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Airtightness retrofit and construction practices, unintended consequences, and ventilation practices

Gathering evidence to improve airtightness in the UK housing stock

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This report forms the third 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

Airtightness retrofit and construction practices influence airtightness, but more research is needed to quantify the effect of a range of airtightness measures across a range of dwellings.

Most unintended consequences of more airtight dwellings are ameliorated with sufficient ventilation. Fire risk is an exception to this rule, and is poorly researched.

Ventilation practices are driven by several stimuli and differ based on the type of ventilation in place, be that natural or mechanical. There is no evidence to suggest that a practically relevant difference in airtightness exists in new dwellings based on ventilation type.

Research purpose

The first aim of this research is to understand the construction practices related to airtightness: the effect of airtightness improvements, airtightness failure points, ways to address airtightness failure points, the relationship between airtightness and build quality, and the influence of PAS 2035:2023 and PAS 2030:2023 in driving higher airtightness standards.

The second aim of this research is to understand the unintended consequences of more airtight dwellings in the UK.

The third aim is to understand how and why occupants ventilate their homes, to know if they do so sufficiently and appropriately, and if they have the knowledge to do so efficiently.

Research methodology

Three Rapid Evidence Assessments were carried out. The first Rapid Evidence Assessment, which screened 1,497 documents for quality and relevance, and subsequently reviewed 26, reviewed research on airtightness construction practices and risks that relate to airtightness in the UK housing stock. The second Rapid Evidence Assessment screened 75 documents and reviewed 36 on the risks and unintended consequences of more airtight dwellings. The third Rapid Evidence Assessment screened 266 documents and reviewed 40 on ventilation practices.

Analysis of secondary data from the Retrofit Revisit project investigated the durability of airtightness over time. Analysis of over 5,000 airtightness tests from existing GB dwellings investigated the presence of clustering around compliance thresholds to detect in-test temporary sealing.

Research findings

The first Rapid Evidence Assessment revealed that:

- Retrofit generally improves airtightness, but could be more effective with greater care and attention paid to preserving the primary air barrier.
- There is no evidence to quantify the effect of any particular airtightness retrofit intervention across a large, diverse sample of UK dwellings.
- External wall insulation and floor sealing are likely to be among the most effective retrofit measures to improve airtightness.
- There is insufficient information to reliably infer typical airtightness failure points by any single dwelling characteristic, but wet-plastered masonry walls are inherently airtight.
- Airtightness failure points relate to service penetrations, careless interaction with the primary air barrier, and reliance on secondary seals in place of a robust primary air barrier.
- Secondary seals can fail over time as they shrink and dry out. Window and door seals can fail as they are used. Both can be fixed with regular maintenance.
- There is insufficient evidence to show that high levels of airtightness are a proxy for build quality when considering the dwelling holistically.
- PAS2030 and PAS2035 promote robust airtightness practices, but further research is needed to evaluate the effectiveness of its implementation.

The second Rapid Evidence Assessment revealed that the unintended consequences of more airtight dwellings are condensation, damp, poor indoor air quality, radon build-up, and overheating. All these issues can be alleviated simply by ventilating appropriately, however. A key unintended consequence that cannot be remedied with more ventilation is fire and smoke risk. There is a dearth of research on the subject and there is a significant gap in the literature relating to changing airtightness regulations and fire/smoke behaviour.

The third Rapid Evidence Assessment revealed that occupant ventilation practices are governed by the available ventilation provision and behavioural drivers. The link between airtightness and ventilation type in new dwellings is too small to be practically relevant. Most UK dwellings are naturally ventilated using operable windows, with mechanical ventilation only common in kitchens and bathrooms. Instantaneous responses to temperature and indoor air quality are the main drivers for natural ventilation use – but the body of literature is contradictory. Mechanical ventilation systems are poorly maintained, sometimes switched off due to noise or draughts, and many occupants do not feel knowledgeable enough to operate them. Current studies use small sample sizes, case studies, or unrepresentative surveys to collect data which prevent broader, nationally representative, conclusions from being drawn.

Analysis of secondary data showed that airtightness deteriorated in 7 out of 10 homes revisited after 10 years by an average of 0.52 $m^3/h.m^2$ @ 50 Pa. There is no evidence to suggest that in-test, temporary sealing occurs in the airtightness database of existing GB dwellings.

Introduction

Background and context to airtightness retrofit and construction practices

Airtight dwellings with adequate purpose-provided ventilation are desirable for reasons of heating energy demand, thermal comfort, air quality, and building durability. Newly built dwellings in the UK are required to meet a certain level of airtightness to comply with building regulations and have done in England and Wales since 2002[1]. The airtightness regulations became more stringent in 2022[2]. There is no such regulation for existing dwellings, even if they have undergone retrofit. Thus, most UK dwellings were built before the current airtightness regulations were introduced and there is great scope for improvements to the airtightness of existing dwellings [1]. However, it is currently unclear what effect specific retrofit measures may have on the airtightness if applied across the UK housing stock.

There is often a difference between the designed and actual performance of a building: the performance gap. This gap may occur both in newly built dwellings and those that have undergone retrofit. The performance gap results in disappointing energy demand reductions without the intended comfort improvements. To address the performance gap, research is needed to identify typical failure points in the airtightness construction and retrofit process, and to determine if typical airtightness failures can be addressed by retrofit, and to quantify how these deteriorate over time. Standards such as PAS 2030 and PAS 2035 are intended to ensure robust airtightness retrofit practices, but their effectiveness requires further investigation.

The reliability of airtightness data needs careful consideration. To comply with airtightness regulations, ‘in-test’ remedial works are often undertaken in new dwellings [2]. This results in a high proportion of test results being just within the compliance threshold (e.g., 5 $m^3/h.m^2$ @ 50 Pa) with a sharp drop off afterwards. This temporary sealing may be effective only in the short term or even removed immediately after the test. While this trend has been observed in new dwellings, there is no evidence to suggest whether or not this practice is employed in existing dwellings.

[1] From 1995, newly built dwellings were required to “limit infiltration” without a specific infiltration or airtightness threshold to comply with [130]. From 2002 a compliance threshold of 10 $m^3/h.m^2$ @ 50 Pa was introduced in England and Wales [131].
[2] With a compliance threshold of 8 $m^3/h.m^2$ @ 50 Pa in new dwellings [132] with mandatory pressure testing in all new dwellings. Prior to this, in 2013, a design target air permeability of 8 $m^3/h.m^2$ @ 50 Pa was in place for dwellings which did not undergo a pressure test [133].

Background and context to unintended consequences and ventilation practices

Building Regulations in the UK are mandating that newly built dwellings are more airtight. This endeavour will reduce heating energy demands, energy costs for households, and national greenhouse gas emissions. In adequately ventilated dwellings, airtightness can improve indoor air quality by allowing closer control over the amount and quality of the outdoor air that enters. “A building cannot be too airtight, but it can be under ventilated” [3].

If airtight dwellings are not adequately ventilated, air quality can deteriorate resulting in damp, mould, overheating, and accumulation of airborne pollutants. If dwellings are overventilated this can increase heating energy demand or summertime cooling requirements. The question remains, however, as to what is known about how UK dwellings are ventilated, if they are ventilated sufficiently, and if the dwelling occupants understand how, when, and for how long to ventilate. As different ventilation rates are required to remove excess heat, water vapour, airborne pollutants, and airborne pathogens, how much is enough? The quality, temperature, and humidity of the ventilating air also matters, and so overcoming the combination of issues is not straightforward.

Previous reports in this series on *Gathering evidence to improve airtightness in the UK housing stock* have focused, predominantly, on infiltration and airtightness [1,4]. Ventilation differs from infiltration in that it is air exchange through purpose-provided openings. Ventilation can be driven naturally, by the wind or stack effect, or mechanically via extractor fans. Whilst infiltration occurs without occupant influence, ventilation is usually occupant-controlled through the operation of windows, vents, and extractor fans. As such, occupants may choose to under-ventilate their homes to reduce wintertime heat loss (thus energy costs), exacerbating mould problems. Equally, knowing what to do and when with ventilation during heatwaves is often not common knowledge for building occupants in the UK where extremely hot summers are only a relatively recent occurrence [5,6].

UK Building Regulations stipulate that new dwellings must be airtight [7] with adequate ventilation provision [8]. Existing dwellings do not need to comply with any such standard, but Part F advises that it is good practice to introduce additional ventilation via trickle vents when windows are replaced.

Aims and objectives

The first aim of this research is to understand the construction practices relating to airtightness.

- O3.1: Conduct a Rapid Evidence Assessment to address research questions RQ1-RQ6.
- O3.2: Analyse secondary data to investigate airtightness degradation over time.
- O3.3: Analyse secondary data to investigate the presence of in-test sealing in the existing GB housing stock.

This report does not present a detailed study of the relationship between *types* of construction and airtightness, e.g., masonry wall versus timber-framed dwellings. This is addressed in an extensive review found in Report 1 [1].

The second aim of this research is to understand the unintended consequences of more airtight dwellings in the UK. The aim will be met via the following objectives:

- O3.4: Conduct a Rapid Evidence Assessment to address research questions RQ7-RQ8.

The third aim is to understand how and why occupants ventilate their homes, to know if they do so sufficiently and appropriately, and if they have the knowledge to do so efficiently.

- O3.5: Conduct a Rapid Evidence Assessment to address research questions RQ9-RQ11.

Research questions

Construction and retrofit practices

The following research questions related to construction practices[3] will be addressed in this report:

- RQ1: What effect does retrofit have on airtightness?
- RQ2: What are the typical airtightness failure points by dwelling type, age, or construction type?
- RQ3: What are the typical failure points in the construction process that can lead to poor airtightness?
- RQ4: How could typical airtightness failures be addressed by retrofit?
- RQ5: Is there a relationship between airtightness and build quality?
- RQ6: Does PAS2035:2023 and PAS2030:2023 contribute to robust airtightness practices?

[3] There is a full review of the dwelling construction *types* and their relationship to airtightness in Report 1.

Unintended consequences

- RQ7: What are the unintended consequences of more airtight homes?
- RQ8: How does airtightness affect overheating?

Ventilation practices

The following research questions related to occupant ventilation practices will be addressed in this report:

- RQ9: How and why do people typically ventilate their homes in the UK?
- RQ10: Do people ventilate their homes sufficiently or appropriately in the UK?
- RQ11: Do people know how to ventilate their homes in the UK?

Report structure

The first part covers construction and retrofit practices via the first of three Rapid Evidence Assessments and analyses of secondary data to investigate the durability of airtightness over time and, on a separate dataset, to determine if in-test airtightness sealing can be detected in a large dataset of existing GB dwellings. The second part covers the unintended consequences of more airtight buildings via the second Rapid Evidence Assessment. The third part of the report covers occupant ventilation practices via the third and final Rapid Evidence Assessment.

Rapid Evidence Assessment 1

Introduction

This Rapid Evidence Assessment aims to review what the current literature says about the construction and retrofit practices that relate to airtightness in the UK housing stock. There are two stages:

- Synthesise evidence on the effect of retrofits on airtightness.
- Investigate the effect of typical airtightness failure points during the construction process which lead to poor airtightness.

Methodology

Overview of methodology

Rapid Evidence Assessments are rigorous and timely reviews of the literature in order to make evidence-based recommendations [9]. The review process was adapted from Drury [10] 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 GRADE system.

A full methodology is provided in Roberts et al. [1]. The search terms and screening criteria specific to Rapid Evidence Assessment 1 are listed in Table 1 and Table 2 respectively.

Table 1: Primary and secondary search terms.

Primary search term	Secondary search term
"Air tightness"	Construction
Airtightness	Techniques
Air leakage	Retrofit
Air permeability	Refurbishment
Infiltration	Building
	Domestic
	House
	"Home"

Table 2: Inclusion and exclusion criteria used to screen the literature.

Inclusion criteria	Exclusion criteria
Written in English	Focuses only on non-domestic buildings
Related to UK case studies or UK construction techniques	Duplicated studies, e.g., where a conference paper became a journal paper
Can be readily accessed online within the time allocated for review	
The abstract indicates relevance to the research question being investigated	
The full text provides evidence for the research question being investigated	

Findings

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 [11] (Figure 1).

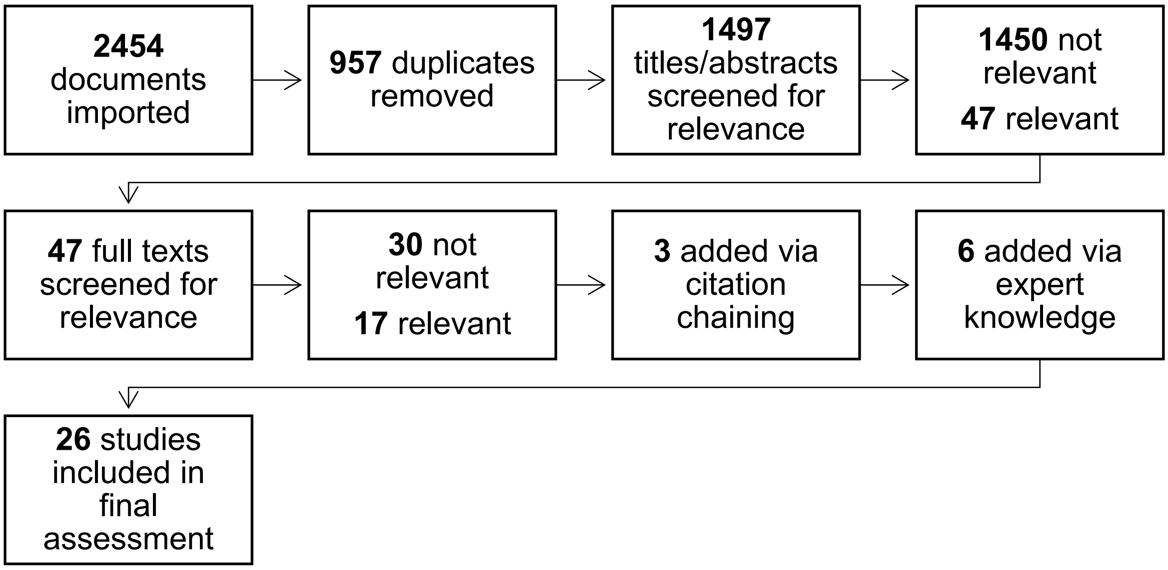

Figure 1: PRISMA diagram, after Page et al., [11].

Key findings:

Retrofit generally improves airtightness, but desired targets are rarely achieved.

Airtightness failure points typically relate to the air barrier, junctions, window seals, and door seals. Service penetrations, poor sealing, and poor workmanship decrease airtightness. Reliance on secondary seals rather than the primary air barrier leads to poor airtightness in the long term, as the secondary seals degrade over time. There is no evidence to suggest this varies by dwelling type, age, or construction – although the inherent properties of some construction types, e.g., wet-plastered masonry, allow airtightness to be achieved automatically.

Retrofit may address airtightness failures, but the improvement is less effective than if implemented during the original construction phase. Sealing of openings and service penetrations is the most effective airtightness improvement intervention.

Build quality is related to airtightness via meticulous detailing, planning to avoid improvised solutions, and ensuring quality workmanship, training, and supervision.

PAS 2053:2023 and PAS 2030:2023 contribute to robust airtightness practices by addressing three common issues related to airtightness in the retrofit process: (1) accurate design, detailing, and targets; (2) ensuring preservation and improvement of the air barrier; (3) focusing on quality workmanship, training, and communication between all parties involved in the retrofit process.

GRADE quality assessment rating:

There is moderate-quality evidence to describe the relationship between construction techniques, retrofit, and airtightness in UK dwellings. Studies are generally single case studies or otherwise small in scale.

In this review, each study is presented individually in ascending order of publication date and then the findings pertaining to each research question are drawn together at the end.

Lowe et al. [12] conducted lab tests and field measurements on three test houses in York, UK. They found plastered masonry walls very airtight; however, the window/wall junction sealing was an element of potential weakness. Window airtightness could be improved by thermally breaking the window reveals and using separate lintels for the inner and outer leaves of the wall. The installation of a prefabricated draught-proofed loft hatch is suggested to have a positive impact on airtightness. Additional positive interventions were boxing vent stacks when passing through the first-floor ceiling and filling those boxes with polyurethane foam. Finally, filling cavity walls with foamed polyurethane improved the airtightness of the houses. Bell & Lowe [13] further suggested that, although wet plastered walls have good airtightness properties, retrofit works that use dry-lining plasterboard-on-dabs systems to replace defective plaster could also reduce airtightness due to the difficulties of the related sealing works between the different technologies. The same study reports that 60-70% air leakage reduction was possible by repairing damaged plaster, installing new wooden window and door frames, and sealing suspended timber ground floors.

Stephen [14] reported on 471 dwellings, part of the BRE database. Minor differences in the average airtightness were found between dwellings with insulated cavity walls and uninsulated cavity walls. Conversely, buildings built using Large Panel Systems (LPS) construction techniques were found to be more airtight, although leakages remained at the joints between the panels. Air leakages also occurred through ground floors, specifically when suspended timber floors were in place. In these cases, weak spots were represented by the edges and the service penetrations. Finally, windows and doors were responsible for 16% of air leakage, and only 9% was due to permanent ventilators.

Ridley et al. [15] reported that retrofitted dwellings are likely to be more airtight than un-retrofitted dwellings and showed that replacing windows increased airtightness by 50% in an English dwelling.

Roberts et al. [16] proposed a new approach for constructing airtight load-bearing masonry dwellings using a dry lining technique. The approach consists of applying a quick-drying airtight barrier to the internal leaf of the external walls. The study is based on a field trial based on one dwelling and estimates a resulting air leakage rate lower than 5 $m^3/h.m^2$ @ 50 Pa and, applied in a refurbishment strategy, reduced the air leakage rate by a factor of 2. This study also highlights the importance of workmanship and detailing in improving airtightness. Specifically, attention should be paid to sealing any opening due to pipework installation or electricity distribution.

In 10 UK dwellings, window replacement increased the dwelling airtightness by an average of 4.6 ach @ 50 Pa [17].

Hong et al. [18] found that a retrofit programme did not improve airtightness, despite draughtproofing and insulation being installed in 1,372 English dwellings. This was because the installation of new heating systems alongside the insulation and draughtproofing work introduced penetrations that resulted in an overall 13% decrease in airtightness.

Johnston & Lowe [19] studied the air permeability of 12 plasterboard-lined load-bearing masonry dwellings in Durham County. The 1970s dwellings were subject to both general and airtightness-targeted works. The air permeability was reduced (made more airtight) to 11.2 $m^3/h.m^2$ @ 50 Pa starting from 24-26, with a reduction of ~55%. The authors list a set of measures that affected the airtightness of the dwellings. Avoiding flues and preferring electric fires to gas fires, polyurethane filling of cavity walls, and sealing the junction between the plasterboard lining and the connection into the soil stack improved the airtightness. Conversely, some factors contributed to worsening the airtightness of the dwellings. For example, in some cases, the plasterboard lining around windows and external doors did not fit with the lining or the sills, leading to gaps of up to 1 cm. In other cases, the mounting plates of gas boilers were mounted directly to the outer walls' inner leaf, creating a discontinuous sealing with the plaster lining. The draught strips on several external doors did not guarantee airtightness when the doors were closed because they were not fully compressed, and large cracks were found in the chipboard, consequent to the central heating pipework installation. Finally, this study identified the sealing of the external walls with expanding polyurethane foam as the most effective measure, reducing the air permeability by ~8 $m^3/h.m^2$ @ 50 Pa. Conversely, sealing the loft hatch and the electrical sockets was the least effective measure, with a minimal reduction of ~0.1 $m^3/h.m^2$ @ 50 Pa. Roberts [20] similarly highlights how external insulation improves airtightness. And Gupta & Howard [21] reported that a full wrap-around layer of external insulation covering external walls, ground floor and roof brought the airtightness of a 1950s council-owned flat building from 3.2 ach @ 50 Pa to 0.67 ach @ 50 Pa, equivalent to an air permeability of 0.92 $m^3/h.m^2$ @ 50 Pa. Retrofit also included replacing windows with fixed windows.

Johnston & Miles-Shenton [22] conducted a detailed analysis of the air permeability of 25 dwellings constructed to conform to Part L1 2002, including the design and construction phases. The study indicates an airtightness of ~5 $m^3/h.m^2$ @ 50 Pa can be achieved just by wet or mechanically plastered masonry cavity construction. More attention should be paid to detailing where dry construction techniques are implemented. Fewer air leakage paths were discovered in wet-plastered masonry apartments. The authors attribute the high levels of air permeability measured across the sample to different factors: the lack of airtightness-oriented detailing and design, and the difficulty of applying design choices in practice due to the lack of adequate training of the contractors.

An extensive study was conducted by Pan [23], who investigated the relationship between the air permeability test results of 287 post-2006 new-build dwellings in the UK and possible influencing factors like construction techniques, dwelling types, design and construction management objectives, and the geometrical parameters of the dwellings. Results show an average air permeability of ~6 $m^3/h.m^2$ @ 50 Pa. Some interesting results include the fact that good levels of airtightness were reached in flats built using precast concrete panels, while masonry and reinforced concrete frame dwellings were leakier. Conversely, for houses, the leakiest dwellings were constructed using site-based labour-intensive construction techniques. Better airtightness levels were reached where ‘self-build’ procurement routes were implemented, and there was a wider extent of innovative building practice precisely and intentionally targeted to airtightness. A good correlation was also identified between airtightness, the number of significant penetrations, and the total envelope area.

An extensive report from Wingfield et al. [24] investigated the gap between the designed and actual energy performance of load-bearing masonry domestic buildings. Considerations on airtightness in this work refer to several topics. Firstly, the authors state the importance of the design phase, expressly to guarantee the continuity of the air barrier from an early stage and to avoid leaving complex problems to be resolved on-site. Design should include accurate detailing of service penetration and dimensional junctions. Secondly, the authors suggest systematic quality control through multiple airtightness tests during the construction phase. Attention to workmanship is also important; along with proper training, it is essential to ensure that working conditions are favourable to meet buildable design solutions. Consequently, training should be carried out on a day-to-day basis, providing contextual instructions about the specific design that is going to be built and its importance in the context of guaranteeing low infiltration rates. Critical importance is attributed to work sequencing, which is to be addressed in the design process. All work phases should be carefully planned to avoid damage to the air barrier that cannot be fully repaired. Finally, the importance of communication between all the involved parties is stated in the report to allow a clear flow of information both upwards and downwards. In the study, a subsample of five homes were measured for airtightness immediately after construction was completed and again after the dwellings had been heated for several weeks. The air permeability increased by up to 30% due to shrinkage of mastic seals after heating. Whilst this occurred during a co-heating test (rather than normal occupation) when the indoor temperatures would be slightly higher than those expected during the winter heating (25-29°C), the authors state that the effect on drying of mastic seals would be similar after a year of occupation. The use of backer rods is recommended to compensate for this. The study also found that sealant failed when applied over debris or on dusty surfaces, which reduces the dwelling airtightness.

Although the analysed sample does not fully represent the typical UK building, Johnston et al. [25] reported that high-quality construction details may not guarantee achieving the airtightness regulatory standards. The report states that light steel frame construction could worsen airtightness, given the difficulties in achieving continuous and durable primary air barriers. This report also confirms that wet plastering techniques have a positive impact on airtightness, but a draughtproof connection with the roof’s boundaries may be difficult to achieve. Conversely, steel-framed construction and dry-lined masonry cavity walls require a higher level of attention to detail and sealing. Furthermore, geometrical complexity also implies a higher likelihood of interrupting the continuity of the air barriers. Overall, the design and construction of easy-to-build approaches prioritising the continuity of the airtightness barriers produced better results than approaches that merely addressed manual sealing of the building fabric.

Banfill et al. [26] recorded that sealing the entire ground floor and all the penetrations of a dwelling in Nottingham reduced air permeability from 8.6 to 5 $m^3/h.m^2$ @ 50 Pa.

In two very airtight dwellings (0.26 $m^3/h.m^2$ @ 50 Pa), most of the decrease in airtightness over time was attributed to deterioration of external door seals during occupancy [27].

In a case study described by Moorhouse & Littlewood [28], the use of internal spray foam insulation between the joists, in the party walls and around the window frames was adopted as a measure to improve airtightness by ensuring the continuity of the sealing.

Gupta & Kapsali [29] analysed the implications for air quality of three refurbishment interventions in the UK. In all considered cases, retrofit failed to meet the designed airtightness targets. According to the authors, the reasons are found in the lack of quality of detailing of junctions, penetrations, and skirtings. In one case, installing a heat pump left a big hole in the airtightness membrane in the ceiling of one of the dwellings.

Gillott et al. [30] report that draught-proofing interventions alone in a UK dwelling led to 9% energy savings. Air permeability was reduced (made more airtight) from 15.57 to 4.74 $m^3/h.m^2$ @ 50 Pa. This was made possible thanks to a high level of attention to detail and to the training for the installers. Poor workmanship was identified as a major cause of quality loss. Additionally, draughtproofing and sealing the joints between the floor and the walls at the skirting board interface were shown to be the most effective approaches, reducing 5.73 and 3.6 $m^3/h.m^2$ @ 50 Pa, respectively.

Roberts et al. [31] found that a thermal efficiency retrofit of a semi-detached house, which replaced single-glazed windows with double-glazed, did not otherwise pay particular attention to airtightness, reduced air permeability by 29%.

Gupta & Kotopouleas [32] conducted a meta-analysis on 188 newly built low-energy homes, including 50 Passivhaus dwellings, identifying a significant performance gap in airtightness between design and construction. Concrete and timber-framed constructions had in-situ performance more similar to the design values, often performing better than the design. Masonry construction, on the other hand, underperformed by an average of 1.3 $m^3/h.m^2$ @ 50 Pa. This performance gap was not evident in Passivhaus construction, proving that, according to the authors, a good level of workmanship and detailing was more important than the construction techniques.

Crawley et al. [33] also emphasised the importance of better quality control during the construction phase. The authors say this may include airtightness testing during construction, to avoid excessive post-construction air leakage. According to the authors, these measures are usually less effective than measures applied to the primary air barrier in the first place.

Ashdown et al. [34] analysed the airtightness of more than 900 dwellings built between 2007 and 2011 and found that a hierarchy can be defined among different construction techniques and their impact on air permeability. Specifically, reinforced concrete frame dwellings performed better than dry-lined masonry dwellings, further followed by timber and lightweight steel frame construction. The authors found that the most important component to preserve airtightness is the primary air barrier; secondary sealing may have a negative impact on the long-term efficiency of the buildings as it is more susceptible to deterioration over time.

Describing retrofit using Passivhaus components of a house in Hereford, UK, Bastian et al. [35] report the importance of airtightness barriers' continuity. The overall approach to achieving airtightness included the draught-proof insulation of suspended ground floors and the filling of an open cavity between one of the house's gable walls and an adjacent building with expanding foam. The authors report designating the outer face of the walls as the airtightness zone to be a robust decision, emphasising the necessity of training the contractors and monitoring the execution.

A Department for Business, Energy & Industrial Strategy (BEIS)[4] [36] report summarises the findings from an investigation conducted over five years on low-carbon housing projects. In one case study, airtightness was poorer than predicted due to the poor integration of wall panels with other built elements. In another case, airtightness was compromised in hybrid construction techniques, including steel and concrete. Analysed homes, in accordance with the rest of the literature, were poorly airtight due to insufficient detailing at floor edges; external doors, defective sealing, and services penetrations also contributed to the issue, especially when services clashed with insulation layers. The report also suggests that design coordination prior to construction would have positively reduced air permeability.

The Demonstration of Energy Efficiency Potential (DEEP) project on 14 case study houses' retrofits highlighted how airtightness strategies are critical for retrofit, as draught-proofing usually does not last and is not effective [37]. The draught-proofing approaches implemented in the analysed cases lead to minor changes in the air permeability of the houses. The most effective measures reported are general sealing and the addition of carpets, which possibly reduced the air permeability of the ground floors, along with ground floor insulation. In general, improving insulation has been found beneficial also for airtightness; however, rigid foam or mineral wool boards were ineffective when applied at the joists level for roof insulation. Finally, the DEEP report also states that it was not possible to identify house characteristics that could be used *a priori* to infer the airtightness of domestic buildings.

Finally, Publicly Available Specifications (PAS) have been reviewed to assess how they relate to retrofit and airtightness. PAS 2030:2023 [38] specifies the installation of energy efficiency measures and includes requirements on installation processes, process management and service provision. These installation requirements must be met for retrofit projects to be awarded public funding. However, the direct reference to airtightness in PAS 2030 is general and is not related to specific energy efficiency measures. Suggestions aim to maintain the integrity of the air barrier and verify that design and detailing take airtightness implications into consideration, recommending but not necessarily including a target post-retrofit airtightness level. Requirements for performance testing also include verification of air permeability. Finally, PAS 2030 prescribes paying attention to sealing of water and draught-proof elements for the

[4] BEIS existed from 2016 until 2023 when it was split to form the Department for Business and Trade (DBT), the Department for Energy Security and Net Zero (DESNZ) and the Department for Science, Innovation and Technology (DSIT).

sake of weatherproofing and to prevent damp and condensation in the long run. This prescription can have a positive impact on airtightness levels.

Producing an airtightness strategy to achieve predetermined targets is also a requirement listed in PAS 2035:2023 [39], which defines the industry standard for retrofit but is not a certification. In PAS 2035, directions are more specific; for example, details are given on how to design an appropriate air barrier. In addition, the standard highlights the importance of accurate detailing, especially for corners and junctions. This includes the possible interaction between different energy efficiency measures.

Addressing research questions RQ1-RQ6

This section extrapolates from the literature review by summarising the key findings relative to each research question.

RQ1: What effect does retrofit have on airtightness?

Although retrofit generally improves airtightness, designed target air permeability levels are rarely reached [40,41]. Retrofit can be less beneficial than expected if insufficient attention is paid to the conciliation of old and new technologies [42], and to the preservation of the air barrier [41,43], or if new penetrations are introduced as the result of other works alongside retrofits (e.g., plumbing and heating systems) [18].

RQ2: What are the typical airtightness failure points by dwelling type, age, or construction type?

There is insufficient UK-based literature to reliably infer typical failure points by house type and age. Wet-plastered masonry walls are usually more airtight [42,44–46], compared to dry construction techniques. Additionally, when correctly installed, panel system construction techniques [14,23,34],and externally insulated walls [20] improve airtightness.

RQ3: What are the typical failure points in the construction process that can lead to poor airtightness?

Most of the typical failure points in the construction process that can lead to poor airtightness are directly related to the integrity of the air barrier. Most of the analysed cases report how detrimental service penetrations can be [37,47–50]. Junctions and sealing are also typical weak spots in the construction phase if appropriate techniques and materials are not implemented [12,13,19].

RQ4: How could typical airtightness failures be addressed by retrofit?

Retrofit strategies that include external insulation can restore air permeability [51] but this is less effective than interventions in the construction phase [52]. Sealing and filling of windows, doors and service penetrations are proven to be effective in reducing air permeability [13,19,26,28].

RQ5: Is there a relationship between airtightness and build quality?

Build quality can have a direct impact on airtightness. The analysed literature shows that this can be controlled by paying attention to two main aspects: accurate and meticulous detailing during the design phase, to avoid builders and contractors from implementing improvised solutions [16,22,24,25,29,32,36], and quality of the workmanship, achieved through training, good communication and supervision [16,24,25,30,35,53].

RQ6: Does PAS 2035:2023 and PAS 2030:2023 contribute to robust airtightness practices?

All suggestions and indications provided in PAS 2035 and PAS 2030 address the three main and more common issues related to airtightness in retrofit processes. Firstly, accurate design and detailing is recommended, including measurable airtightness targets. Secondly, preservation and improvement of the air barrier, in any form, is a recurring theme in both PAS 2035 and PAS 2030. This includes directions on how to merge different energy efficiency measures. Finally, points are made on workmanship training and good communication between all parties involved in the retrofit process.

Research gaps

1. There is a lack of studies quantifying the direct impact of individual construction and retrofit techniques on the airtightness of the national UK housing stock. The current literature generally focuses on small samples of homogeneous dwelling types or single case studies.
2. High levels of build quality related to airtightness lead to improvements, yet it is not clear whether this translates to other parts of the build process. More research is needed before airtightness can be used as a proxy for build quality.
3. Whilst the existence of PAS 2030 and PAS 2035 may well drive improvements in airtightness construction practices, there are no studies which examine how the specific PAS 2030 and PAS 2035 practices are enacted, and so there is a need for further research in this area.

Analysis of data to investigate the durability of airtightness over time

Introduction

The aim of this section is to review and summarise the findings from the Building Performance Evaluation on the retrofit of 10 UK-based case studies homes, regarding airtightness improvements and applied retrofit techniques collected in the report *"Retrofit Revisit: 10 case studies"* [54].

Methodology

Overview of methods

The following approach was applied to the analysis:

1. Review the individual case study reports.
2. Extrapolate data from cross-project results.
3. Review new data selection and analysis, considering what is presented in existing reports.

Data sources

Case study reports were analysed for 10 retrofit interventions, identified with the following names: Blaise Castle Estate, Culford Road, Grove Cottage, Hawthorn Road, Hensford Gardens, Passfield Drive, Princedale Road, Rectory Grove, Shaftesbury Park Terrace, and Wilmcote House.

A cross-project dataset was used as the main source of data. The dataset includes results from blower door airtightness measurements before retrofit and right after retrofit, and low-pressure pulse and blower door results from testing conducted 10 years later. Pre-retrofit tests were available for only four cases. Data was available for air change rates and air permeability of the envelope.

Results

Four of the Retrofit Revisit case studies had an airtightness test pre-retrofit, demonstrating either air leakage rate, N_{50} (Figure 2) or air permeability, AP_{50} (Figure 3). All 10 case studies had an airtightness test immediately after retrofit (via blower door) and again, all 10 had a test 10 years later (by blower door test and low-pressure pulse test). The retrofit reduced the air leakage rate or air permeability (i.e., increased airtightness) in all cases[5]. In the 10 years after the retrofit, seven of the dwellings became less airtight by a mean average of 0.52 m³/h.m² @ 50 Pa (Figure 2 and Figure 3). The maximum increase in air permeability (becoming less airtight) was 2.58 m³/h.m² @ 50 Pa. The minimum increase in air permeability was -1.41 m³/h.m² @ 50 Pa (meaning that the dwelling became more airtight since the retrofit).

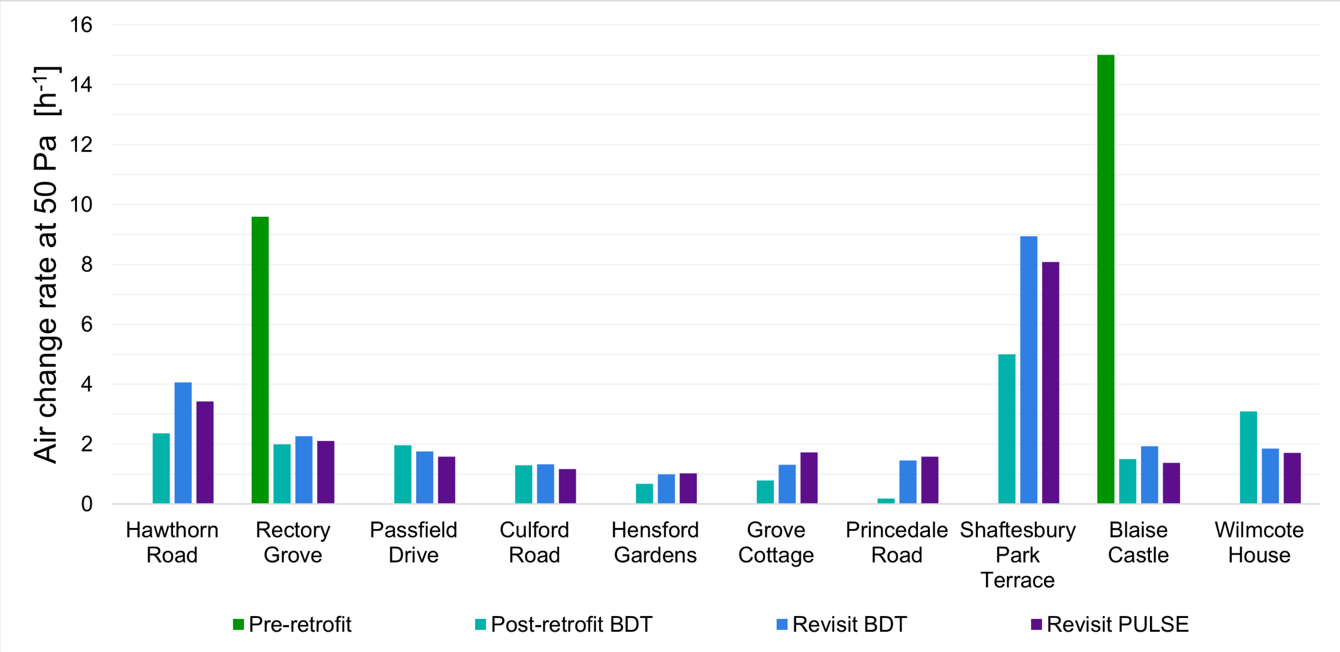

Figure 2: Air leakage rate (N_{50}) of 10 case studies before, immediately after, and 10 years after retrofit.

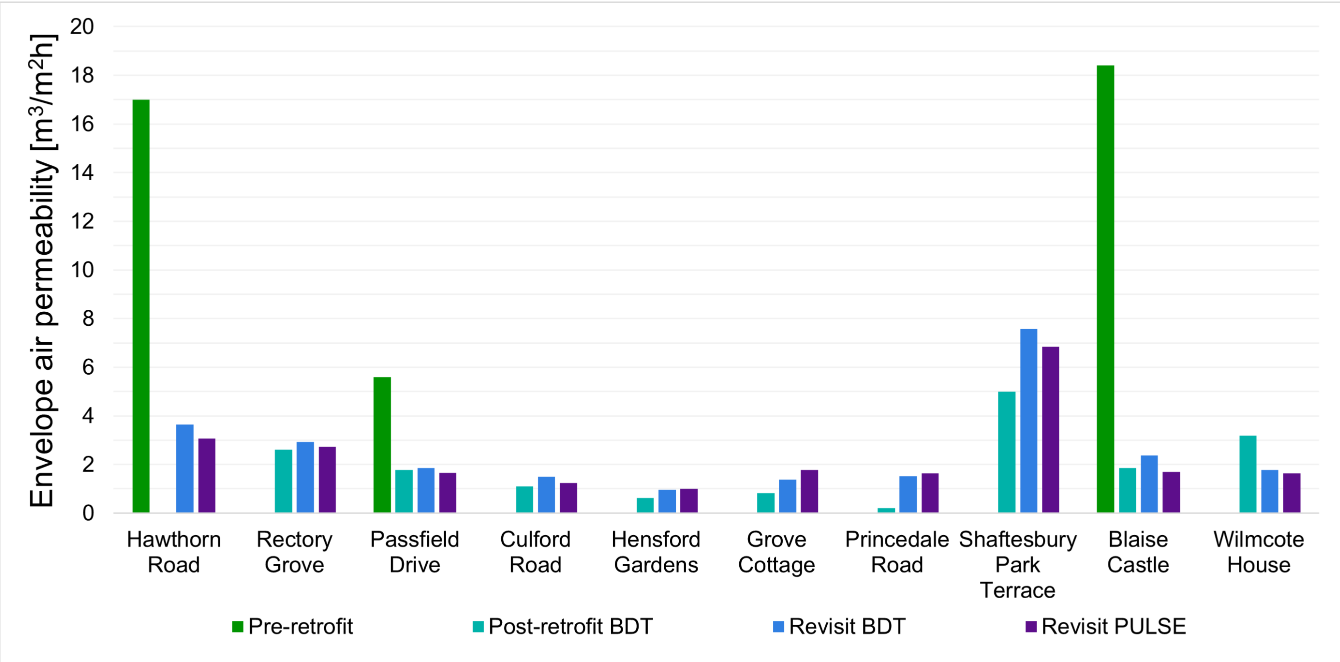

Figure 3: Envelope air permeability (AP_{50}) of 10 case studies before, immediately after, and 10 years after retrofit.

[5] All four cases where both a pre- and post-retrofit airtightness test was available.

Some construction practices employed influenced the airtightness of the buildings. For instance, in one case, using cement rather than lime in brick mortar repairs on the north side resulted in visible deterioration and cracking of the façade. Similarly, another case improved high airtightness by meticulously applying high-quality flexible tapes and glue, guided by well-trained builders. Conversely, some case studies faced leakage around folding sliding doors and sash windows, showcasing the vulnerability of certain design elements to airtightness issues. These examples underscore the importance of material selection, workmanship, and attention to detail in achieving and maintaining airtightness.

Maintenance and occupant behaviour affected the preservation of the post-retrofit airtightness levels. One of the cases demonstrated that careful analysis of air paths and draughts during the original retrofit, coupled with timely remedial actions, contributed to the sustained airtightness of the building. In contrast, a flood incident is reported to have disrupted the airtightness membrane repairs over time, emphasising the need for prompt and effective remediation to maintain retrofit integrity. The potential impact of ongoing cladding work on sealing effectiveness was also reported, highlighting the importance of considering the entire lifecycle of a building when evaluating airtightness.

Exploring unintended consequences revealed more diverse results. While some properties experienced higher airtightness ratings in cooler rooms, others reported minimal unintended consequences. The connection between airtightness and air quality emerged in one case, where the installation of a heat recovery ventilation unit followed a decrease in natural infiltration, indicating a potential influence of airtightness on indoor air quality.

Discussion and conclusions

The review and analysis of the Retrofit Revisit report and dataset highlighted how, in 70% of cases, post-retrofit airtightness decreased over time, but remained considerably more airtight than pre-retrofit, even with the degradation[6]. Several factors can contribute to this phenomenon and can be ascribed to two main phases of the building lifespan: the retrofit process itself and the care the occupants put into maintenance. Window and door seals are a key airtightness failure point, but these could be ameliorated with regular adjustment of hinges and periodic replacement of seals.

The use of appropriate materials and techniques for window sealing and draught-proofing, supported by expert or trained workmanship, was important in guaranteeing the quality of the air barrier at the point of retrofit.

Homes where maintenance interventions were timely, planned and implemented showed better airtightness levels 10 years after the retrofit, emphasising the importance of designing maintenance plans for the entire lifespan of the building.

[6] In the four cases where pre-retrofit airtightness was measured.

Analysis of data to detect presence of in-test air sealing

Introduction

There is evidence to suggest that “in-test sealing” occurs during airtightness tests in new dwellings both in the UK [2] and France [55]. These remedial works, perhaps only sealing a gap or hole with whatever material is to hand, may not be effective in the longer term [24]. Yet, up to 39% of new dwellings have temporary, non-compliant, sealing interventions at the point of testing [56]. This action of secondary sealing distorts the test results for new builds, but there is not yet any evidence to suggest whether this occurs in existing dwellings. The aim of this section is to investigate whether there is a clustering of airtightness test results close to airtightness thresholds that may be aimed at during retrofits.

Methodology

An airtightness dataset identified in the Rapid Evidence Assessment in Report 1 [1], and used in analyses there, was used in this study. After a conversion and cleaning process (see Report 1) the remaining dataset was arranged in a histogram to investigate the presence of clustering around specific air permeability values.

Results

Across all dwellings in the sample (N=5,125), the mean AP_{50} air permeability was 8.6 $m^3/h.m^2$ @ 50 Pa. Visualising the distribution AP_{50} results in histogram form (Figure 4) indicates an approximately symmetric distribution, with positive skew resulting from a small proportion of values exceeding 16 $m^3/h.m^2$ @ 50 Pa. There is no evidence of bunching around design targets, with frequency dropping off steadily after a single peak at 7–8 $m^3/h.m^2$ @ 50 Pa.

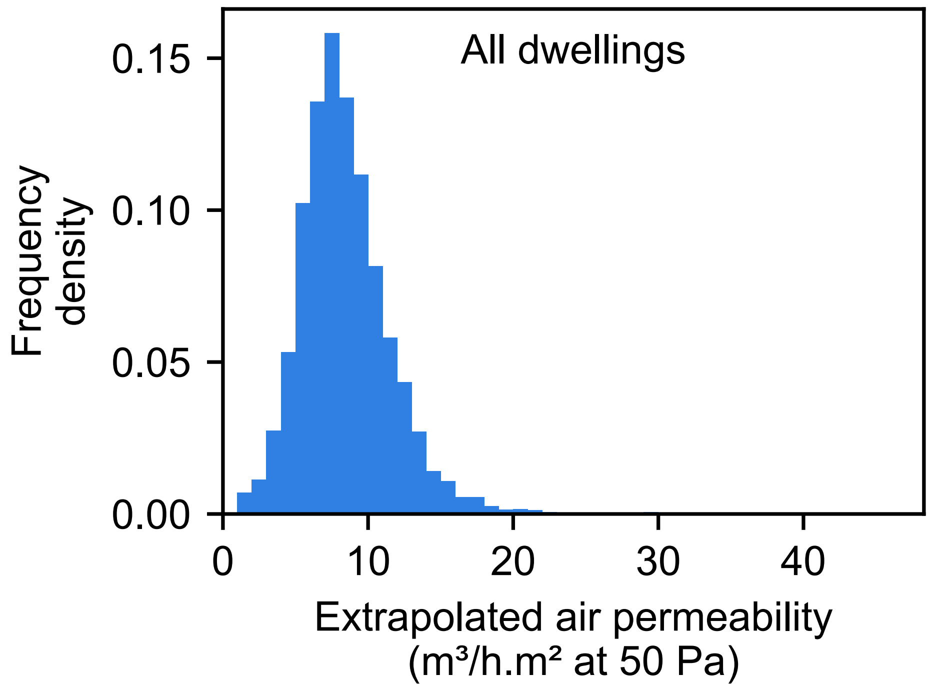

Figure 4: Distribution of per-dwelling AP_{50} air permeability results (N=5,125).

Discussion and conclusions

Unlike previous studies of the airtightness in *newly built* dwellings, there is no evidence to suggest that in *existing* dwellings in-test (temporary) air sealing is widespread in this sample of the existing GB housing stock. This could be the case for several reasons. Firstly, there are no air permeability compliance thresholds that existing dwellings must adhere to, even after they are retrofitted – the current Building Regulations only apply to new dwellings. Secondly, not all the dwellings in the dataset would have undergone a retrofit, so there is no incentive to “aim” for any specific airtightness value. Finally, there are relatively few very airtight dwellings in the dataset[7]. Thus, as buildings become more airtight, and increasingly aim for a specific standard of airtightness, e.g., EnerPHit, such clustering trends may emerge. The mean air permeability of this sample was 8.6 m³/h.m² @ 50 Pa, which is close to current building regulations for new dwellings. However, it cannot be inferred that there is any relationship between current building regulations for new dwellings and the airtightness of the existing stock[8]. Therefore, degradation over time from failure of temporary seals is unlikely to occur.

[7] E.g., less than 1 ach @ 50 Pa which aligns with the EnerPHit Passivhaus-equivalent standard for retrofit.
[8] Refer to Report 1 [1] for a fuller analysis, including extrapolation to the national stock.

Rapid Evidence Assessment 2

Introduction

This Rapid Evidence Assessment will review what the current literature says about the unintended consequences of more airtight UK homes.

Methodology

The methodology is as described for Rapid Evidence Assessment 1, page 12 and [1].

Search terms

Search terms were selected for RQ7 and RQ8 (Table 3) and exclusion criteria were as Rapid Evidence Assessment 1 (Table 2).

Table 3: Search terms for RQ7 and RQ8.

Search terms and Boolean operators
fire AND safety AND buildings AND air AND tightness OR airtightness
Restricted to relevant construction journals: Buildings and Environment, Fire Safety Journal, Journal of Building Engineering, Fire Technology, Buildings, Energy and Buildings, Energies, Sustainability Switzerland, Renewable and sustainable Energy Reviews, Construction and Building Materials, ASHRAE Fire and Materials, Energy Procedia, Ventilation of Buildings, Sustainable Cities and Society, Journal of Building Physics, Journal of Applied Fire Science, Indoor Air, Energy Efficiency

Findings – unintended consequences

RQ7: What are the unintended consequences of more airtight homes?

Key findings:

Many unintended consequences are caused by poor ventilation, not more airtight homes. Fire risk is a notable exception, which is poorly researched with respect to airtightness, and so is the focus of this review.

GRADE quality assessment rating:

There is moderate-quality evidence to identify several unintended consequences of more airtight homes. These can all be mitigated with increased ventilation, except for fire risk.

Indoor air quality, damp, and overheating

Several unintended consequences of more airtight dwellings are suggested by the literature: condensation, damp, poor air quality, radon build-up, overheating [57], and higher incidence of asthma[9] [58]. Yet, all these issues can simply be ameliorated with properly designed ventilation. Thus, airtightness does not cause any unintended consequences – poor ventilation does. For example, in 24 newly-built dwellings with airtightness of less than 5 m³/h.m² @ 50 Pa, the air quality in bedrooms was found to be poor at night [59]. This was attributed to windows being closed at night. Similarly, relying only on trickle vents for ventilation may not provide adequate outdoor air in airtight dwellings without other sources of ventilation [60]. Overheating is considered in more detail in the RQ8 review (following section).

Fire

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 [11] (Figure 5).

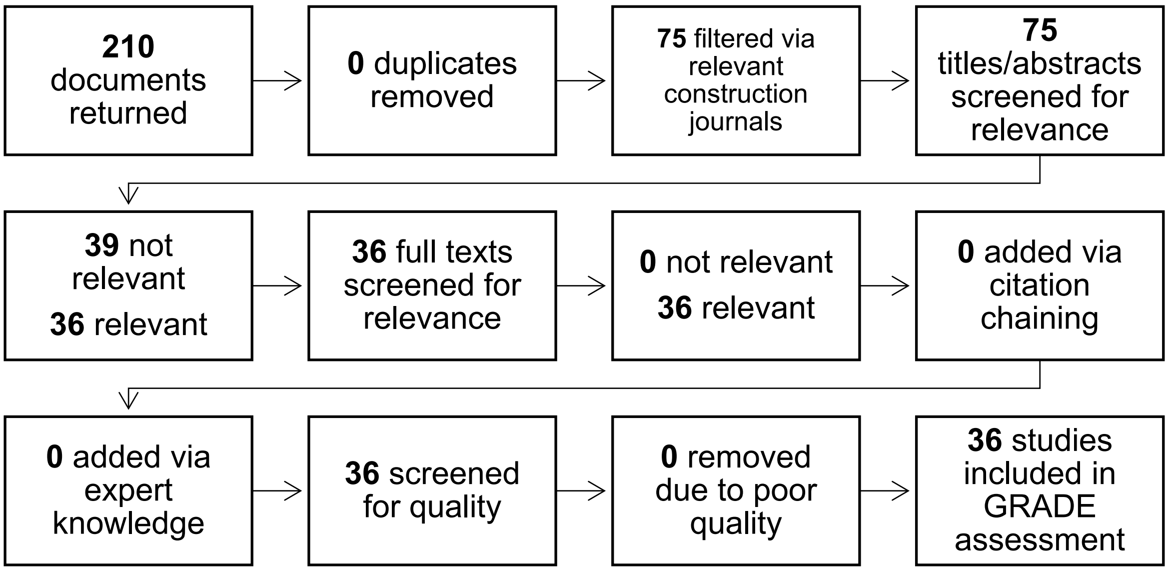

Figure 5: PRISMA diagram, after Page et al. [11]**.**

Fire risk is a notable exception to the unintended consequence of more airtightness, as it cannot be remedied with more ventilation. This section of the Rapid Evidence Assessment was undertaken to identify published research directly and indirectly associated with relationships between the airtightness of buildings and the potential risks relating to smoke and fire.

Although it is clear that the subject is under researched, some related phenomena have been addressed through simulations of air movement and models of fire development and behaviour. Those studies, which have empirical merit, have focused on multistorey developments and identified some risks. Although not specifically addressed by the research, it

[9] This study talks of "more energy efficient" homes and did not make any particular reference to airtightness, however.

may be assumed that similar behaviours would be present in all enclosed spaces where airtightness is increased (see the discussion of the risks below). There is, however, a need to test any propositions and assumptions made here as the evidence is limited. Based on this review, further investigation into low rise residential buildings as well as increasing the research in high rise and multipurpose developments, would be of benefit. There is a significant gap in the literature and knowledge relating to the changing airtightness regulations and fire/smoke behaviour.

The general knowledge of fire behaviour in confined building spaces is embryonic. Most fire and buildings research is concerned with the combustibility of materials, spread of fire and escape mechanisms in the event of fire. There are few studies that specifically examine the impact of making buildings airtight and the behaviour of fire. The current research builds on some well understood phenomena associated with fire behaviours. However, very little attention has been afforded to the regulated practice of improving airtightness in new and existing domestic buildings and risks associated with fire and smoke. While the greatest risk exists in high-rise buildings, low-rise buildings represent the bulk of the housing stock and the risks associated with fire and smoke in airtight residential buildings requires further research.

Concerns are raised regarding construction practice that leaves voids in the building structure that can induce the passage of fire into and through the building. There are also related concerns that inadequate ventilation can lead to problems with combustion in gas appliances, in some instances. Due to the limited science in this area, it is not possible to know how regulated practices relating to airtightness and ventilation affect such risk - meaning that some risks may remain or be exacerbated even when regulation is followed.

From the review, findings suggest that in the event of a fire, airtight structures are prone to:

- Intensified air flow through the remaining voids.
- Depressurisation encourages increased air movement through gaps, cavities and voids, this would occur where the fire is not extinguished as a result of limited oxygen.
- As air flows towards the fire, fire can travel across internal and external surfaces and through voids (“flashover”), spreading away from the fire and potentially passing into neighbouring rooms and properties. The risk of this can increase where openings and gaps provide strong flows of air.
- Air flow is increased through gaps in the structures due to depressurisation and more concentrated air movement.
- Fire can develop within cavities in the structure.
- Depressurisation in confined spaces as the fire develops.
- Changes in the direction of air movement can occur – potentially reversing the direction of air in ventilation ducts and rooms. Such changes can impact on compartmented escape zones, eliminating the positive pressure used to prevent smoke entering such zones.
- Negative pressures may make doors and windows difficult to open.

Relating to combustion, but not uncontrolled fire, there is concern that gas appliances may not operate effectively in airtight structures where effective ventilation is not provided. In such situations, there is an increased risk of incomplete combustion, increasing the risk of carbon monoxide (CO) production where purpose provided ventilation is not adequate.

Several papers reiterated key points, in particular, that by changing the airtightness of a structure, the development and behaviour of fire changes. Fire is known to travel through voids and gaps where compartmentation is breached [62]. In forensic investigations of 34 fires in roof voids (confined spaces) breaches in compartmentations, ducting, cavities, and around fire stops, provided dominant passages for smoke and fire. This can lead to fire and smoke passing through voids and gaps that would not normally provide the dominant passage [63].

The research reviewed placed emphasis on the impact of differential pressures, that may be exacerbated by fire in airtight structures. For example, the positive pressures in protected shafts and ducts may change, increasing the risk of fire entering the buildings [64,65]. As depressurisation occurs it may become difficult to open doors and windows as a means of escape [65]. The reduction of pressure can also lead to structural damage, when air pressure drops as a result of developing fires [66].

Government research suggests that airtight homes may not meet minimum ventilation provision [67]. In the brief review it is reported that of 55 airtight homes, only 2 buildings complied. The lack of proper ventilation, it is suggested, could lead to incomplete combustion in gas appliances, heightening the risk of carbon monoxide poisoning. Other studies also report increased potential of CO poisoning, even when heating appliances are outside the main dwelling, the ventilation air flows into the building can transport the CO [68].

The manner that air moves within and around airtight buildings should be better understood. The research is currently very limited and piecemeal, making it difficult to understand the degree of scientific endeavour that underpins the observations made.

Fire: an overview

Mostly the papers reviewed here were focused on the modelling and measurement of fire and risks within buildings, building elements, and components. In most cases, airtightness was addressed as an associated condition of the component or building that affects or is affected by fire, rather specifically considering the performance of the building, as associated with the regulated change in airtightness. The methodologies and discussion papers reported here all passed comment how changes in airtightness impacted on fire – clearly the relationship has a considerable impact on how fires might behave, develop, and spread. As oxygen (within air) is one of the essential components of fire (the other elements in the fire triangle being heat and fuel), limiting air supply through airtightness measures would be expected to reduce the risk although this is not always the case.

Fire and smoke related to changes in envelope airtightness

There is a dearth of research dealing with how energy efficient measures and regulated changes to airtightness changes impact on fire performance of the building. The exception to this is the work undertaken by Littlewood and Smallwood [69] and Littlewood et al. [70]. Their research addresses the topic of energy efficient measures and airtightness, when new build or retrofit measures are not undertaken properly. Here the risks are highlighted through case studies and test methodologies that expose the risk associated with fire and smoke.

The work refers to the inherent weaknesses, ineffective designs or poor practice in the construction process which result in substandard energy performance, but equally, presents “building fabric weaknesses [that] can also contribute to the overall building performance compliance for mandatory smoke and fire spread mitigation” [69]. In a later paper, Littlewood et al. [70], develop and examine methods for pressurising buildings and making use of a blower door and smoke generators to forensically expose the passage of smoke. The findings report air barriers and fire breaks being bypassed leading to the passage of smoke within and between buildings. The changes to a building’s design as a result of energy efficiency measures and increasing a building’s airtightness increases the movement of air through any gaps in the structure. The report identifies defects and gaps in the fabric as a result of construction methods, designs, and incompatible codes and guidance (including robust details). The research found that in most cases, the airtightness defects are impossible to detect with the naked eye, but can be recognised through an in-construction testing methodology using smoke and blower doors to identify paths of bypass.

Although the research reported above addresses general breaches in compartmentation and fire stopping, and that in some cases these breaches were introduced as part of thermal upgrade work, it does not specifically address the impact of changes in airtightness and fire risk. However, it can be seen through this and the other studies reported, that a strong relationship exists between airtightness and behaviour and/or development of fire. As changes in airtightness limit the supply of oxygen, where gaps in the construction exist, the voids channel air and inadvertently the passage of smoke or fire. The airtightness of the building also affects many other fire related phenomena. Although only indirectly related to airtightness, the keywords of articles reviewed provide an indication of factors that have been considered when addressing fire and smoke risks, most of which would also be relevant to airtightness.

The review of the keywords used in these papers may be useful for future research and reviews. The subject of airtightness and fire and smoke risk is dependent on, and related to, many factors and phenomena. Equally, the methodologies for measuring, modelling, and defining risk associated with buildings, airtightness, and the progression of smoke and fire can be considered from many different perspectives. The following table of keywords (Table 4) provides examples of terms used that could be relevant for future reviews.

Table 4: Keywords referenced in relevant literature reviewed – (keywords listed under relevant thematic headings, however no priority or relationship across the cells is intended).

Phenomena impacted or impacting	Building, Component and elemental factors	Analysis / factor / method of modelling or measurement
Air	component	Construction
indoor air	element	construction stages
air quality	doors	const. equipment
indoor air quality	fire doors	architectural design
indoor air pollution	escape route	design
ventilation	fire protection	
	fire floor	performance /
airflow / air flow-rate	compartment fires	building performance
airtightness / airtightness	air-tight compartment fire	thermal performance
infiltration / air infiltration		
buoyancy	building/s	pressure effects
pressure	In-buildings	pressure differences
compressed air	housing/ houses	effective leakage area
stack effect	dwellings	leakage area
pressure variations	residential building	leakage
natural ventilation	apartment houses	
neutral pressures	multi-unit	flow rate
flow coefficients	high Rise Building/s	air leakage
sudden expansion	tall Buildings	fire safety
outdoor temperature	high Rise	building codes
	multistorey Building	smoke control
fires	high-rise buildings	
fire risk	/ high rise residential building	measurement method
fire behavior/ behaviour	super high-rise Building / s	testing methods / testing method
fire dynamics	office buildings	
fire resistance	mobile homes	blower door testing / blower door
fire growth	solar buildings	
Cooling		forecasting
	building envelope	computational fluid dynamics, CFD
smoke	/ building envelopes	
smoke abatement	enclosures	computer simulation
smoke suppression	cold storage	FDS – fire dynamic simulator / simulation

Phenomena impacted or impacting	**Building, Component and elemental factors**	**Analysis / factor / method of modelling or measurement**
smoke spread/s		wind tunnels
smoke movement	construction Industry	aerodynamics
smoke management	sustainable development	
smoke control system	sustainable building	decision making
carbon dioxide	sustainability	testing
water vapor		life cycle
condensation	air conditioning	energy conservation
PM 2.5	heating	costs
concentration (composition)	heating and cooling	
	HVAC	social benefits
energy	air handling equipment	safety engineering
energy utilization	ventilation systems	risk assessment
energy efficiency	ducts	parametric study
energy savings/ energy-savings	mechanical ventilation	numerical model
	cooling systems	modelling / modeling
	floors	
Well Being	air curtains	structural analysis
		mechanical properties
	thermal Insulation	bending strength
	structural component	compressive strength
	walls (structural Partitions)	durability
	stairwell	
	elevators	
	elevator Shafts	
	elevator Door	
	materials selection	
	building materials	
	advanced materials	
	reinforced concrete	
	high performance concrete	
	plant shutdowns	

Summary and associations of fire papers related to airtightness

Table 5: Tabulated summary of papers related to fire and building airtightness

Authors	Title	Association between airtightness and smoke and fire	Focus of the paper	Implications - association
Bae et al. 2013 [71]	Improvement in the applicability of the airtightness measurement using a sudden expansion of compressed air	Airtightness is an important parameter for both smoke suppression in a fire and for the energy efficiency of buildings	Ability to measure airtightness	
Bedon et al. 2019 [72]	Structural characterisation of adaptive facades in Europe - Part II: Validity of conventional experimental testing methods and key issues	Adaptive facades are required to satisfy rigid structural performances. A minimum of safety and serviceability levels under ordinary design loads, durability, robustness, fire resistance are required	Lack of standards and guidance for adaptive skins, care needs to be given to conventional methods for testing and non conventional testing may be more appropriate	

Authors	Title	Association between airtightness and smoke and fire	Focus of the paper	Implications - association
Lozinsky and Touchie 2020 [73]	Inter-zonal airflow in multi-unit residential buildings: A review of the magnitude and interaction of driving forces, measurement techniques and magnitudes, and its impact on building performance	Inter-zonal airflows within multi-unit residential buildings (MURBs) have profound impacts on an array of building performance metrics, including energy, indoor air quality (IAQ), fire and acoustical separations, and distribution of ventilation air. Although there are wide-ranging implications, most building codes/standards have yet to incorporate airtightness requirements for interior partitions in large, multi-zone structures, and instead focus primarily on exterior envelope airtightness	Measurements do exist, but no requirement in building codes or standards. Call to refine methods.	Chanes to different elements, components influence airtightness, air flow and potential fire propagation.

Authors	Title	Association between airtightness and smoke and fire	Focus of the paper	Implications - association
Volf et al. 2018 [74]	Application of building design strategies to create an environmentally friendly building envelope for nearly zero-energy buildings in the central European climate	Development of an alternative to aluminium curtain wall systems for new constructions or renovations. Prototypes tested to verify their technical performance (air- and water tightness, fire resistance, acoustic properties, short- and long-term hygrothermal monitoring)	Some components that offer airtight solutions offer more sustainable and potentially better fire resistance than others	Changes in components and materials can improve sustainability and meet standards.
Lee M.J.; Kim N.I.; Ryou H.S. 2011 [75]	Airtightness measurement with transient methods using sudden expansion from a compressed chamber	Airtightness in an escape route of a building is important in preventing a fatal disaster by smoke spreading during a fire.	Dynamic measurement techniques evaluated. Suggestion that transient methods may be more suitable for such compartments.	Implications for different types of room and classification of rooms. Methodologies and measurements for airtightness related to fire and smoke may be different to conventional approaches.

Authors	Title	Association between airtightness and smoke and fire	Focus of the paper	Implications - association
McKeen and Liao 2022 [76]	Numerical analysis on the hazards of open stairwell doors in high-rise residential buildings	Protecting egress route (vertical paths) from the infiltration of smoke is essential for safe evacuation. Passive fire safety strategies have addressed this by using fire-rated compartmentation. CFD modelling of air flow.	Airtightness / compartmentation can be compromised by doors propped open or damaged.	Air and smoke circulation changes dependent on air paths available.
Cabral and Blanchet 2024 [77]	Prioritizing Indicators for Material Selection in Prefabricated Wooden Construction	Material selection in buildings profoundly affects project success.	Critical sub-criteria identified were fire resistance, watertightness, local availability, occupant health, and safety and protection.	Material selection – affects airtightness and fire resistance.
Mckeen and Liao 2019 [78]	The influence of building airtightness on airflow in stairwells	Stack effect in tall buildings can create significant pressure differentials in vertical shafts when differences in outdoor and indoor temperature exist. Improving airtightness of the building envelope or vertical shafts can have a significant impact on airflow.	Stack effect driven airflow will change according to size and distribution of leakage paths	The effect of airflow within vertical shafts has consequences on smoke spread. The benefit of reducing leakage in buildings can be understood by comparing the quantity and patterns in airflow in and out of stairwells.

Authors	**Title**	**Association between airtightness and smoke and fire**	**Focus of the paper**	**Implications - association**
Lin and Wang 2013 [79]	Forecasting simulations of indoor environment using data assimilation via an Ensemble Kalman Filter	Data assimilation is widely used in weather forecasting and other complex forecasting problems such as hydrology, meteorology, and fire dynamics.	Modelling and forecasting methods and a case study of forecasting the concentrations of a tracer gas in a multi-zone manufactured house by using a mass balance model with an EnKF	by using EnKF, the predictability of the simple indoor air model for the multi-zone space was improved significantly
Hostikka et al. 2017 [66]	Fire-induced pressure and smoke spreading in mechanically ventilated buildings with air-tight envelopes	Investigates whether airtightness can change the fire development and pose new risks for structural and evacuation safety	Impact of decompression or compression as a result of fire and impact on structure	During decompression the structure could be at risk of movement and damage.
Littlewood and Smallwood 2015 [69]	Testing building fabric performance and the impacts upon occupant safety, energy use and carbon inefficiencies in dwellings	Airtightness and building fabric weaknesses can contribute to the overall building performance compliance for mandatory smoke and fire spread mitigation.	Three case-studies involving independent testing and performance evaluation undertaken on social housing dwellings	Smoke passes through gaps in the fabric and around design and construction defects.

Authors	Title	Association between airtightness and smoke and fire	Focus of the paper	Implications - association
Littlewood et al. 2017 [70]	A New Methodology for the Selective Measurement of building Performance and Safety	Evaluates the present evidence of smoke spread due to problems in compartmentation and also reviews different test methods which can be employed to identify these problems during construction stages.	Defects can compromise the ability of compartmentation to resist fire and smoke spread between dwellings and also into places provided as a means of escape.	Impact of the defects could ultimately be detrimental to occupant safety, care staff with the occupants and also fire fighters, in the event of a real fire.

RQ8: How does airtightness affect overheating?

Key findings:

Increasing airtightness causes a reduction in heat loss via infiltration. With adequate ventilation provided and used, any increased risk of overheating associated with greater airtightness can be mitigated.

GRADE quality assessment rating:

There is low-quality evidence to quantify the influence of airtightness on overheating. Studies are confounded by several interrelating factors associated with greater airtightness such as greater levels of insulation and modifications to the exposed thermal mass.

Several studies make unsubstantiated claims that airtightness may increase overheating, e.g., [57,79,80]. It is presumed that greater airtightness will reduce overall dwelling air change rates[10] and decrease ventilative cooling. Whilst much research has shown that increased airtightness reduces dwelling heat loss [1], there are few studies which specifically show that this leads to greater incidence of overheating in occupied homes, presumably because purpose-provided ventilation can be increased to replace the lost infiltration air exchange. One such example of overheating in a very airtight dwelling is presented, however. A Passivhaus standard dwelling was found to overheat due to a combination of high heat retention and low thermal mass with which to moderate the indoor temperature [82]. However, the main cause of overheating was attributed to poor management of the dwelling (lack of ventilation for cooling).

Some studies confuse increasing insulation with greater airtightness, e.g., [57] and claim this causes increased overheating. They incorrectly cite Tink et al. [83] in this regard, when in fact, Tink et al. found that overheating would not increase if sufficient night ventilation occurred. If properly designed, in a holistic manner which considers all aspects of building design, there is no reason for highly energy efficient (and airtight) dwellings to overheat any more than a typical dwelling. For example, monitoring of the summertime temperatures in 82 Passivhaus-certified[11] dwellings in the UK showed that 82% of houses and 85% of flats did not overheat according to the Passivhaus assessment criteria [84]. However, the Building for 2050 project found that people living in low carbon homes reported overheating occurring, but this was ameliorated over time as the new occupants got used to using their ventilation systems, installed solar shading, or implemented new window opening routines [36]. Thus, these studies highlight both the importance of assessing summertime overheating at design stage [85], as now required by Part O of the Building Regulations, and of ensuring that occupants know how best to operate their homes to ensure summertime overheating is reduced.

[10] In this case via infiltration, in which airtightness plays a major, but not exclusive, role in governing the rate at which this adventitious air exchange occurs.
[11] I.e., they were highly insulated and would have an airtightness of <0.6 ach @ 50 Pa.

Very airtight dwellings may, indeed, actually protect against overheating by limiting indoor-outdoor air exchange during the hottest parts of the day when it is cooler indoors than out [86]. Although experimental work has shown infiltration rates to be low during summer [87], so attributing this benefit to airtightness may be overstated. Recent national survey analysis by Lomas et al. [88] also points towards air exchange via infiltration being low on hot summer days as the indoor-outdoor temperature difference is low and the study shows more broadly that more energy efficient dwellings do not increase the prevalence of overheating.

It has been shown that the amount of infiltration that occurs in summer is lower than might be expected for a dwelling with an air permeability of ~15 $m^3/h.m^2$ @ 50 Pa. Experimental work has shown average infiltration air flow rate in a test house to be 13 l/s [87]. The summertime ventilation flow rate through four top-hung open windows[12] in a bedroom in the same house was up to 34 l/s [89], which indicates that any reduction in infiltration rate can be compensated via increased ventilation.

Sensitivity analysis using dynamic thermal simulation presented in Report 2 [4] suggests that infiltration (which is influenced by airtightness) affects overheating using the method set out in Part O of the Building Regulations. Porritt [90] and Roberts et al. [91] have found similar trends.

Unintended consequences (RQ7-8): 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 moderate-quality evidence to identify several unintended consequences of more airtight homes. Whilst several factors are identified, fire and smoke risk is less well researched, but an important issue given that it cannot be mitigated with more ventilation.
- There is low-quality evidence to quantify the influence of airtightness on overheating. One of the main issues is that airtightness is investigated alongside, and in combination with, other factors such as insulation and thermal mass. The effects of airtightness alone on overheating are difficult to identify. Ultimately, any overheating problem associated with making a dwelling more airtight can be alleviated via increased ventilation.

[12] With a combined free opening area of 0.56 m^2.

Rapid Evidence Assessment 3

Introduction

This Rapid Evidence Assessment will review studies which highlight how, when, and why occupants use ventilation.

Methodology

The methodology is as described for Rapid Evidence Assessment 1, see page 12 and [1].

Search terms

Search terms were selected for RQ9, RQ10, and RQ11 (Table 6). Exclusion criteria are per Rapid Evidence Assessment 1 (Table 2).

Table 6: Search terms for RQ9, RQ10, and RQ11.

Search terms			
Primary	**Secondary**	**Tertiary**	**Quaternary**
Ventilation	Occupant	Houses	UK
Purpose-provided	Behaviour	Homes	England
Windows		Dwellings	Scotland
Fans		Residential	Wales
Trickle vents			Northern Ireland

Findings – ventilation practices

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 [11] (Figure 6).

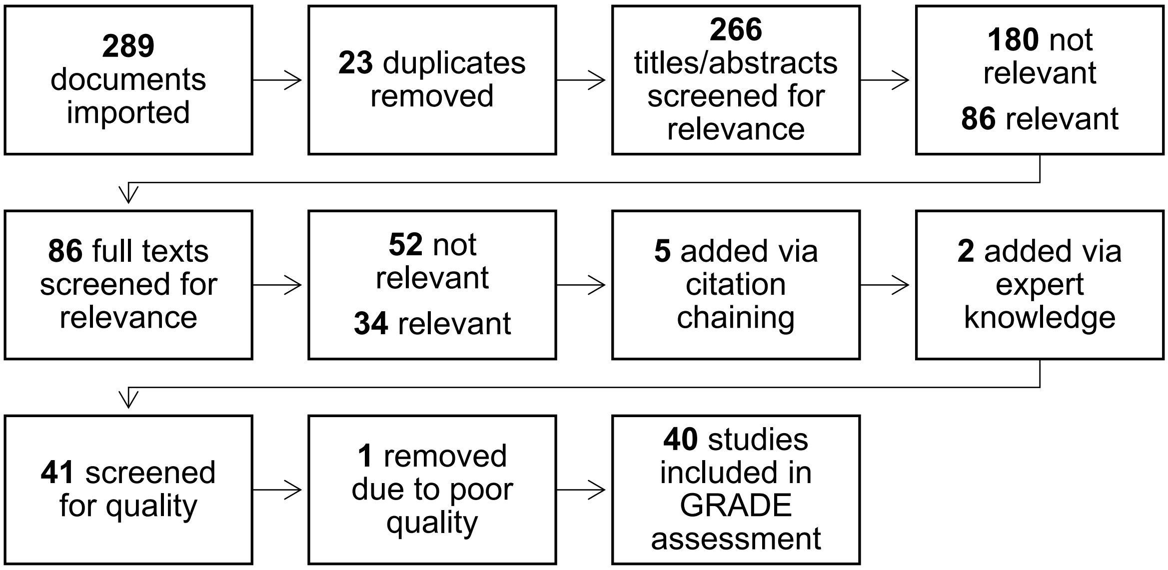

Figure 6: PRISMA diagram, after Page et al. [11]**.**

RQ9: How and why do people typically ventilate their homes in the UK?

Key findings:

How: Most UK homes are ventilated using operable windows, a form of natural ventilation. Mechanical extract ventilation is currently only commonly used in kitchens and bathrooms, yet less than half of dwellings have such ventilation in these rooms.

Why: The most frequent reason for ventilating UK homes is either a response to temperature (indoor or outdoor) or indoor air quality. Several reasons (drivers and barriers) for ventilation operation are suggested from small sample case studies or questionnaire surveys. However, the literature presents a contradictory story with covarying factors, case-specific findings, and small sample sizes that cannot be widely extrapolated to the national housing stock or population.

GRADE quality assessment rating:

There is moderate-quality evidence regarding **how** UK homes are ventilated.

There is moderate-quality evidence regarding **why** UK homes are ventilated.

How do people ventilate their homes?

Operable windows remain the primary means of ventilation in UK dwellings [92]. As dwellings become more airtight and better insulated it is likely that mechanical ventilation with heat recovery (MVHR) will increase [92]. No studies relate dwelling airtightness to ventilation provision and effectiveness. One study links airtightness to ventilation type, but found no link between ventilation type and airtightness in new dwellings[13] [93], despite the English Building Regulation requirements for mechanical ventilation in more airtight dwellings [8].

The vast majority of British dwellings have operable windows in every room[14] (94%) and these are used for purge and background ventilation [94]. Van Rooyen & Sharpe [94] reported that 67% of homes did not have a minimum provision of ventilation to be compliant with standards. Of the 1861 respondents, 55% had mechanical ventilation in both their kitchens and bathrooms; 49% had trickle vents on some windows, and 59% had trickle vents on all windows. Adequate ventilation provision increased as the dwelling age decreased (newer dwellings had better ventilation provision) – meaning new homes were more likely to have trickle vents on all windows and mechanical ventilation in wet rooms. Tenure was a significant factor in how people might have the opportunity to ventilate. Owner-occupied dwellings were least likely to have ventilation provision in compliance with current building regulations. Of the rented dwellings, social housing had better ventilation provision than private rented. Most dwellings were ventilated with windows and mechanical ventilation in bathrooms (59%) and 36% relied only on natural ventilation (via windows). Very small numbers had MVHR (3%) or positive input ventilation (PIV) (2%) installed. Thirty-four percent of respondents had only natural ventilation in their bathroom and 21% had no ventilation (or didn't know) in their kitchen [94].

Why do people ventilate their homes?

The collective of reviewed studies suggested several drivers of ventilation and several barriers to ventilation (Table 7). Drivers indicate ventilation happens due to this factor; barriers indicate ventilation stops happening because of this factor. There are no nationally representative studies which identify specific attributes of the UK housing stock, such as airtightness, dwelling type, or dwelling age, in relation to occupant ventilation behaviours.

Drivers include:

- Indoor temperature
- Outdoor temperature
- Thermal comfort
- Season (related to temperature)
- Wind speed
- Relative humidity

[13] Whilst a statistically significant difference was detected, it was too small to be practically relevant.
[14] This study claims to be "nationally relevant" in terms of occupant demographics, but is not nationally representative in terms of the characteristics of the housing stock (built form, age, wall type, etc.).

- Rainfall or predicted rainfall
- To remove moisture, odours, smoke
- To improve indoor air quality, to “freshen the air”, or to recirculate the air
- To dry clothes
- The time of day
- Habits
- Culture
- Presence of occupants
- Presence of pets
- Perception of freshness
- Room type
- Dwelling type

Barriers include:

- Noise (outdoor entry via windows or indoor generated by the ventilation system)
- Security concerns
- Outdoor temperature
- Thermal comfort
- Wind speed
- Advice
- Misunderstanding of intended use
- Lack of knowledge of how to operate or unclear operating instructions or a perception of a lack of control (particularly with MVHR systems).
- Accessibility issues (unable to open windows or change filters in mechanical systems)
- Insect entry
- Allergies (hay fever)
- Habits
- Poor performance of the ventilation system
- Weather
- Heat loss concerns
- Draughts
- Forgetting to adjust (trickle vents)
- Energy costs (from running a mechanical ventilation system)

These drivers and barriers are not arranged in any particular order. From the collection of literature is it difficult to rank the drivers and barriers in order of importance or influence. Some individual studies do attempt to do so, but there is often conflicting information between studies. Other studies make no attempt to rank the drivers and barriers and so even those which are uninfluential in the majority of cases are mentioned. Most of the literature contains small sample sizes (Table 7), which often makes it difficult to establish window operation trends, e.g., a study of six dwellings showed a great variation in window operation duration and frequency [95].

Outdoor temperature

Outdoor temperature appears among the most influential of the drivers and barriers of ventilation, e.g., [96]. The trend is for increasing window opening as outdoor temperature increase[15] [97]. In 20 retrofitted dwellings occupied by elderly residents, it was found that windows were open for a longer duration during heatwaves (very hot weather) [98]. Windows were open less frequently as outdoor temperature dropped, which resulted in higher CO_2 concentrations in bedrooms over the course of monitoring [99].

In newbuild dwellings in Scotland, occupants reported closing windows mainly to prevent heat loss (59%) in relation to the outdoor temperature. This was deemed a more influential factor than a desire to reduce noise (17%), increase security (11%), and stop pollution entering (5%) [100]. Another study found a desire to keep windows closed due to the weather (73%), to prevent heat loss (42%), and to prevent cold draughts (40%) – i.e., due to thermal comfort concerns [101].

Indoor temperature

In bedrooms, Jones et al. [96] found that indoor temperature (and outdoor temperature) was the most important driver of window operation (opening and closing). Van Rooyen & Sharpe [94] found that “reducing high temperatures” was the second most important driver of opening windows (28% of respondents), which came second to a desire to improve air quality (57% of respondents).

In 18 low-energy flats in London, window opening was found to be very low during the winter heating period and indoor temperature was the most important factor driving window operation [102]. In agreement, indoor temperature was the main driver of window operation (opening and closing), whilst indoor air quality was not a significant driver in the living rooms of six flats in London [103].

In 17 newly-built dwellings, the indoor temperature was shown to be the most important driver of window operation, whilst indoor air quality was not a significant driver [104]. Windows were generally left open for more than 30% of the time between July and October, but then mainly closed between October and April. It should be noted that these dwellings were also equipped with decentralised MVHR. During the months when window opening was common, window opening times were irregular between different dwellings, e.g., some opened regularly at noon,

[15] This study did not, however, measure indoor temperature, so the change is attributed to outdoor temperature.

some in the afternoon, and some at random times. The study further showed that the windows were operated similarly in dwellings with and without MVHR [104].

In Scottish newbuild housing, when asked “which of these things would make you open a window?”, 75% of respondents said that it being too warm was a driver of window opening in living rooms and 72% said so for bedrooms [100]. The same study reported that other drivers of window opening included removal of moisture, removal of odours, to dry clothes, or to bring in “fresh air”, but these were less important than being “too warm”.

Season

Seasonal effects may covary with indoor and outdoor temperature or, equally, this could also be related to habitual behaviour repeated at certain times of the year. It is not clear from the literature which is the underlying cause of this driver, however. In some studies, it is shown that windows are open for longer periods during the summer than the winter, but it is not possible to establish whether this seasonal variation is driving window opening due to the indoor or outdoor temperature, or a combination of both, e.g., [95,105]. Loveday et al. [106] showed that in living rooms, window opening was greater in the summer (37% open) than the winter (20% open) and is one of the only studies to consider the degree of window opening – finding that windows may be slightly open in summer but are generally fully closed in winter. Seasonal variation is often confounded by other factors, e.g., in summer there were fears of spiders entering the bedroom which prevented windows from being opened [107]. This resulted in more window opening at night in winter in this study.

Indoor air quality

There is disagreement amongst the literature as to whether indoor air quality is a driver of occupant ventilation behaviour. In a small study of six dwellings, it was suggested that window operation was driven by the desire to remove odours and reduce indoor humidity after showering [108]. Three other studies found that indoor air quality was *not* a significant driver of window operation [102–104].

Despite this disagreement amongst the literature, in one of the studies with the largest samples that was reviewed, Van Rooyen & Sharpe [94] found that the main reason for opening windows was to improve indoor air quality. Specifically, this was to bring in “fresh air” or “recirculate air in the room” (57% of respondents). However, only a very small number of respondents opened windows to remove moisture (5%) or odours (3%), which are also aspects of indoor quality. For mechanical ventilation however, there was a much stronger drive to use this to reduce moisture/damp (44%), to get rid of odours (33%), or to remove smoke (32%) [94]. Perhaps this is because the study found that mechanical extract ventilation is most commonly found in kitchens and bathrooms where moisture and odours would be generated.

A questionnaire survey of 89 London residents showed that they were most likely to open their windows for “fresh air”, i.e., due to concerns about indoor air quality [109]. Indoor air temperature, which has been identified as most important in several studies, was only reported a driver by 46% of respondents. This could be due to security concerns and noise concerns, because 55% and 37% respectively said they would not open their windows for those reasons.

The study goes on to report that 11% of respondents would not open their windows even on a very hot night. Harvie-Clark et al. [110] note that occupants make a choice between acoustic comfort (closed windows) and thermal comfort (open windows).

Indoor air quality may drive occupants to choose to use natural ventilation systems instead of mechanical. A preference for natural ventilation could be inferred from the desires of householders to maintain air flow in their homes, even if it meant higher heat loss [26]. Interviews were held with 20 households (with 66 permanent occupants) living in owner-occupied, solid-walled homes in the East Midlands of England. One respondent spoke of a preference for “the natural feeling of a breeze” and an aversion to living in an airtight house. Another respondent reported perceived air quality concerns of airtight homes and a wish to “breathe fresh air” [26]. Perceptions of MVHR were similarly negative, despite none of the interviewees living in a home with such a system installed. They initially voiced expectations of poor indoor air quality if living in a home with MVHR. Once the research team explained the MVHR system in more detail, interviewees were generally more positive about the system. This potentially indicates a lack of knowledge causing the initial negative reactions.

Wind speed

Whilst indoor and outdoor temperature affect both window opening and window closing behaviours, wind speed was only an important driver in window closing (increasing wind speed drove window closure) [96]. As wind speeds increased, windows were more likely to be closed [97].

Rainfall

Whilst most other studies describe window operation as an instantaneous response to a stimuli, Fox [97] highlighted a propensity for windows to be closed if rainfall was forecast that day. The study notes that most occupants were out during the day, and perhaps they were taking advanced action to close windows during rain.

Another study found rainfall to be a somewhat influential driver of window operation, but sunshine levels were not [96].

Relative humidity

The evidence is inconclusive regarding relative humidity. In one study, relative humidity (indoor and outdoor) was somewhat influential in driving window operation [96]. This could be due to the inverse relationship with temperature and relative humidity, however. Other studies found no relationship between relative humidity and window operation [102].

Presence of occupants

On this note, occupancy was a vital factor – windows were far more likely to be open at weekends (when people are at home) than during the week [97]. In contrast with many studies on offices, in this domestic environment there was no correlation between an occupant arriving or leaving with window opening [102].

Time of day

The time of day is also important. There was more window opening in bedrooms and bathrooms in the morning and in the kitchen during the evening, and no windows open on the ground floor at night even during heatwaves [97], linking in with security concerns.

Time of day was influential when combined with indoor temperature and occupancy, with most window operation occurring in the morning before occupants left for work [96]. Equally, another study found most windows to be open during the day, when the 100 elderly residents who took part in the study would likely be at home [101].

Advice

Other barriers to ventilation are external, e.g., in one case the occupants were advised not to open their windows or adjust the MVHR settings in social-rented Passivhaus dwellings [111].

Dwelling type

In 20 retrofitted dwellings (flats) occupied by elderly residents, windows tended to be opened and left open, but in bungalows the windows were frequently opened and closed [98]. Ground floor flats tended to have fewer windows open than the upper floors of houses [97]. This is likely related to security concerns.

Room type

Room type (living room or bedroom) determined how long windows were open based on occupancy [112]. The study did not consider wet rooms (kitchens and bathrooms). Interestingly, there was no relationship between individual room type and other drivers for window opening such as temperature. Thus, the study states that the difference between rooms is mainly attributed to their occupancy duration. Other studies mention living rooms and bedrooms in isolation and make it difficult to draw comparisons, but suggest there is some difference in ventilation behaviour, e.g., [95].

It is common for bedroom windows to be open at night, even in winter, and even if MVHR systems are present [53,106]. Similarly, in a survey of 100 elderly people in Scotland, 19% said they normally opened bedroom window(s) at night in winter [101]. Yet, other studies disagree. One found that bedroom windows may be closed at night due to noise and security concerns in the inner city location where the study took place [109]. Another showed that bedroom windows were closed when sleeping, but the occupants used a mechanical extract ventilation (MEV) system for ventilation [113].

Pets

Occasionally studies document extreme behaviours such as leaving an external door open for up to 13 hours per day during the heating season to allow a household pet to move between the house and garden [108]. Another study also notes door opening for pet access, but in this case the doors are only open for one minute each time during the heating season, but for much longer during the summer [95].

Noise

Noise from outdoors was a driver for windows being closed, as was noise from the MVHR unit, resulting in the system being frequently being turned off [114]. Noise issues may lead to a preference of natural ventilation use over mechanical ventilation. Torresin et al. [115] reported that when natural ventilation was in use, outdoor sounds dominated the soundscape. When mechanical ventilation was in use, the sounds of the ventilation system in operation dominated and affected the ability for speech to be heard intelligibly. Unless in a busy, urban location, natural ventilation may be used in preference to mechanical ventilation if both are available [115,116]. Indeed, in Scottish newbuild dwellings, noise driving windows to be closed was less a less important factor (17%) than closing windows to reducing heat loss (59%) [100].

Other studies disagree that mechanical ventilation noises increase the chance of occupants turning them off, with just 13% of respondents citing an issue [94]. Generally, the study found that there was no barrier to using mechanical ventilation (45%), but a smaller number were concerned with the cost of running the system (19%).

Security

A questionnaire survey with 1,861 respondents found that mainly there were no barriers to window opening (32%), however some reported concerns about security (19%). Less important were pests/insects (10%), heating costs (9%), outdoor noise (8%), and pollen/allergies (4%) [94]. Security was also seen as less important than heat loss in Scottish newbuild housing, with 11% saying they would close the window for security reasons compared to 59% to reduce heat loss [100]. Security was a more important concern in dwellings in London, however [109].

Culture

Cultural factors play a role in when windows are opened. In a study of 40 dwellings, it was found that White British households had lower CO_2 concentrations, a proxy for ventilation, than those of Asian British occupants [117]. It was determined via observations and questionnaire surveys that all (100%) of the White British households kept windows open “most of the time” in summer. In contrast, 30% of the Asian British households “never opened the windows” and 22% “hardly ever opened the windows”.

Trickle vents

Drivers of trickle vent use are rarely described in the literature, with the focus being on window operation and mechanical systems. One such study exists, however, and shows that trickle vents were mainly operated for indoor air quality (54%), and less so to specifically remove moisture/damp (17%) [94]. Barriers to trickle vent use tend to be more widely reported. The same study shows barriers to trickle vent use to be minimal as most (54%) did not have problems or concerns with trickle vent use, although a small number stated heating costs (7%) and draughts (6%) prevented their use. This contrasts with most other research which highlights draughts to be a key barrier to trickle vent use [97,100].

Table 7: Summary of studies and drivers of occupant ventilation practices. Sample size "n" is the number of dwellings.

Author	n	Method	Drivers	Barriers	Vent. type
Brundrett 1977 [118]	123	Measurement; observation	Outdoor temperature; season; room type		NV
Macintosh & Steemers 2005 [92]	38	Observations; interview	Perception of freshness	Noise; misunderstanding of intended use perception of a lack of control	NV, MVHR
Fox 2008 [97]	120	Observation; weather	Outdoor temperature; occupancy; room type; dwelling type	Wind speed	NV
Banfill et al. 2012 [26]	20	Interview	IAQ		NV, MVHR
Behar & Chiu 2013 [119]	3	Interview	Indoor temperature; IAQ	Lack of knowledge; accessibility	MEV, MVHR, PSV
Ridley et al. 2014 [107]	2	Measurement; survey; interview	Outdoor temperature	Insect entry; habits	NV, MVHR
Sharpe et al. 2014 [105]	26	Measurement	Season	Noise; security; insects; allergies	NV, MVHR
Baborska-Narozny & Steveson 2015 [114]	40	Interviews		Noise, outdoor temperature	MVHR, MEV
Sharpe et al. 2015 [100]	200 (40 detailed)	Measurement; interview	Indoor temperature; moisture; odours; drying clothes; IAQ	Noise; heat loss prevention	NV
McGill et al. 2015 [59]	24	Measurement; diary		Poor performance	NV, MEV, MVHR

Author	n	Method	Drivers	Barriers	Vent. type
McGill et al. 2015 [120]	8	Measurement; diary		Lack of knowledge	NV, MVHR
Gupta et al. 2016 [29]	6	Measurement; survey	Outdoor temperature; IAQ		NV, MVHR
Loveday et al. 2016 [106]	15 (31 people)	Survey	Season		NV
Jones et al. 2017 [96]	10	Measurement	Indoor temperature; outdoor temperature; relative humidity; wind speed; rainfall; season; time of day		NV, MEV, MVHR
Mavrogianni et al. (2017) [109]	89	Measurement; survey	Indoor temperature; IAQ	Noise; security	NV
Cosar-Jorda et al. 2018 [108]	6	Measurement; interview	Humidity; IAQ; pets		NV
Gupta et al. 2018 [53]	6	Measurement; survey; diary	IAQ; habits		NV, MVHR
Sharpe et al. 2018 [121]	63 (8 detailed)	Measurement; survey		Lack of knowledge, creation of dust	NV, MEV, MVHR, PSV
Zhao & Carter 2020 [111]	16	Interview		Instructions	NV, MVHR
Tahmasebi et al. 2022 [103]	8	Measurement	Indoor temperature		NV
Sharpe et al. 2020 [101]	100	Measurement; microbiological sampling; interview	Time of day	Weather, heat loss, draughts	NV, MEV, MVHR, EAHP

Author	n	Method	Drivers	Barriers	Vent. type
Wang et al. 2021 [102]	18	Measurement	Indoor temperature		NV, MVHR
Gupta & Gregg 2022 [95]	6	Measurement; survey	Season; pets		NV
Wang et al. 2022 [112]	18	Measurement	Room type		NV, MVHR
Wang et al. 2022 [104]	17	Measurement	Indoor temperature		NV
Satish et al. 2023 [117]	40	Measurement; survey; observations	Culture		NV
Zahiri & Gupta 2023 [98]	24 (6 detailed)	Measurements; survey	Outdoor temperature		NV
Rastogi et al. 2023 [99]	29	Measurements	Outdoor temperature		NV
Van Rooyen & Sharpe 2024 [94]	1861	Survey	Remove moisture; remove odours; remove smoke; IAQ; thermal comfort	Cost; noise; security	NV, MVHR, PIV
NV = natural ventilation (windows or trickle vents); MVHR = mechanical ventilation with heat recovery; PIV = positive input ventilation; MEV = mechanical extract ventilation (without heat recovery); PSV = passive stack ventilation, EAHP = exhaust air heat pump.					

RQ10: Do people ventilate their homes sufficiently or appropriately in the UK?

Key findings:

Ventilation rates tend to be insufficient to provide adequate air quality and prevent overheating. Mechanical ventilation, particularly MVHR, may provide sufficient ventilation rates if correctly designed, commissioned, operated, and maintained. Trickle vents do not provide sufficient ventilation. Airflow is reduced when curtains or blinds are closed, and so this mainly affects bedrooms at night.

Ventilation practices may be inappropriate with respect to improper window ventilation, increasing wintertime heating demand or summertime overheating. Mechanical ventilation tends to perform poorly when occupants intervene and switch off the system or block outlet vents. Mechanical systems can be poorly maintained. There are no nationally representative studies available.

GRADE quality assessment rating:

There is low-quality evidence to understand ventilation provision in the UK housing stock.

There is moderate-quality evidence to assess the appropriateness of natural and mechanical ventilation practices in the UK.

Is ventilation sufficient?

Research commissioned by the Ministry of Housing, Communities and Local Government of the United Kingdom (MHCLG) found that only two out of 55 naturally ventilated dwellings (3.6%) met the building regulations guidance for ventilation provision and one of 25 mechanically ventilated dwellings (4%) [67]. Others concur, suggesting that ventilation rates tend to be poor in UK dwellings [42].

There are differences between naturally and mechanically ventilated dwellings, with those with MVHR better ventilated than those with windows only, as evidenced by average CO_2 concentrations of 858 ppm for MVHR and 1292 ppm[16] for naturally ventilated dwellings [105]. However, MVHR may underperform due to breakdowns, poor commissioning, and where dwelling air permeability exceeds 5 $m^3/h.m^2$ @ 50 Pa [27][17].

[16] An indoor CO_2 concentration of 1292 ppm in the naturally ventilated dwellings, whilst higher than the 858 ppm recorded in those with MVHR, is not particularly concerning as a proxy for ventilation in terms of the provision of sufficient uncontaminated air for health [134] and is lower than the maximum design standard upper limit for most schools prior to the COVID-19 pandemic [135].

[17] Where a dwelling has a design air permeability lower than 5 $m^3/h.m^2$ @ 50 Pa, English Building Regulations stipulate that a continuous mechanical extract ventilation system should be installed to provide acceptable indoor air quality [8]. At air permeabilities above this value, such ventilation systems may run inefficiently and may not be required as infiltration provides additional outdoor air.

Several studies point towards inadequate ventilation in bedrooms at night [38]. This could be due to undesirable ventilation practices (from an IAQ perspective), such as turning mechanical systems off due to noise [114], or closing bedroom window due to security concerns [109].

With regards to reducing summertime overheating, there is evidence of people using external doors to provide additional ventilation for cooling during heatwaves [122]. This indicates that the ventilation provision via operable windows is insufficient to exhaust excess heat from the dwelling. During the 2003 heatwave in the UK, it was suggested that bedrooms are insufficiently ventilated, which leads to greater overheating [123]. Another study also found that insufficient bedroom ventilation[18] resulted in high indoor temperatures and relative humidity - beyond that suitable for human health [105].

Flats that relied solely on MEV to provide ventilation had lower ventilation rates than those using windows. Measurements were conducted in flats with operable windows and MEV between June and January (i.e., capturing summer, autumn, and winter). In the first flat, all the windows were closed for 20% of the occupied period and calculated ventilation rates were deemed to be below that for acceptable indoor air quality [113]. For the remaining 80% of occupied hours, at least one window was open and the ventilation rates were deemed acceptable. In a second flat, windows were closed while the space was occupied for 55% of the time, and ventilation rates were calculated to be insufficient for air quality for 70% of that period. The second flat was reliant on the MEV to provide outdoor air, and this was insufficient for most of the time to provide adequate air quality.

In dwellings with an airtightness of < 5 $m^3/h.m^2$ @ 50 Pa, indoor air quality was worse in dwellings with natural ventilation and MEV, and better in the dwellings with MVHR [59]. Ventilation rates were calculated to be below 8 l/s/person[19] in naturally ventilated dwellings and 39% of MVHR dwellings.

Trickle vents

Experimental work has shown ventilation rates provided by trickle vents to be insufficient to provide satisfactory indoor air quality in summer weather conditions [87]. Similarly, post-occupancy evaluation studies have found trickle vents, even if open, to supply insufficient amounts of outdoor air [59,119]. Even with trickle vents open, ventilation was limited with average bedroom CO_2 concentrations over 1500 ppm. CO_2 concentrations were, however, lower if an internal door was left open (~1000 ppm) [100].

Influence of window coverings

Even if windows are open at night, they could be occluded by window coverings (e.g., curtains or blinds) which reduced the ventilation rates; or stack and cross-ventilation limited by closed internal doors [105] – 46% of people reported closing bedroom internal doors at night [101]. Experimental work has shown ventilation rates in bedrooms to be up to 20% lower with

[18] As determined using CO_2 concentration as a proxy.
[19] Which is the Workplace (Health, Safety and Welfare) Regulations 1992 [136] minimum fresh air supply rate (5-8 l/s/person) for workplaces.

curtains closed compared to open [124] and a survey of 100 people found that 100% kept bedroom curtains/blinds closed at night [101].

Inappropriate natural ventilation practices

Experimental work has shown that during heatwaves, window opening can increase indoor temperatures by allowing the ingress of warmer outdoor air to the cooler indoor space [124]. As such, the *Heatwave Plan for England* provides guidance to keep windows closed on very hot days [125]. Contravening this guidance, it was found that in 20 retrofitted dwellings occupied by elderly residents, windows were open for a longer duration during heatwaves (very hot weather) [98]. Similarly, improper use of window opening during a heatwave led to higher indoor temperatures because living rooms windows were left open during the day allowing ingress of warmer air [95].

On winter days and nights, windows were usually reported to be closed in 71 and 93% of dwellings respectively [94]. Summer window operation is higher, with windows regularly being closed in the day (36%) and at night (73%), i.e., windows were open as much on a summer's night as they were on a winter's day.

Opening windows when the heating is on has been observed [119]. This will increase heating demand, but there may be benefits with respect to air quality and reducing indoor humidity and mould growth.

Inappropriate use of the windows has implications for wintertime heating demand and summertime overheating. There is evidence to show that overuse of windows in winter and underuse of windows in summer caused increased heating energy demand in winter and increased the incidence of summertime overheating [107].

In Scottish newbuild housing, the occupants reported "never opening" living room (22%) and bedroom (16%) windows. However, windows were opened once or more per week in the living room (33%) and bedroom (34%) suggesting that windows are occasionally used for purge ventilation [100]. Another study noted that an elderly resident reported not being able to open the kitchen window, as it was behind a sink and she could not reach it [35]. Thus, appropriate or not, there was no option to use the ventilation in that room.

It has been shown that changes to occupant ventilation practices can influence indoor air quality. Measurement of the indoor environment and binary window operation status in the living rooms of six London flats revealed that the mean window open time was 4.9 hours prior to the COVID-19 pandemic lockdowns and 2.9 hours during the lockdown [103]. This increased average indoor CO_2 concentration by 300 ppm.

One of the largest studies used a nationally representative cross-sectional online survey to collect data from over 10,000 respondents [126]. The survey asked: "how often did you open the windows at home to improve ventilation in the last seven days?" in a data collection period spanning 26 October to 2 December 2020. The results showed that, respectively, 30% and 27.5% of people "very frequently" and "frequently" opened their windows; while 23.7% "occasionally", 10.6% "rarely", and 7.2% "never" opened their windows. No information was reported on the length of time that windows remained open, in which rooms they were opened, or drivers for this window operation. It should be noted that this study was conducted during the COVID-19 pandemic and additional questions were asked in relation to this, including how the respondents felt that ventilation could help reduce the spread of the disease. Thus, the responses may have been influenced by this. The study does not give information on the appropriateness of this window opening or its effect on the indoor environment (temperature, humidity, air quality), and so it has little value in answering broader questions.

Inappropriate natural ventilation usage can reduce the performance of accompanying mechanical systems. For example, in a post-occupancy evaluation of six dwellings with MVHR, there was unexpected window opening in winter which increased heating energy demand which was partly due to habitual (window opening) behaviours of the occupants [53]. Two of the homes in the study ventilated appropriately and kept their windows closed during the winter. However, two ventilated inappropriately by keeping windows (and the back door) open for long periods during the day when the heating was on. Another study has similar findings. The MVHR systems in two Welsh Passivhaus dwellings were shown to have good indoor air quality with MVHR running, although they performed at lower heat recovery efficiencies than quoted by the manufacturer, and it was believed that bedroom windows were left open at night in one dwelling, even in winter [107].

Trickle vents

Very little interaction occurs with trickle vents, with occupants occasionally adjusting them in only 9% of dwellings. Reasons for not adjusting trickle vents included “feeling no need” (41%), lack of knowledge/awareness (32%), or due to them causing draughts (24%) [100]. In another study, just under a third of people never change the position of their trickle vents (32%) whilst a similar number change the position seasonally (30%) [94]. Trickle vents closed due to draughts in late autumn were then not reopened in spring or summer [97].

Inappropriate[20] mechanical ventilation practices

MVHR systems are designed to be left running continuously. It was found that only 25% of MVHR systems were used as designed, and over half switched the system off entirely in the summer months, and often switched off at night due to the “nuisance” noise [114].

Evidence shows further misuse of mechanical ventilation systems such as outlet vents being blocked above a bed to prevent the perceived flow of cold air [121], being unintentionally blocked due to the placement near shelves or cupboards with items on them [119], and decentralised mechanical extractors in kitchens and bathrooms manually turned off at the isolator switch [121]. However, the study found that the airflow rates through the fans were insufficient, and would not provide adequate ventilation if even they had not been switched off.

Misuse of MVHR systems has been shown where the occupants turn them off, which negatively affects indoor air quality [53]. In this post-occupancy evaluation study of six dwellings, there were issues with the MVHR such as an imbalance between supply and extract

[20] Inappropriate practices refer to those which produce undesirable outcomes for indoor air quality and/or indoor temperature control.

airflow, inaccessible fan units (resulting in poor maintenance), MVHR terminals being closed by occupants due to perceptions of cold air, systems being perceived as expensive due to being “always on” and so turned off by the occupants, breakdowns (often without the knowledge of the occupants), and poorly commissioned or hidden controls. This led to poor indoor air quality in the homes [53]. The study suggests that more intuitive controls, better integration of the heating and ventilation system, and sensible placement of MVHR systems to allow easy access for maintenance would improve the operation of these systems [53].

Macintosh and Steemers [92] further show that MVHR can be operated improperly due to four factors: noise (from fans and air moving through ducts), lack of perceived control, lack of perceived freshness, and a misunderstanding of the MVHR system’s intended use. Regarding noise, despite being in an urban location in central London, there was no correlation between street-level noise and window operation. It was found that, in one case, the MVHR system was as noisy indoors as the surrounding street sounds. Although there were mixed views on the noise of the MVHR system, the consensus was that it was less intrusive than street sounds. Regarding perceived freshness of air, it was found that because incoming air via the MVHR was closer to room temperature it was not perceived as fresh, unlike the cooler air that may enter through a window. This was despite the MVHR air being filtered for particulate matter likely generated by nearby traffic, versus the unfiltered air entering through a window. Furthermore, the dust appearing around the MVHR ventilation inlets was also a cause for concern for the householders who felt this indicated dirty air from outside. In fact, it was indoor dust being entrained as the indoor air was being *removed* from the dwelling. Residents tended to prefer the operable windows as this ventilation method gave “greater control” – with windows being opened 14.6 times per week, compared to the MVHR system being adjusted 0.86 times per week. Some householders, though, commented that they felt no need to adjust the MVHR. Finally, the study found that householders were unsure of the MVHR’s intended use with only 21% saying they use the system more in winter than summer, which is optimal for reducing heating energy demand [92].

Lack of maintenance of mechanical systems

Fifty-three percent of respondents either never, or did not remember when, they last maintained or cleaned their mechanical extract ventilation [94]. A study participant reported they had not done any maintenance on their mechanical ventilation system in four years and noted the system was getting noisier [119]. In some cases, access to the system for maintenance is difficult due to its common placement in loft spaces [120].

RQ11: Do people know how to ventilate their homes in the UK?

Key findings:

Mechanical ventilation and non-standard natural ventilation systems (e.g., passive stack ventilation) may not be initially understood, easily controlled, or properly maintained by around half of all users, several studies suggest. Equally, natural ventilation via windows may be used at the wrong time, leading to increased wintertime heating demand or summertime overheating. Better guidance on how to ventilate homes in the UK is needed.

GRADE quality assessment rating:

There is moderate quality evidence to show if people know how to ventilate their homes in the UK.

A frequent theme with regards to dwellings with mechanical ventilation is that the occupants do not understand how the system works, how to control it, how it operates, and how it should be maintained [92,119–121]. For example, just under half (47%) of the 38 households in a newly renovated block of London flats made no adjustment to their MVHR controls throughout the year and one household disabled the system altogether [92]. There was little knowledge of the MVHR's settings, with 16 households (46%) not knowing what setting the MVHR control was on. Occupants did not know how to use centralised mechanical ventilation systems in an energy efficient manner [92]. The study observed more windows open than would be expected given the local weather conditions – even when the outdoor temperature was 4°C. Similar issues have been observed for non-standard natural ventilation systems such as passive stack ventilation – occupants found it difficult control and to balance air quality and temperature [119] [121].

With natural ventilation systems, such as windows and vents, occupants can still have difficulties operating them. One dwelling had inaccessible roof vents which led to overheating until the social housing provider gave the tenants a pole to open the vents with. Once the tenants knew how, and had the ability, to control their ventilation, the overheating problem was solved [119]. Another resident in the same study was unaware of a safety catch on windows which had prevented them from fully opening, until later being shown how to operate them.

More guidance is needed. An elderly resident reported having no confidence in their ability to control the MVHR, as they were not a technically-minded person, but sought to gain knowledge from younger family members and staff from the social housing provider [119]. Other studies have shown the source of information to come from friends or family (8%), but most said there is a lack of credible and authoritative advice on how to ventilate their homes [94].

Occupants may not know when and for how long to ventilate their dwellings. Studies have shown this to result in over-ventilation[21] due to excessive window opening in winter which increases heating energy demands (whilst improving air quality) [53]; or summertime overheating [98] when high ventilation rates of warmer outdoor air into a room increases the indoor temperature [124].

Trickle vents are designed to provide background ventilation, but it has been found that they were only open in 4 of 17 (23.5%) of dwellings [127]. This may be due to vents being closed in winter and not reopened in spring or summer [97]. Trickle vents are rarely used, as 82% of occupants were unaware of their presence [121], while they are invariably closed due to the perception of admitting unwanted cold air [128]. Yet, encouraging greater use may be futile, as trickle vents often do not provide adequate ventilation [87,128].

Critique of methods

None of the studies included in the Rapid Evidence Assessment measured the degree to which windows were opened. All used either a binary “open or closed” sensor or relied on occupant diaries or post-use surveys. McGill et al. [5] note that the use of diaries to record window operation means the reliability of the data cannot be guaranteed. Without knowing the throw length of the operable window (opening angle) and its degree of use, binary sensors will record a slightly open and a fully open window as the same, despite the likelihood of different ventilation rates, subject to wind speed, direction, and indoor-outdoor temperature differences. Loveday et al. [106] asked about the degree to which windows were open, but being an online questionnaire, the results are not guaranteed to be representative of reality.

Responses of self-reported ventilation provision, which are common in the studies in this Rapid Evidence Assessment, rely on the respondent having a basic knowledge and awareness of their ventilation system and could introduce errors [94]. Furthermore, observation biases occur when surveys are conducted in particular seasons and respondents are influenced by the ventilation systems and practices used in the current season. Other errors can likely occur when occupants are asked to recall previous seasons, as done by Mavrogianni et al. [109], who asked about “the previous summer”.

Jones et al. [96] state that their method was unable to detect the potential variety of drivers of window operation such as removal of odours, occupant presence, air quality, and other factors which influence thermal comfort such as metabolic activity and level of clothing insulation. Most other studies do not explicitly acknowledge this, yet it may affect them.

Another methodological issue with the aforementioned studies is the small sample sizes. There are no nationally-representative studies with which to answer RQ9, RQ10, or RQ11. Although Van Rooyen & Sharpe [94] selected a representative sample in terms of occupant demographics, their study was not representative of the British housing stock.

[21] Indoor CO_2 concentration (commonly used as a proxy for ventilation [135]) was below 500 ppm [53] indicating close to outdoor conditions.

Identification of bias in the literature

There is a bias in the literature towards studies on ventilation in low energy and Passivhaus standard dwellings (Figure 7). There is a further bias towards the type of ventilation investigated. Whilst natural ventilation features in most (90%) of studies, there are a large proportion on mechanical ventilation systems, despite these being uncommon in UK dwellings (Figure 8).

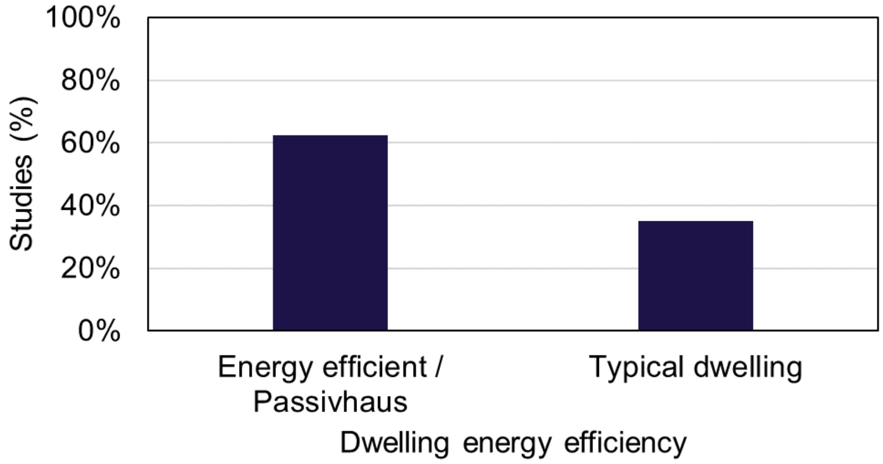

Figure 7: Studies on energy efficient or typical UK dwellings.

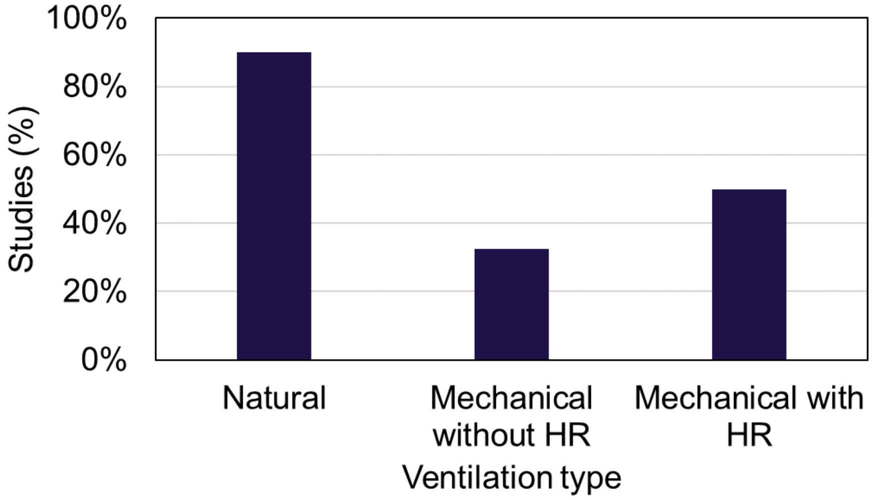

Figure 8: Studies on different ventilation types.

Ventilation practices (RQ9-11): 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 moderate quality evidence regarding how UK homes are ventilated. There are several case studies available, although they are generally limited with regards to sample size and representativeness.
- There is moderate quality evidence regarding why UK homes are ventilated. Similarly, sample size and representativeness are key limitations to these studies.
- There is low-quality evidence to understand ventilation provision in the UK dwellings stock. No surveys of ventilation provision have been done to capture a nationally representative sample of dwellings. One study exists which claims to be “nationally relevant”.
- There is moderate quality evidence to assess the appropriateness of natural and mechanical ventilation practices in the UK. Again, the evidence is reliant on mostly small samples, and studies using larger samples (>1000 respondents) are limited due to reliance on self-reported behaviours.
- There is moderate quality evidence to show if people know how to ventilate their homes in the UK.

Report summary

RQ1: What effect does retrofit have on airtightness?

It remains unclear what effect specific retrofit measures may have on the airtightness of different types of dwellings across the UK housing stock. Most prior studies focus on a small, homogeneous sample, or one or two case studies. It is not possible, at present, to quantify the effect of any particular retrofit measure on airtightness. Most retrofit measures increase airtightness, although there are examples of retrofits being ineffective unless close attention is paid to floor sealing, for example, or if additional penetrations are made in the primary air barrier if plumbing works are carried out alongside energy efficiency retrofits. External wall insulation increases airtightness, but special attention should also be paid to airtightness in other retrofits.

Studies revealed that replacing windows can lead to increased airtightness of 29-50%, targeted draughtproofing can achieve a 55% increase in airtightness and sealing of ground floor penetrations an increase of 42%. It is important to note that these studies are based on small samples or case studies only.

RQ2: What are the typical airtightness failure points by dwelling type/age/construction type?

It was not possible to identify particular failure points by dwelling type, age, or construction type. Some construction types, e.g., wet plastered masonry walls, are inherently more airtight without additional consideration for airtightness. For example, using wet-plaster internally can allow air permeabilities of 5 $m^3/h.m^2$ @ 50 Pa to be achieved with relative ease. There is no reason that a similar airtightness level could not be achieved with similar construction types, providing airtightness details are thoughtfully designed and implemented to a high standard.

RQ3: What are the typical failure points in the construction process that can lead to poor airtightness?

Service penetrations, overreliance on secondary sealing, and poor workmanship associated with the primary air barrier, are all causes of decreased airtightness. Over time the materials commonly used for secondary sealing dry out, shrink, and crack due to exposure to heat and air – or if not correctly applied during construction. If a robust primary air barrier is not in place, airtightness will decrease as the secondary seals fail. For example, airtightness degradation of 30% was observed over several weeks of heating a home. Window and door seals deteriorate in-use, but these can be remedied with proper maintenance, as was shown in the secondary data analysis of the Retrofit Revisit study [54]. In-test air sealing does not appear to be present in the airtightness dataset of existing dwellings, as was shown by secondary data analysis. Therefore, degradation over time from failure of temporary seals is not likely to be an issue.

RQ4: How could typical airtightness failures be addressed by retrofit?

Retrofits primarily focused on reducing conduction heat transfer, e.g., external wall insulation, also have benefits of increasing airtightness in dwellings because they contribute to sealing a common air leakage path which occur around window seals and plumbing penetrations. These paths can also be addressed with simpler (and cheaper) retrofit measures by sealing around the external or internal wall area. Such interventions have been shown to reduce air permeability (increase airtightness) by around 8 $m^3/h.m^2$ @ 50 Pa in dwellings which started at 24-26 $m^3/h.m^2$ @ 50 Pa pre-retrofit.

RQ5: Is there a relationship between airtightness and build quality?

Build quality impacts airtightness. Highly airtight dwellings can be achieved where airtightness details have been correctly designed and articulated with meticulous attention to detail. The opposite is also true. There is not strong evidence which shows whether or not this continues to other aspects of the building, and so more research is needed before airtightness can be used as a proxy for build quality.

RQ6: Does PAS2035:2023 and PAS2030:2023 contribute to robust airtightness practices?

The standards contain guidance which contributes to robust airtightness practices by addressing three common issues: (1) accurate design and detailing; (2) preserving the air barrier; and (3) focusing on quality workmanship. There are, however, no studies which examine how the specific PAS2030 and PAS2035 practices are enacted in reality, and so there is a need for further research in this area.

RQ7: What are the unintended consequences of more airtight homes?

Most unintended consequences of more airtight homes manifest due to insufficient ventilation. The unintended consequences are: condensation, damp, poor indoor air quality, radon build-up, overheating, and a higher incidence of asthma. With properly designed ventilation, these issues can be ameliorated as the reduced infiltration air exchange due to increased airtightness can be replaced by purpose-provided ventilation.

An under-researched unintended consequence is fire and smoke behaviour in airtight buildings. The body of knowledge is embryonic, but there is scope and need for a large amount of work to be done in this area to improve our knowledge and understanding of the risks.

RQ8: How does airtightness affect overheating?

There is low-quality evidence to quantify the influence of airtightness on overheating. One of the main issues is that airtightness is investigated alongside, and in combination with, other factors such as insulation and thermal mass. The effects of airtightness alone on overheating are difficult to identify. Ultimately, any overheating problem associated with making a dwelling more airtight can be alleviated via increased ventilation.

RQ9: How and why do people typically ventilate their homes in the UK?

People typically ventilate using window operation as the primary means. Mechanical ventilation is typically only used in kitchens and bathrooms. More complex, centralised, systems are currently only used in a small number of dwellings.

Window operation is influenced by several drivers and barriers, identified in this review. The drivers of indoor temperature, outdoor temperature, and indoor air quality are often claimed to be the most influential, but there are contradictions between studies. Outdoor noise, rainfall, and security are some barriers to window opening. Barriers to the use of mechanical ventilation are typically noise, a perception of draughts, and a lack of understanding how to operate (specific to MVHR).

RQ10: Do people ventilate their homes sufficiently or appropriately in the UK?

There are no nationally representative studies, but evidence from case studies suggests that ventilation rates tend to be insufficient to provide adequate indoor air quality (particularly in winter) and for ventilative cooling to prevent summertime overheating. Inappropriate window operation may drive an increased winter heating demand and summertime overheating. Trickle vents are insufficient for ventilation and often operated inappropriately (left closed all the time). Mechanical ventilation may provide sufficient ventilation rates, but only when they are properly designed and commissioned. Inappropriate use of mechanical ventilation usually involves occupants switching the system off, blocking vents, or use alongside window opening which reduces the efficiency of the system.

RQ11: Do people know how to ventilate their homes in the UK?

There is a lack of knowledge particularly with centralised mechanical ventilation (e.g., MVHR) and non-standard natural ventilation systems such as passive stack ventilation. A common theme is that occupants do not understand how the system works, how they can control it, and how they should maintain it. With respect to window operation, occupants may not know how long to ventilate their dwelling for to achieve adequate indoor air quality, and they risk over-ventilating, which increases heating demand. Guidance on the operation of ventilation, both natural and mechanical, is needed from a reputable source.

Further work

The following further work is suggested, and will be discussed in more detail in Report 4 [129]:

- How do different construction elements e.g., windows, party walls, vents, and chimneys, contribute to airtightness, infiltration, and ventilation?
- How can more airtight construction and retrofits be repeatedly and reliably assured to reduce the energy performance gap?
- Experimental research on fire and smoke behaviour in airtight versus average buildings[22].
- Development of a source of reputable guidance on ventilation operation.
- A nationally representative survey (regarding both demographics and housing stock) on ventilation provision and ventilation practices.

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

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