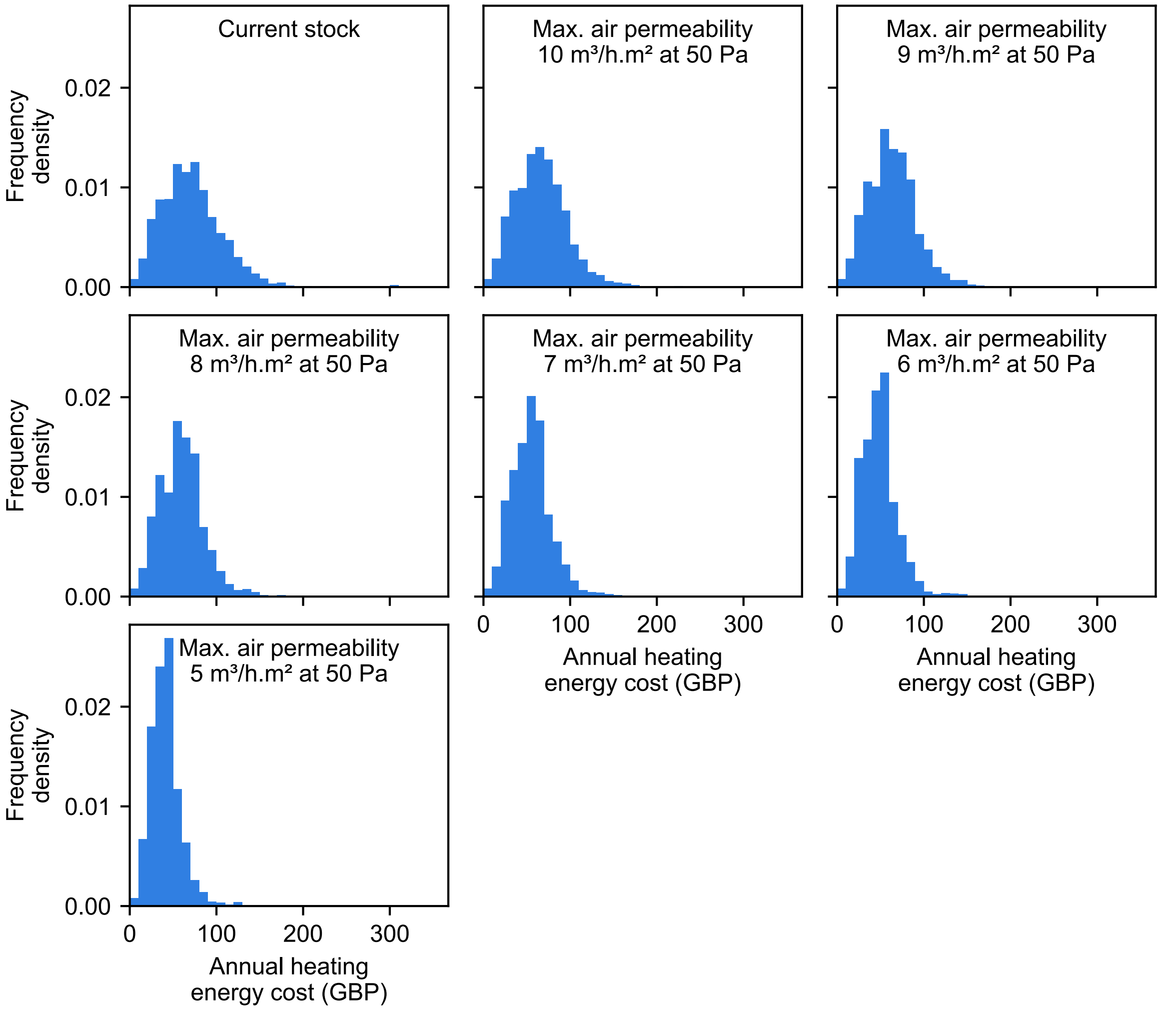


Figure 12: Histogram representation of distribution of per-dwelling annual heating energy demand associated with infiltrative heat losses, following airtightness improvements to achieve the indicated maximum dwelling air permeability levels, weighted to GB stock.

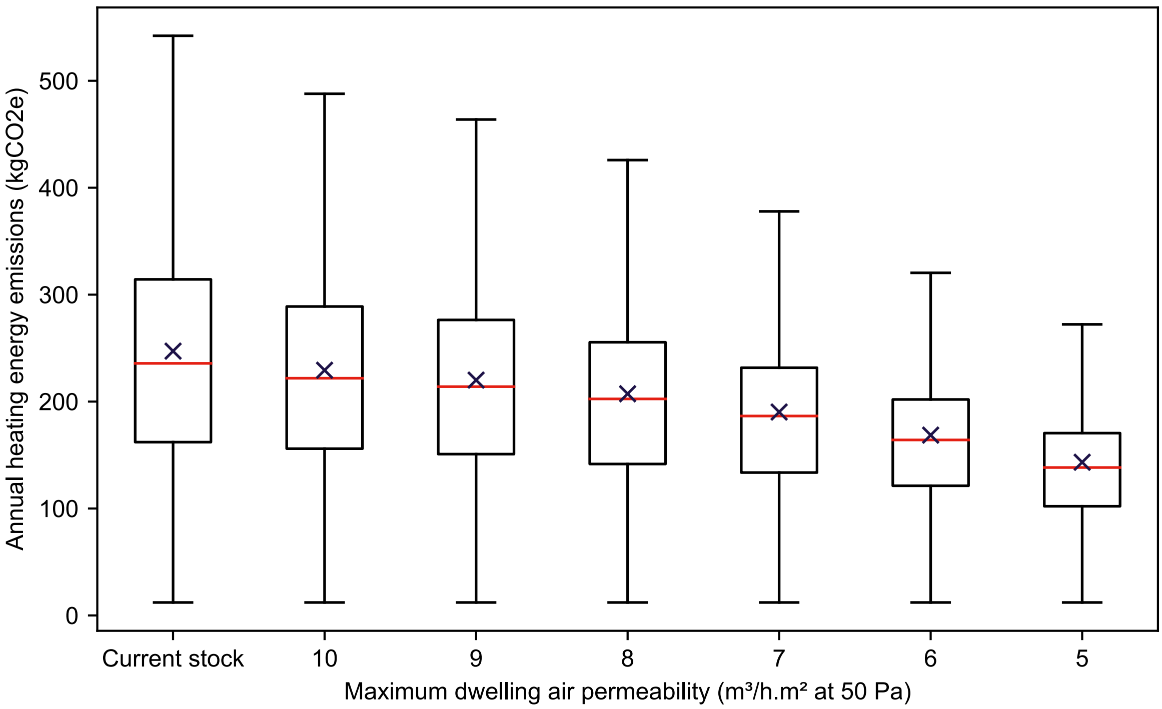
Comparison of annual GB emissions associated with heating to counter infiltrative losses, calculated before and after airtightness improvements (Table 9), showed that:

- The annual emissions reduction associated with achieving GB-wide maximum air permeability of 10 m³/h.m² @ 50 Pa is estimated at 0.5 $MtCO_2e$ (500 $ktCO_2e$) — an average annual reduction of 66 $kgCO_2e$ per treated dwelling.
- The annual emissions reduction associated with achieving GB-wide maximum air permeability of 5 m³/h.m² @ 50 Pa is estimated at 2.88 $MtCO_2e$ (2,880 $ktCO_2e$) — an average annual reduction of 115 $kgCO_2e$ per treated dwelling.

Table 9: Estimated carbon emissions associated with infiltrative heat losses, following airtightness improvements to achieve specified maximum dwelling air permeability levels, weighted to GB stock.

Maximum dwelling air permeability ($m^3/h.m^2$ @ 50 Pa)	Number of dwellings treated (1000s)	Carbon emissions associated with infiltrative losses		Emissions reductions relative to current stock		
		GB total ($MtCO_2e$)	Per dwelling mean ($kgCO_2e$)	GB total ($MtCO_2e$)	Per-dwelling mean ($kgCO_2e$) *	Per treated dwelling mean ($kgCO_2e$) †
Current stock	0	6.86	247.19	—	—	—
10	7,543 [27%]	6.37	229.33	0.50	17.86	65.73
9	10,774 [39%]	6.11	220.09	0.75	27.10	69.82
8	14,305 [52%]	5.75	207.28	1.11	39.91	77.43
7	18,617 [67%]	5.28	190.23	1.58	56.96	84.92
6	22,430 [81%]	4.68	168.63	2.18	78.56	97.21
5	25,082 [90%]	3.98	143.27	2.88	103.92	115.00

* The GB total emissions reductions divided by total number of dwellings in the GB stock. † The GB total emissions reductions divided by the number of dwellings in the GB stock that received airtightness improvements.



Box bounds indicate lower and upper quartiles (Q1 & Q3), red line indicates median, × indicates mean, tails indicate minimum and maximum values not including outliers. (Outliers defined as values lying outside of the range $[Q1 - 1.5 \times IQR, Q3 + 1.5 \times IQR]$, where $IQR = Q3 - Q1$.)

Figure 13: Boxplot representation of distribution of per-dwelling annual emissions due to heating demand associated with infiltrative heat losses, following airtightness improvements to achieve the indicated maximum dwelling air permeability levels, weighted to GB stock.

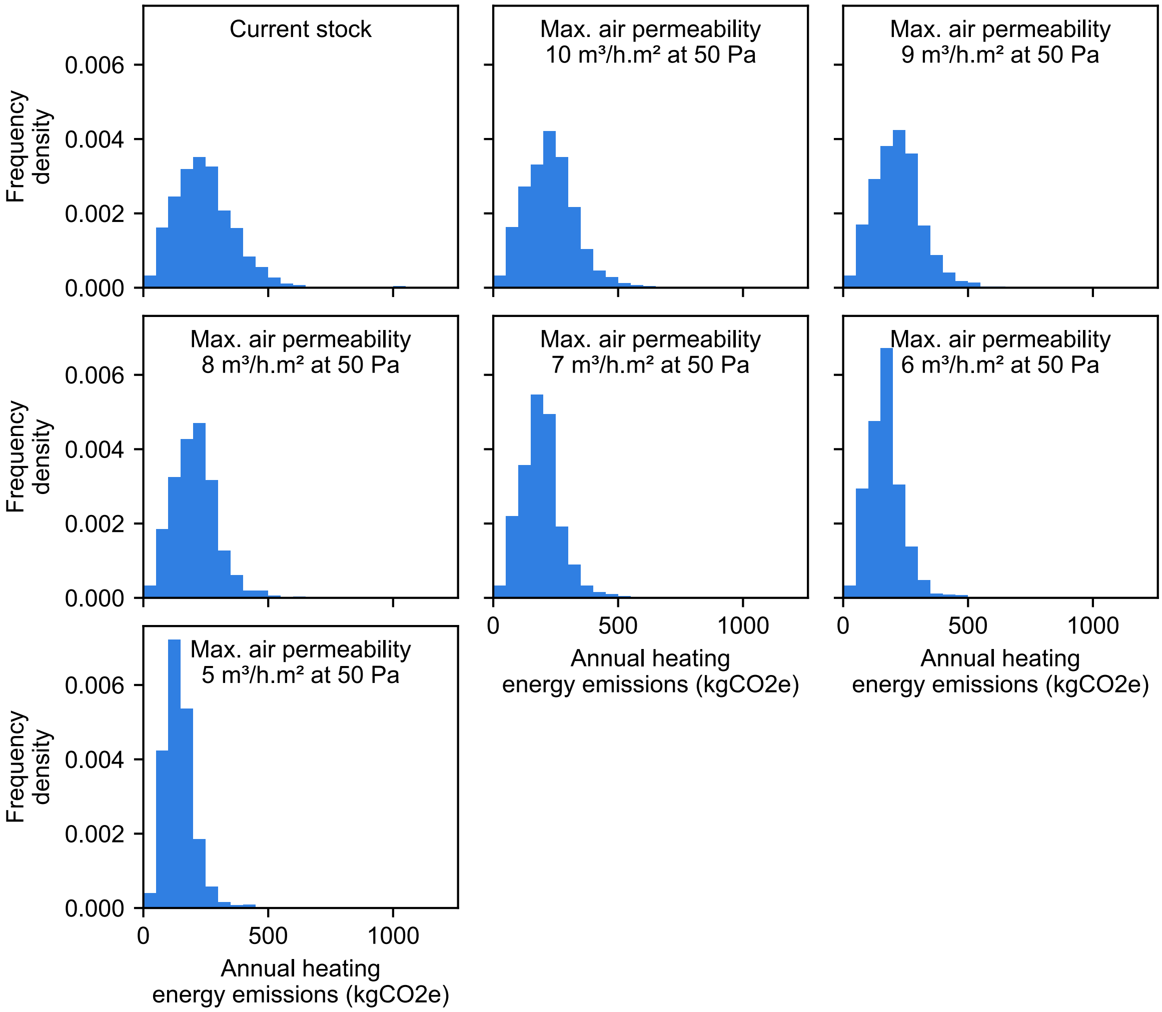


Figure 14: Histogram representation of distribution of per-dwelling annual heating energy demand associated with infiltrative heat losses, following airtightness improvements to achieve the indicated maximum dwelling air permeability levels, weighted to GB stock.

Discussion and conclusions

Analysis of 5,125 airtightness tests which were extrapolated to represent the national stock revealed that GB dwellings are more airtight that previously thought. The mean air permeability was calculated to be 8.6 $m^3/h.m^2$ @ 50 Pa (median 8.1 $m^3/h.m^2$ @ 50 Pa). This compares to previous estimates of 8.9-9.0 $m^3/h.m^2$ @ 50 Pa [20] and of 11.5 $m^3/h.m^2$ @ 50 Pa [21], using data collected pre-2010 and pre-1994 respectively.

The current analyses found that dwellings built between 1965 and 1980 were the most airtight. This contrasts with previous work which has suggested that dwellings built between 1980-1994 were the most airtight, with those built 1970 to 1979 the least airtight [21]. This difference is perhaps unsurprising because the data analysed by Stephen [21] were collected before 1994 and retrofits and structural changes have been made to many dwellings over the last 30 years. In the present study, it is interesting that dwellings constructed post-1990 were the least airtight. This is surprising because it coincides with the period when stricter building regulations were enforcing airtightness standards.

Flats were found to be the most airtight, which agrees with the work of both Stephen [21] and Pan [22] who analysed dwellings built pre-1994 and 2006-2010 respectively. Dwellings with system-built walls were found to be the most airtight which concurs with the findings of Stephen. Uninsulated solid masonry walls were the least airtight, whereas Stephen reported that dwellings with masonry cavity walls were the least airtight followed by uninsulated solid masonry walls.

Across the three categories investigated, (built form, age, and wall construction), there was a large amount of variation in dwelling air permeability within each sub-category, as indicated by large ranges. There were also small differences in means and medians between sub-categories and overlapping interquartile ranges. This indicates that there may be other factors which have a greater correlation with air permeability (and so, airtightness) than those considered in this study. The Rapid Evidence Assessment identified several other factors which may influence airtightness, and they warrant further investigation.

If all dwellings in the GB stock were to be made more airtight such that they had an air permeability <5 $m^3/h.m^2$ @ 50 Pa, then heating energy consumption, heating energy costs, and carbon emissions associated with infiltration heat loss would be reduced by 15.2 TWh (0.61 MWh per treated dwelling[22]), £840 million (£33 per treated dwelling), and 2,880 ktCO_2e (115 kgCO_2e per treated dwelling) per annum respectively. To put this into perspective, GB domestic space heating demand for a normal year was predicted to be 221 TWh [118]. Given that the UK intends to move to a net zero emissions economy by 2050 [119], improving airtightness might contribute to 6.9% of this.

[22] The analysis in Report 2 [120] is not directly comparable to Report 1. In Report 2, heating demand was predicted using a steady-state and dynamic model with a varying infiltration rate in a single dwelling with specific weather conditions. This is different to the analysis in this report which changes airtightness (not infiltration directly, which is captured in the underlying equation) across the entire GB housing stock (with 90% of the dwellings being retrofitted to derive the per treated dwelling figure), under different weather conditions.

Suggestions for improvements to this methodology

Infiltration was estimated from airtightness using the divide-by-20 method. This method is commonly used by others, (see review in Report 2 [120]), to estimate the average heating-season infiltration rate. The method has, however, drawn criticism for its unreliability, particularly when looking at individual buildings outside of the main UK heating season [4,36]. In other work, Jones et al. [20] used a more sophisticated model of infiltration estimation (DOMVENT3D), but this has not been extensively validated and its accuracy cannot be assured without further research [25]. Overall, therefore, it is difficult to know whether an alternative infiltration model could improve the estimate of stock level infiltration without further research.

Previous research on inter-dwelling air leakage is inconsistent and some methods used to measure it have been reported as inaccurate. It is important to understand airflow paths because whether air moves into a dwelling from an unconditioned space (e.g., outside) or from a conditioned space (e.g., the attached dwelling), affects the heating demand [121]. This area warrants further work to quantify the effect of inter-dwelling air flow on airtightness, infiltration, and heating demand.

The 4 Pa to 50 Pa conversion formula used in this analysis is taken from TM23 [15], which is referenced in the Building Regulations for England and Wales [8]. Other studies indicate that this formula is reliable in UK dwellings that are relatively airtight compared to the wider stock, e.g., [52]. The formula produced errors that were, on average, less than 15%, but up to ± 30% in some cases. In dwellings closer to the stock average airtightness, there is some evidence to suggest that the gap between airtightness measured at 50 Pa and that converted to 50 Pa from 4 Pa may be greater. Both the BEIS SMETER project [35] and the DESNZ DEEP project [34] suggest that the difference in airtightness measured by different methods[23] is greater in their sample of leakier than average dwellings. It would be a worthwhile endeavour to explore this further to determine whether the calculation of the airtightness of the GB stock should be revised given the greater proportion of “leaky” dwellings that are present in the stock.

[23] E.g., blower door (50 Pa) versus low-pressure pulse (4 Pa).

Report summary

RQ1: What is the airtightness of existing UK dwellings?

A review revealed that very few previous studies attempt to calculate the airtightness of the UK housing stock. Just two studies were found. The first is 26 years old and relies on airtightness data from 384 dwellings built before 1994 [21]. The second uses airtightness data from 671 dwellings, of which 384 come from the first study and the remaining 287 are from a 14-year-old study of dwellings built around 2006 [20]. The study makes two assumptions about party wall air permeability, which leads to two calculations of airtightness (Figure 15).

Analysis conducted in this study uses a much larger dataset of 5,125 dwellings from the British (GB)[24] housing stock. It calculates the airtightness (strictly the air permeability) of the GB dwelling stock to be 8.6 m³/h.m² @ 50 Pa (Figure 15), which is lower than previously thought by Stephen [21] and Jones et al. [20].

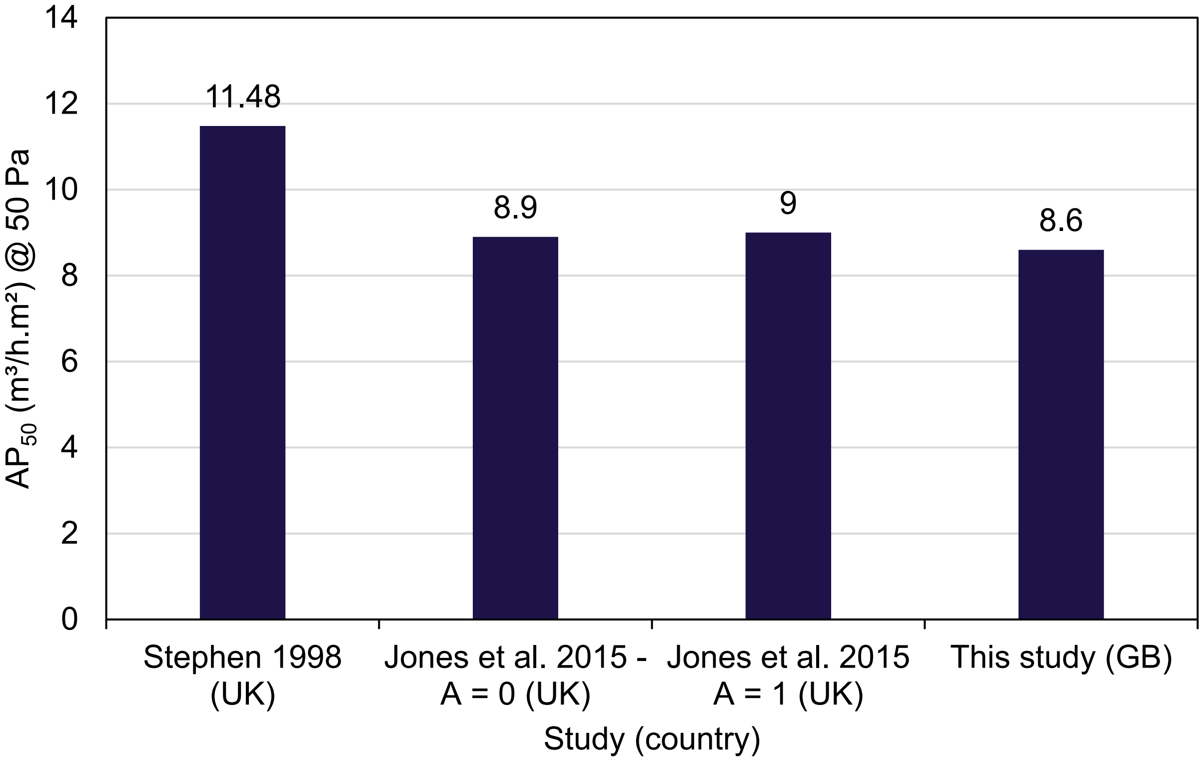


Figure 15: Bar chart of mean UK/GB dwelling stock airtightness from previous studies identified by the REA and from new analysis in this study. “A = 0” indicates an impermeable party wall assumed. “A = 1” indicates a permeable party wall assumed.

[24] Analysis of the entire UK housing stock was not possible due to a lack of data from Northern Ireland.

RQ2: How does the airtightness of UK dwellings compare to that of dwellings from other European countries and countries with a similar climate?

Due to the low-quality evidence about the airtightness of existing dwellings in other countries in Europe, or countries with a similar climate to the UK, an inter-country comparison was not possible. Comparisons could be drawn between newly built dwellings, but this is not straightforward due to variations in testing methodologies between countries (different envelope elements are sealed during airtightness tests and different test reference pressure are used).

RQ3: How does airtightness differ in existing UK dwellings with respect to built form, age, and construction type?

Previous research provides limited evidence for the influence of various building characteristics on the airtightness of the existing UK dwelling stock. A historical study containing only pre-1994 dwellings found that the most airtight dwellings were dwellings built pre-1919 or 1980-1994 and those constructed of pre-cast concrete. The least airtight (leakiest) were those with masonry cavity walls. Construction age is particularly confounded by several interrelating variables such as floor type, wall type, degradation, and design targets. The literature is inconclusive about the effect of wall (construction) type.

The analyses performed in this study provide new insight for GB dwellings. Regarding built form, flats and bungalows are the most airtight dwellings (mean air permeability of 7.3 and 7.6 $m^3/h.m^2$ @ 50 Pa respectively). Terraced and semi-detached houses are the least airtight (9.1 and 9.2 $m^3/h.m^2$ @ 50 Pa respectively). Regarding age, air permeability progressively decreases (become more airtight) between the pre-1919 dwellings and those in age band 1965-1980 (8.9 to 7.9 $m^3/h.m^2$ @ 50 Pa). Air permeability progressively increases (becomes less airtight) in post 1981 dwellings (to 8.6 $m^3/h.m^2$ @ 50 Pa for 1981-1990 and to 9.3 $m^3/h.m^2$ @ 50 Pa for post-1991 dwellings)[25]. There is no difference in airtightness between any construction type, although dwellings with solid wall insulation are slightly more airtight than uninsulated solid walls (air permeability 8.2 versus 8.9 $m^3/h.m^2$ @ 50 Pa). Between the three categories of built form, age, and wall type, the difference in means and medians was generally quite small with a broad, and generally overlapping, interquartile ranges for each sub-category. This indicates that there is a large amount of variation in dwelling airtightness within each of these categories and so it may be that other non-investigated categories have a stronger correlation with airtightness.

[25] This is surprising given that building regulations were stipulating increased airtightness post-1990. There are other factors which likely influence airtightness which may cause this increase, which is evidenced by the large variation in air permeability in each category.

RQ4: What is the potential impact on energy, cost, and carbon emission reductions of improving airtightness in the UK housing stock?

One study previously quantified the effect of infiltration (predicted using airtightness and other dwelling factors) on energy and carbon emissions. No previous studies have explored the effect of improvements in airtightness (and the estimated reductions in infiltration).

New analysis in this study has shown that heating energy consumption could be reduced by 15.2 TWh pa. (average 0.61 MWh pa. per dwelling) if the airtightness of the entire GB stock was reduced to 5 $m^3/h.m^2$ @ 50 Pa, which is the specification for the notional dwelling in the Building Regulations for new dwellings. This would require airtightness improvements to 25 million dwellings (90% of the stock). The stock level energy cost savings of this would be £840 million pa. (mean £33 pa. per treated dwelling), and the stock level carbon emissions reductions would be 2,880 $ktCO_2e$ pa. (mean 115 $kgCO_2e$ pa. per treated dwelling).

Bringing all dwellings to a minimum of 8 $m^3/h.m^2$ @ 50 Pa, which is the current minimum standard for new dwellings in the Building Regulations, would require improvement to 14.3 million dwellings (52% of stock) and would reduce heating energy demand by 5.84 TWh per annum (0.41 MWh pa. per dwelling). The stock level energy cost savings of this would be £320 million pa. (mean £22 pa. per treated dwelling), and the stock level carbon emissions reductions would be 1,110 $ktCO_2e$ pa. (mean 77 $kgCO_2e$ pa. per treated dwelling).

Further work

The following further work is suggested, and is discussed in more detail in Report 4 [122]:

- A field trial including homes in Northern Ireland to allow an assessment of the airtightness of the UK stock, rather than GB.
- A field trial to include more dwellings to increase the alignment of the sample to the national stock, specifically, to improve the overall weighting efficiency (representativeness rating).
- A field trial to collect air infiltration data for a representative sample of the UK stock, which would enable the validation of infiltration estimation models.
- A field trial of several pairs of dwellings and experiments in an appropriate full-scale test facility (i.e., a pair of adjoining test houses) would provide conclusive evidence of the extent and effect of inter-dwelling air leakage during fan pressurisation tests, low-pressure pulse tests, and under normal conditions (infiltration).
- A field trial, and experiments in a full-scale test facility, to examine the variation in measured airtightness between the two methods recognised by English and Welsh Building Regulations, blower door and low-pressure pulse.

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Appendices

Appendix A: Rapid Evidence Assessment – detailed methodology

Define research questions

The research questions were defined based on the DESNZ invitation to quote and were listed previously.

Develop search terms

Search terms were selected for each research question (Table 10). The search terms were chosen based on the research questions, from the knowledge of the research team, through considering the keywords used in peer reviewed literature, and from a previous review for DESNZ which highlighted influencing factors on infiltration [123]. From the identified keywords, primary and secondary search terms were developed (Table 10). Searching for literature already known to the researchers, and which the search strategy should find, was used to validate the selected search terms. The search terms were refined to ensure a manageable collection of documents were retrieved. E.g., “home” and “homes” were searched as exact terms rather than “home*”, which returned many irrelevant papers from the biological and medical fields (e.g., homeostasis, homeopathy, etc.).

Table 10: Primary and secondary search terms.

Primary search term	Secondary search term
Air tightness	Dwelling*
Air permeability	Domestic
Air leakage	Housing
Infiltration	House*
Ventilation	“Home”
	“Homes”
	Residen*
	Flat
	Apartment
	Bungalow
	Stock

Develop literature screening criteria

Inclusion and exclusion criteria were defined and used to screen the literature (Table 11).

Table 11: Inclusion and exclusion criteria used to screen the literature.

Inclusion criteria	Exclusion criteria
Written in English	Focuses only on non-domestic buildings
Relating to the UK, Europe, or with a predominantly Cfb Köppen climate classification	Focuses only on a single dwelling or limited case studies in a field study without comparison with other dwellings of different characteristics
Can be readily accessed online within the time allocated for review	Focuses only on low energy dwellings, e.g., Passivhaus (RQ1 only)
The abstract indicates relevance to the research question being investigated	Uncommon construction for UK dwellings, e.g., log cabins or caravans
The full text provides quantitative evidence for the research question being investigated	Duplicated studies, e.g., where a conference paper became a journal paper

Table 12: List of countries included in the literature search.

Europe	**Europe (con't)**	**Oceania**
Albania	Lithuania	New Zealand
Austria	Luxembourg	Tasmania
Belgium	Moldova	
Bulgaria	Netherlands	
Croatia	Norway	
Czech Republic	Poland	
Denmark	Portugal	
Estonia	Romania	
Finland	Serbia	
France	Slovakia	
Germany	Slovenia	
Greece	Spain	
Hungary	Sweden	
Iceland	Switzerland	
Ireland	Ukraine	
Italy	United Kingdom	
Latvia		

Identify databases and information sources

Literature sources deemed to have comprehensive coverage of academic and grey literature across several disciplines [18] were chosen: Scopus, Compendex, Google Scholar, the Construction Information Service, and the UK Government website. Additional literature was provided directly by DESNZ and those listed in the report acknowledgements.

Conduct literature searches, combine results, and remove duplicates

Articles published prior to 1 January 2024 were captured in the search. The results from the various sources were combined and duplicates removed using reference manager software. A total of 1,610 documents were imported and 407 duplicates removed (Figure 1). A further 14 documents were added through citation chaining or via expert knowledge.

Screen documents for relevance

A first stage screening of titles was done by reading the title only and marking the literature as “relevant”, “irrelevant”, or “uncertain” based on the inclusion and exclusion criteria (Table 11). For those marked “uncertain”, a further screening process was carried out by reading the abstract. Those subsequently marked as “irrelevant” were discarded. A second stage of screening was applied to those which had been marked “relevant” or “uncertain” by reading the full document (Figure 1).

Screen based on quality

Reporting and research quality screening was performed in compliance with the UK Government Quality Assessment Scale [124], following the methods used in reviews by Lomas et al. [125] and Drury [18]. Documents achieving a reporting and research quality score of greater than six points (Table 13) were taken forward to data extraction and synthesis of findings (Figure 1).

Table 13: Reporting and research quality assessment matrix.

Points	Quality assessment criterion
Reporting quality	
0-1	Does the author or publishing organisation have a credible track record in the area?
0-2	Are the rationale and research questions clear and justified?
0-2	Does the document acknowledge funding sources, project contributors, and possible conflicts of interest?
0-1	Are the methods used suitable for the aims of the study?
Research quality	
0-2	Has the document been peer reviewed or independently verified by one or more reputable experts?
0-1	Do the conclusions match the data presented?

Extract data and synthesise findings

The remaining documents which satisfied the relevance and quality screening were extracted to a data collection template. Then each document was read in full and key information recorded.

Classify evidence based on GRADE system

After synthesis of the evidence, the review of the studies as a whole was considered using the GRADE system (Grading of Recommendations, Assessment, Development, and Evaluation) [126] (Table 14).

Table 14: GRADE quality assessment definition and criteria [126]**.**

Quality	Definition	Criteria
High	Further research is unlikely to change our confidence in the estimate of the effect.	Several high-quality studies with consistent results; OR One large, high-quality, multi-centre trial
Moderate	Further research is likely to have an important impact on our confidence in the estimate of the effect and may change the estimate.	One high-quality study; OR Several studies with some limitations
Low	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.	One or more studies with severe limitations
Very low	Any estimate of effect is very uncertain.	Expert opinion; OR No direct research evidence; OR One or more studies with very severe limitations

Appendix B: Detailed methodology for calculating the baseline airtightness of the GB domestic stock

The airtightness measurement datasets, identified from the Rapid Evidence Assessment, were evaluated to identify the most appropriate data for representing the housing stock. These data were cleaned, the characteristics of the GB[26] housing stock were assessed, and then a weighting factor was calculated for each dwelling measurement so that the dataset could be scaled to represent the GB housing stock. The resulting nationally representative airtightness data were analysed to understand the distributions across the housing stock, and by age band, main wall construction type, and built form. Further analysis was carried out to quantify the energy, cost, and carbon saving potential from retrofitting the housing stock to improve airtightness.

Availability of stock level airtightness data for UK dwellings

The UK airtightness datasets of existing homes identified in the Rapid Evidence Assessment (Table 1) were out of date or from small studies. The 130,000 results lodged with the Air Tightness Testing and Measurement Association (ATTMA) database annually [29] for newly constructed dwellings do not represent the existing UK stock, may be unreliable representations of airtightness due to “in-test” sealing [27], are not nationally representative [30], and are not publicly available or available for this project.

The only available dataset of airtightness results and dwellings metadata that is large and diverse enough to be extrapolated to the existing stock of UK homes was that owned by BTS (Build Test Solutions Ltd.). These data are not publicly available but were provided by BTS for use in this study. All airtightness results in the BTS dataset were collected using the low-pressure pulse method [15] between August 2021 and October 2023. EPC-reported age bands for the dwellings in the dataset covered every age band from pre-1900 to 2007 onwards. Extrapolated AP_{50} values[27] provided in the dataset were calculated as $AP_{50} = 5.2540 \times AP_4{}^{0.9241}$, where AP_4 is the measured air permeability at 4 Pa in accordance with CIBSE TM23 [15], which is the procedure referred to in Part L of the English and Welsh Building Regulations [7,8]. The indoor-outdoor pressure difference of 4 Pa is that exerted across the building envelope during the low-pressure pulse test [117].

Dataset cleaning

The dataset comprised 12,277 test results gathered from 8,933 unique addresses. These data were submitted to four data cleaning phases, as described below.

1. Initial filtering on test validity, geography, and property type, which reduced the dataset to 8,465 test results associated with 6,627 unique addresses located in Great Britain.

[26] The subsequent data cleaning process identified insufficient data from Northern Ireland to enable analysis of the UK stock, so only data for Great Britain (GB) were analysed.
[27] AP_{50} is the extrapolated air permeability at 50 Pa (m³/h.m²) in accordance with CIBSE TM23 [15]; similarly, AP_4 is that measured at 4 Pa.

   a. Removed test results not marked as valid in the dataset. This removed test results where the lowest background pressure rise was not below 4 Pa, or the highest background pressure rise not above 4 Pa. (3,262 results removed).
   b. Removed test results where the notes indicated test conditions inconsistent with guidance in CIBSE TM23 (CIBSE 2022). This removed test results where the trickle vents were open, windows were open, outer doors were open, other vents were open/unsealed, chimney open, air extractor open, door(s) taped, or other non-standard test conditions used at the request of the site agent. (62 results removed).
   c. Removed test results not related to GB dwellings. This first removed 286 test results associated with non-domestic properties, with the remaining results all corresponding to UK dwellings. Among these, there was only one result for a dwelling in Northern Ireland: this result was removed. (287 results removed).
   d. Removed duplicate test results i.e. the where same test was recorded twice. (199 results removed).
   e. Removed a single result which was unfeasibly high[28].
   f. Removed a single test result with inconsistent test notes.
2. Matching of test results with dwelling Energy Performance Certificates (EPCs) which reduced the dataset to 6,133 results associated with 5,083 unique addresses. EPC data were obtained using the UK EPC API[29] [127] for dwellings in England and Wales, and the Scottish EPC Register[30] [128]. England, Wales, and Scotland EPCs were searched to identify possible matches with addresses of properties in the airtightness dataset.
   a. Removed test results whose address had no match in the collated EPC data. (1,464 results removed).
   b. For results associated with addresses with more than one possible EPC match (i.e. multiple EPCs available for the same address):
      i. If the test result was not flagged as being pre- or post-retrofit, it was associated with the EPC whose inspection date was nearest that of the test.
      ii. If the test result was flagged as being pre-retrofit, it was associated with the EPC whose inspection date was nearest that of the test while being no more than 7 days after the test date.

[28] The exclusion criterion for this being any AP_{50} >100 m³/h.m² @ 50 Pa.
[29] The UK EPC API is an Application Programming Interface (API) which provides access to Energy Performance Certificate (EPC) data for dwellings in England or Wales. The API was used to search for and retrieve EPC data associated with the English and Welsh dwelling addresses in the dataset.
[30] The Scottish EPC Register (SEPCR) is the data repository for Scottish Energy Performance Certificates (EPCs). Data were retrieved for every valid domestic EPC assessment recorded in the SEPCR, which corresponded to those conducted from October 2013 to September 2023.

   iii. If the test result was flagged as being post-retrofit, it was associated with the EPC whose inspection date was nearest that of the test while being no more than 7 days before the test date.
   iv. Any test results flagged as being pre- or post-retrofit for which (b) and (c) above failed to identify an EPC match were removed. (868 results removed across steps i–iv).

3. Treatment of addresses with multiple test results sought to reduce the number of results associated with each unique dwelling to one. This reduced the dataset to 5,334 dwellings, each matched with a unique EPC, across 5,083 unique addresses. Addresses with multiple test results corresponded to those where the airtightness test data indicated tests conducted before and after the implementation of an energy-driven retrofit: in these instances, provided both the pre- and post-test EPCs were available, the test results were treated as corresponding to two different dwellings (i.e., pre- and post-retrofit). For any address having multiple test results:
   a. For any subset of these results matched against a single EPC, only the result with the highest R^2 was retained[31]. (558 results removed).
   b. Among the remaining results (all now matched against distinct EPCs):
      i. If more than one pre-retrofit result was flagged the result with the highest R^2 was retained. (0 results removed).
      ii. If more than one post-retrofit result was flagged, the result with the highest R^2 was retained. (0 results removed).
      iii. If more than one result, which was neither before or after a retrofit, was flagged, only the result with the highest R^2 was retained. (80 results removed).
   c. If any of the remaining results were flagged as being pre- or post-retrofit, any results flagged as neither pre- nor post-retrofit were dropped. (131 results removed).
4. Removal of dwellings lacking sufficient metadata for weighting, which reduced the dataset to 5,125 results. The variables required for weighting were built form, age band and main wall construction type. Most of the removals here were due to EPCs providing a U-value for the main wall construction, rather than a description of the construction. (209 results removed).

[31] R^2 is the correlation coefficient reported in the low-pressure test result, for which a higher value indicates a better fit of the data to the model assumed in the low-pressure pulse analysis algorithm.

Dataset corrections

Dataset corrections were considered to account for inter-dwelling air leakage across party walls and changing performance over time. However, no alterations were applied as there was insufficient robust evidence at this time.

The dataset was not altered to account for inter-dwelling air leakage. Firstly, because the Rapid Evidence Assessment presented evidence for inter-dwelling air leakage in only a small sample of UK homes built pre-1994. Secondly, findings from the DESNZ DEEP project suggested that inter-dwelling air leakage is an artefact of the blower door test method and the low-pressure pulse test used in the BTS dataset may be less susceptible to the “phenomenon”. The DESNZ DEEP project calls for further research into suitable conversion factors that could be used to account for inter-dwelling air leakage.

The dataset was not altered to account for seasonal variation in airtightness or medium-to long-term changes (degradation) because the evidence from the REA was inconclusive about the extent of this phenomenon and what a suitable correction factor might thus be. As the airtightness in most dwellings degrades rapidly immediately after construction for the first one to three years, this issue is unlikely to affect this dataset of existing dwellings.

Assessing the characteristics of the GB domestic stock

Data describing the characteristics of the GB domestic stock were collated from national housing condition datasets accessed through the UK Data Service:

- The English Housing Survey (EHS), 2017: Housing Stock Data [129].
- The Scottish House Condition Survey (SHCS), 2012–2019 [130].
- The Welsh Housing Conditions Survey (WHCS), 2017–2018 [131].

Data from 2017 (and 2017–2018 for Wales) were used, as this was the most recent year for which data were available for all three countries[32].

The EHS, SHCS, and WHCS datasets comprised data gathered from samples of the respective national housing stocks. For each sample, the data providers assigned a weighting to the individual dwellings indicating the number of similar dwellings in the national stock. For the present study, these weighted counts were summed across all three datasets to determine the number of dwellings falling into different categories for each of the following dwelling characteristics:

- Built form.
- Construction age band.
- Main wall construction type.

[32] The most recent national housing stock data releases for England, Scotland and Wales having been for 2020, 2021 and 2017–2018, respectively.

Built form was mapped onto five subcategories (Table 15): flat; terraced house; semi-detached house; detached house; and bungalow. Built form categorisation in the SHCS data for Scottish dwellings did not include a standalone categorisation for bungalows; rather, bungalows were included in the terraced, semi-detached, and detached categories.

Table 15: Mapping of dwelling built forms from England, Scotland and Wales survey data to GB categories.

GB	England (EHS)	Scotland (SHCS)	Wales (WHCS)
Flat	Converted flat; purpose built flat, low rise; purpose built flat, high-rise	Converted flat; purpose built flat	Converted flat; purpose built flat; flat plus non-residential
Terrace	End terrace; mid terrace	End terrace; mid terrace	End terrace; mid terrace
Semi-detached	Semi-detached	Semi-detached	Semi-detached
Detached	Detached	Detached	Detached
Bungalow	Bungalow	[No separate category for bungalows ‡]	Bungalow

Categorisations for England, Scotland and Wales are those reported in the EHS, SHCS, and WHCS, respectively.
‡ Bungalows included in other categories for Scotland, with no standalone “bungalow” categorisation.

Age band was mapped onto six categories (Table 16). The GB categories followed those used in the EHS; however, the 1991–2000 and post 2000 age bands were combined into a single age band (post 1990) due to heavy underrepresentation of post 2000 dwellings in the BTS sample[33].

Age band categories used in the WHCS matched those in the EHS, except for post 1990 dwellings which were split into those built between 1991 and 2002 and those built after 2002, rather than 1991–2000 and post-2000 as in the EHS. The use of a single post-1990 category meant that this difference was of no consequence.

Age band categories used in the SHCS differed from those used in the EHS:

- The 1965–1982 category, was mapped onto the 1965–1980 category.
- To align the 1983–2002 and post 2002 categorisations, the number of Scottish dwellings constructed in the period 1981–1990 was estimated as follows:

$$\frac{N_{ENGWAL,1981-1990}}{N_{ENGWAL,1981-}} \times N_{SCO,1983-} \tag{1}$$

where:

[33] Dwellings constructed after 2002 accounted for 0.9% of dwellings in the cleaned BTS sample, compared with 7.9% of the GB stock.

- $N_{ENGWAL,1981-1990}$ is the number of English and Welsh dwellings built between 1981–1990, as reported in the EHS and WHCS.
- $N_{ENGWAL,1981-}$ is the number of English and Welsh dwellings built from 1981 onward, as reported in the EHS and WHCS.
- $N_{SCO,1983-}$ is the number of Scottish dwellings built from 1983 onward, as reported in the SHCS.

The number of Scottish dwellings constructed post 1990 was estimated in a similar way.

Table 16: Mapping of dwelling age bands from England, Scotland and Wales survey data to GB categories.

GB	England (EHS)	Scotland (SHCS)	Wales (WHCS)
Pre 1919	Pre 1919	Pre 1919	Pre 1919
1919–1944	1919–1944	1919–1944	1919–1944
1945–1964	1945–1964	1945–1964	1945–1964
1965–1980	1965–1980	1965–1982	1965–1980
1981–1990	1981–1990	1983–2002; post 2002 ‡	1981–1990
Post 1990	1991–2000; post 2000	1983–2002; post 2002 ‡	1991–2002; post 2002

Categorisations for England, Scotland and Wales are those reported in the EHS, SHCS, and WHCS, respectively.
‡ Numbers of Scottish dwellings in the 1981–1990 and post 1990 categories were estimated based on proportions of English and Welsh dwellings built in each of these periods.

Main wall construction types reported in survey data were mapped onto 5 categories (Table 17), following those used in the EHS and WHCS. Although the SHCS employed a greater number of categorisations for wall construction type, these each mapped directly onto the EHS and WHCS categories.

Table 17: Mapping of main wall construction types from England, Scotland and Wales survey data to GB categories.

GB	England (EHS)	Scotland (SHCS)	Wales (WHCS)
Cavity with insulation	Cavity with insulation	Cavity wall with insulated cavity; cavity wall with internal or external insulation; cavity wall, built post 1982, assumed insulated	Cavity with insulation
Cavity uninsulated	Cavity uninsulated	Cavity uninsulated	Cavity uninsulated
Solid with insulation	Solid with insulation	Solid wall, insulated by retrofit; solid wall, built post 1982, assumed insulated	Solid with insulation
Solid uninsulated	Solid uninsulated	Solid wall, uninsulated pre-1919; solid wall, uninsulated post-1919	Solid uninsulated
Other	Other	Other	Other

Comparing the characteristics of the dwellings in the study sample against those for the GB domestic stock:

For built form (Figure 16), there is substantial under-representation of detached dwellings (7% in the sample, compared with 18% for the GB stock), and over-representation of bungalows (17% sample, 8% GB). Terraced and semi-detached dwellings are slightly over-represented, while flats are slightly under-represented.

For dwelling age bands (Figure 17), dwellings built prior to 1965 were over-represented in the sample (73% sample, 55% GB), while those built from 1965 onwards were under-represented. The age bands most over-represented were pre 1919 (28% sample, 21% GB) and 1945–64 (27% sample, 19% GB), while dwellings built after 1990 were the most strongly under-represented (5% sample, 17% GB). Note: Due to mismatches between dwelling age bands used in EPC reporting and national housing surveys (EHS, SHCS, WHCS), the EPC-derived age bands for the dwellings in the study sample were mapped onto those used when characterising the GB stock (Table 18).

For main wall construction types (Figure 18), cavity wall constructions were under-represented in the sample (52% sample, 69% GB), while solid wall constructions were over-represented (36% sample, 28% GB). Other construction types — comprising system built, timber frame and park home constructions — were substantially over-represented (12% sample, 2% GB).

As the sample distributions of the examined dwelling characteristics were inconsistent with those reported for the GB stock, weighting of the sample was deemed necessary to produce a nationally representative dataset.

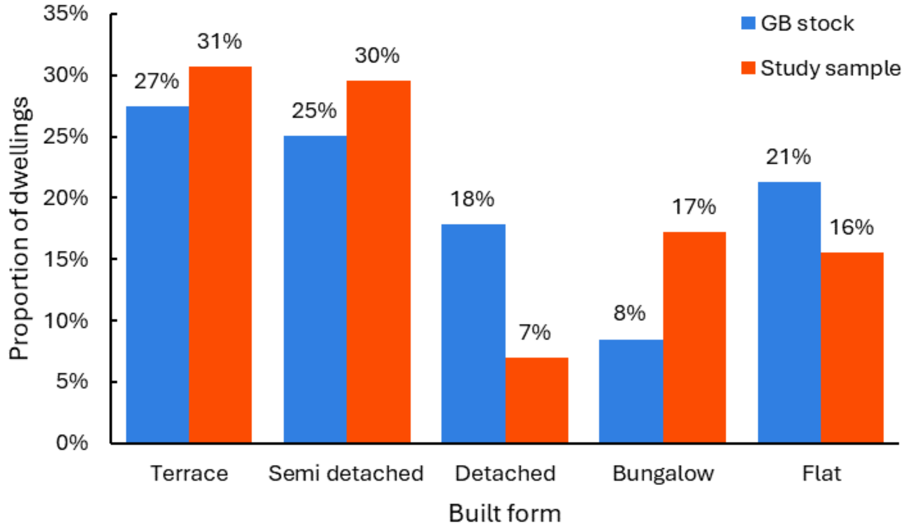


Figure 16: Dwelling built form distribution in the GB domestic stock and the study sample (N = 5,125).

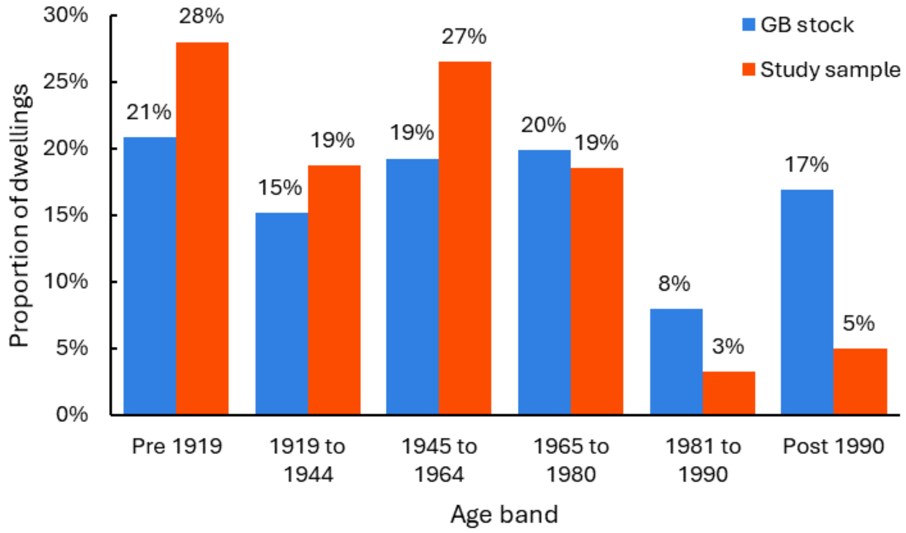


Figure 17: Dwelling age distribution the GB domestic stock and the study sample (N = 5,125).

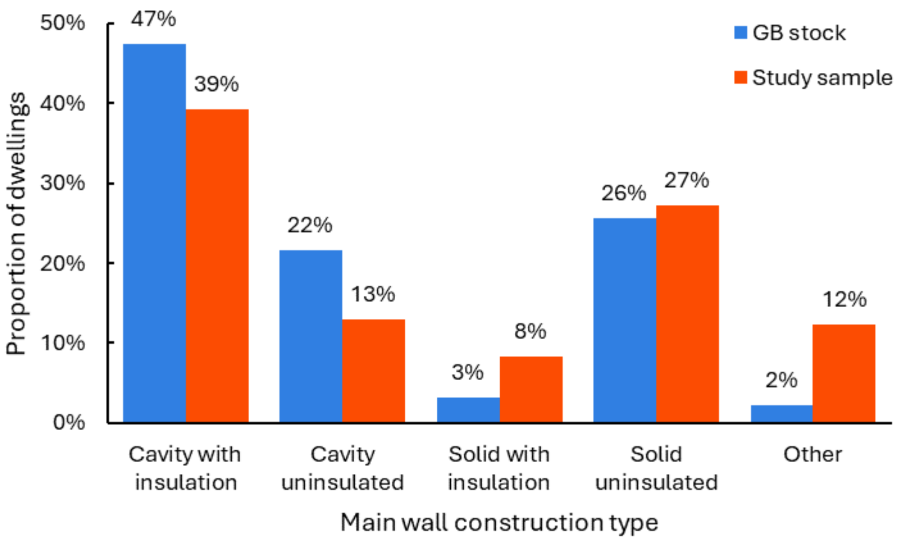


Figure 18: Main wall construction type distribution in the GB domestic stock and the study sample (N = 5,125).

Table 18: Mapping of EPC age bands onto GB stock age bands.

GB stock age band	EPC age bands	
	England & Wales	**Scotland**
Pre 1919	Before 1900, 1900–1929	Before 1919
1919–1944	1930–1949	1919–1929, 1930–1949
1945–1964	1950–1966	1950–1964
1965–1980	1967-1975, 1976–1982	1965–1975, 1976–1983
1981–1990	1983–1990	1984–1991
Post 1990	1991 onwards	1992 onwards

Calculating weighting factors

Weighting factors for the airtightness test results were calculated using a Random Iterative Method (RIM), based on main wall construction type, built form and age band, using target proportions derived for the GB stock (Figures 16–18). Weights were then calculated by scaling to the size of the GB stock (N=27,755,120). The weighting efficiency was 51%, compared with 84%, 80% and 71% respectively when weighting on each of construction type, built form and age band alone.

Analysis of the nationally representative airtightness dataset

The nationally representative airtightness dataset was analysed as follows:

- Descriptive statistics were calculated for airtightness values (extrapolated AP_{50}) for the weighted, nationally representative airtightness dataset, categorised according to built form, age band and construction.
- Distributions of airtightness among different dwelling categories were visualised and compared using boxplots and histograms.

Quantifying the impact of airtightness improvements

To assess the potential impact of stock-wide airtightness improvements, per-dwelling annual heating energy demand associated with infiltrative losses was estimated across the study sample. This was done using both the measurement-derived airtightness values, and following hypothesised airtightness improvements applied to achieve prescribed minimum levels of airtightness across the whole sample. These heating energy demands were then scaled up to GB stock level by summing across the GB stock-weighted sample, and the impact of the airtightness improvements quantified through comparison of energy demands calculated before and after their implementation. Associated annual energy costs and greenhouse gas emissions were calculated and compared similarly.

Under the hypothesised national airtightness improvement scenarios, all dwellings with measurement-derived air permeability AP_{50} exceeding a prescribed maximum value AP_{max} (m³/h.m² @ 50 Pa) were assumed to have been treated to bring their air permeability down to AP_{max} (while those with $AP_{50} \leq AP_{max}$ were unaltered). Energy demands, costs and emissions were calculated for 6 scenarios, with $AP_{max} = 10, 9, 8, 7, 6, 5$ m³/h.m² @ 50 Pa.

For each dwelling in the dataset, the annual heating energy requirement $ED_{h,inf}$ associated with infiltration was estimated as

$$ED_{h,inf} = \frac{1}{3} nV \times HDD \times \frac{24}{100} \quad [\text{kWh}] \qquad (2)$$

where:

- n is the assumed air change rate (h^{-1}), given by $\frac{AP_{50}}{20}$, where AP_{50} is the air permeability[34] (m³/h.m² @ 50 Pa, extrapolated from the result of a low-pressure pulse test conducted at 4 Pa).
- V is the volume of the dwelling, as reported in the low-pressure pulse test data (m³).

[34] The divide-by-20 method for estimating infiltration from airtightness is commonly used by others (see review in Report 2 of this project [120]). It is noted that this approach has drawn criticism for the reliability of its predictions, particularly when looking at individual buildings outside of the main UK heating season [4,36]. In other work, Jones et al. [20] used a more sophisticated model of infiltration estimation (DOMVENT3D), but this has not been extensively validated and its accuracy cannot be assured without further research [25]. Simply, it is difficult to say with any certainty whether an alternative infiltration estimation model could improve the estimation of stock level infiltration without further research.

- HDD is the heating degree days to a given base temperature. A standard HDD value of 2021°C.days to base temperature 15.5°C — the UK average for 1998-2007, as per CIBSE TM46 [132] — was used.
- $\frac{1}{3}$ is a conversion factor from m³/h to W/K, and $\frac{24}{1000}$ a conversion factor from watt-days to kilowatt-hours.

The national heating energy demand associated with infiltrative losses was then calculated by summing over the GB stock-weighted sample.

Heating energy demands were then recalculated for each airtightness improvement scenario, replacing the measured AP_{50} value (Equation 2) with the improved value $AP_{max} = 10, 9, 8, 7, 6, 5$ m³/h.m² @ 50 Pa in all dwellings for which $AP_{50} > AP_{max}$. The post-improvement national heating energy demand at each level of improvement was calculated by summing across the GB stock-weighted sample.

Resultant energy savings associated with each level of hypothesised airtightness improvements (achieving maximum air permeability $AP_{max} = 10, 9, 8, 7, 6, 5$ m³/h.m² @ 50 Pa) were calculated:

1. At GB stock level by calculating the difference between the national heating energy demand calculated using low-pressure pulse test-derived AP_{50} values and the corresponding national heating energy demand calculated after reduction of maximum air permeability to AP_{max} among those dwellings.
2. At mean per-dwelling level by dividing the stock level energy savings from 1 by the number of dwellings in the GB stock.
3. At mean per treated dwelling level by dividing the stock level energy savings from 1 by the number of dwellings in the GB stock-weighted sample requiring treatment to reduce their air permeability to AP_{max}.

Given a heating energy demand of ED (kWh), the associated heating fuel cost EC (GBP) and greenhouse gas emissions EE may be calculated as

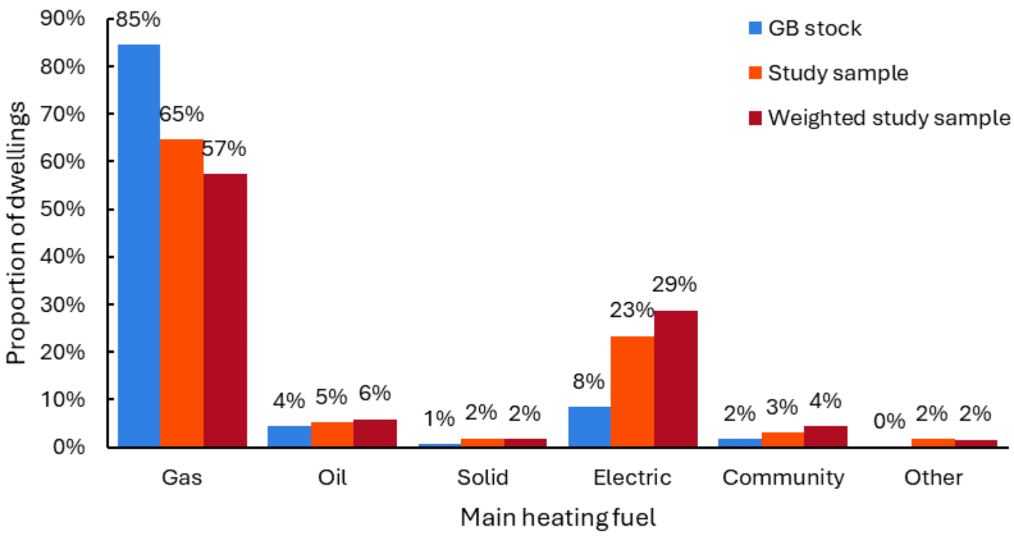
$$EC = ED \times UC \tag{3}$$
$$EE = ED \times CF \tag{4}$$

where:

- UC is the unit cost of the heating fuel (GBP/kWh).
- CF is the emissions factor for the heating fuel ($kgCO_2e$/kWh).

Note: Costs and emissions calculated using these formulations do not account for any efficiency losses. Calculated energy demands (and associated costs and emissions) pertain only to energy converted to heat within dwellings, rather than the total input heating fuel energy demands. This produces results that are heating system agnostic.

Comparing the distribution of main heating fuels in the study sample (as reported in EPC data) with that for the GB stock (derived from 2017 EHS, SHCS and WHCS data), the distribution in the sample — both before and after weighting — was not representative of the distribution at national level (Figure 19): dwellings using gas as the main heating fuel were under-represented (57% weighted sample, 85% GB), while those using electric main heating systems were over-represented (29% weighted sample, 8% GB).



GB figures derived from 2017 EHS, SHCS and WHCS data.

Figure 19: Distribution of main heating fuels in the GB domestic stock and the study sample.

Due to the weighted sample's poor representation of the national distribution of main heating fuels used, it was deemed inappropriate to use per-fuel unit costs and emissions factors in estimation of stock-level energy costs and emissions associated with heating demand due to infiltrative losses. Instead, weighted averages were calculated to produce a single unit cost UC and emissions factor CF:

$$UC = \frac{\sum_f p_f UC_f}{\sum_f p_f} \tag{5}$$

$$CF = \frac{\sum_f p_f CF_f}{\sum_f p_f} \tag{6}$$

where:

- Σ_f is the sum over all main heating fuel types.
- p_f is the proportion of the GB stock using main heating fuel f.
- UC_f is the unit cost of fuel f (GBP/kWh).
- CF_f is the emissions factor for fuel f ($kgCO_2e$/kWh).

Unit costs and emissions factors (Table 19) were sourced from Government Green Book supplementary guidance on value of energy use and greenhouse gas emissions [133]. Values were only available for gas, oil and electricity; thus the sum Σ_f was calculated over these three fuels only[35]. The unit costs used were central long run variable cost (LRVC) estimates for 2024, while the emissions factor for electricity was the 2024 long-run marginal consumption-based cost.

Table 19: Heating fuel unit costs and emissions factors. Source: Government Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal, data tables 1–19 (DESNZ, 2023).

Fuel	Proportion of GB stock using as main heating fuel	Unit cost (p/kWh)	Emissions factor ($kgCO_2e/kWh$)
Gas	85%	4.45	0.183
Oil	4%	4.88	0.244
Electricity	8%	16.4	0.230
Weighted average	—	5.51	0.190

Unit costs are central LRVC estimates for 2024. The p/kWh cost for oil was derived from the p/litre cost, assuming a gross calorific value of 10.3 kWh/litre.
The emissions factor for electricity was the long-run marginal, domestic consumption-based cost for 2024; factors for other fuels were fixed values not dependent on year.

Using the derived national average unit fuel cost (0.0551 GBP/kWh) and emissions factor (0.190 $kgCO_2e/kWh$), the costs and emissions for the heating demands associated with infiltrative losses were calculated for the stock-weighted sample, both before and after the hypothesised application of airtightness improvement measures, along with savings made for each level of improvement.

[35] The impact of omitting other fuels from this calculation is expected to be small, as they account for no more than 3% of the GB domestic main heating fuel mix (as per Figure 19).

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