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Evidence to support an update to the methodology for estimating infiltration rates in SAP

Gathering evidence to improve airtightness in the UK housing stock

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This report forms the second 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”.

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Contents

Executive summary

Existing infiltration estimation methods are unreliable when validated using existing datasets, with limitations. The new method proposed for inclusion in HEM was the most accurate and precise of the 12 tested and could be a promising improvement on the SAP method, subject to further validation work and method development. Infiltration influences predictions of overheating and energy demand, so accuracy is vital.

Research purpose

Gather evidence to support an update to the method used to estimate infiltration rates in SAP.

Research methodology

A Rapid Evidence Assessment reviewed 73 documents after relevance and quality screening. An empirical validation exercise evaluated the reliability of 12 infiltration estimation methods. Dynamic thermal and steady-state models of overheating and heating season energy demand were used to examine the effect of varying infiltration rates on model predictions.

Research findings

There is high-quality evidence to suggest that current infiltration estimation methods produce unreliable estimates of infiltration rates in English dwellings, when validated using point-in-time measurements tested with small indoor-outdoor temperature differences. There is moderate-quality evidence to indicate the reliability of estimations of mean heating season infiltration.

Empirical validation and inter-model comparison revealed that the new infiltration estimation method proposed for the DESNZ Home Energy Model (HEM) estimates infiltration with greater accuracy and precision than all other methods investigated in the case study dwelling under spring/summer weather. Yet, when wind speeds are low, the HEM method estimates infiltration less reliably. Therefore, the HEM infiltration estimation model could be improved with the inclusion of ΔT to account for the stack effect, which is the dominant driving force of infiltration at low wind speeds. The effectiveness of this has been demonstrated in other methods. All methods require further testing and validation in a range of dwellings under a range of weather conditions, before final conclusions can be made, however.

Varying the infiltration rate of a house in a calibrated dynamic thermal model revealed that the predicted hours of overheating (Criterion A) were reduced from 5.8 to 2.3% in a bedroom when the value of infiltration was increased from 0.3 to 0.8 ach (the infiltration rate measured vs. estimated by the divide-by-20 method). This means the house would be compliant with Building Regulations on Overheating (Part O) using the estimated (higher) infiltration rate, but not compliant if the real, measured (lower), value for infiltration was used in the model.

Introduction

Background and context

Infiltration (and exfiltration) is the adventitious[1] air leakage into (and out of) a building at normal indoor-outdoor pressure differences[2]. The building envelope airtightness influences the amount of air that enters a building, but not exclusively so. The adventitious airflow across the building envelope is also related to the indoor-outdoor temperature difference, the building height, and the outdoor weather conditions (which is also influenced by location and sheltering) [1]. Ventilation differs from infiltration in that it allows air to move in and out of a building through purpose-provided openings, rather than adventitious openings.

Reducing infiltration is desirable because it allows uncontrolled, unconditioned air to enter a building which may allow outdoor pollutants to enter, could cause uncomfortable air movement (draughts), increase the heating or cooling demand, and drive moist air into the building fabric where interstitial condensation may form. Quantifying the infiltration rate of a dwelling is therefore useful to decide where to target airtightness retrofits.

Infiltration rates can be measured directly using a tracer gas test. This is the most accurate option but is expensive and time-consuming [2]. Alternatively, dwelling airtightness can be measured via a pressure test and then converted to an infiltration rate using an infiltration estimation method. A pressure test is usually quicker to undertake than a tracer gas test. The downside is that a pressure test measures the properties of the building fabric which relate to infiltration (airtightness), but not infiltration rate directly and does not account for wind and temperature effects [1,3]. However, infiltration estimation methods may not produce reliable results [2,4]. Deriving reliable estimates of infiltration from pressure tests is desirable, however, because all UK dwellings are pressure tested after construction [5–8], and so there is a large airtightness database available from which to potentially derive infiltration in newbuilds.

Reliable estimation of infiltration is a challenging task due to its dynamic nature in response to changes in wind speed, wind direction, and the indoor-outdoor temperature difference, as well as differences in the data from which it might be calculated. The reliability of infiltration estimation methods can be quantified by empirical validation, but this requires both an airtightness test and a measure of infiltration rate, that latter of which is particularly rare.

Unreliable estimation of infiltration rate has severe implications for accurately predicting national heating demand and overheating. Now that UK Government policy on overheating risk in residential buildings requires new dwellings to undergo an overheating assessment to prove compliance [9], and the infiltration rate input to the model is usually estimated, reliability is paramount to ensure that dwellings are designed to be habitable in the future climate.

[1] Adventitious refers to unintended, unwanted, and undesigned air leakage.
[2] I.e., not those artificially induced by a pressure test.

Aims and objectives

The aim of this research is to gather evidence to support an update to the methodology used for estimating infiltration rates in the Standard Assessment Procedure (SAP). The aim will be addressed via the following objectives:

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

Research questions

The following research questions will be addressed in this report:

- RQ1: (a) What is the divide-by-20 rule of thumb and (b) how is it used?
- RQ2: What are the limitations of the divide-by-20 rule of thumb?
- RQ3: How should the SAP methodology for estimating infiltration rates be changed or improved?
- RQ4: How does infiltration impact heating energy demand and overheating in steady-state and dynamic thermal models?

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

Report structure

The first section provides details of a Rapid Evidence Assessment of the currently available literature. The second section presents analysis of an existing infiltration dataset used to conduct an empirical validation and inter-model comparison. The third section builds a dynamic thermal model and a SAP model of the Loughborough Matched Pair tests houses to demonstrate the impact of varying infiltration rates on predictions of energy demand and overheating. The final section draws together the findings from the literature and the analyses conducted to address the research questions.

Rapid Evidence Assessment

Introduction

This Rapid Evidence Assessment reviews what the current literature says about infiltration estimation methods and their use, and identifies gaps in the evidence base. It specifically:

- Identifies the infiltration estimation methods used, describes them, states where they are used, and notes their strengths and limitations.
- Reviews studies which suggest improvements to the methods.

Methodology

Overview of methodology

Rapid Evidence Assessments are rigorous and timely reviews of the literature to make evidence-based recommendations [10]. The review process was adapted from Drury [11] 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. [12]. The search terms specific to this Rapid Evidence Assessment are listed in Table 1 and screening criteria in Table 2.

Table 1: Primary and secondary search terms.

Primary search term	Secondary search term
Leakage	Ratio
Infiltration	Method
Air	Estimation
	Model

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

Inclusion criteria	Exclusion criteria
Written in English	Focuses only on non-domestic buildings
Can be readily accessed online within the time allocated for review	Uncommon construction for dwellings, e.g., log cabins or caravans
The abstract indicates relevance to the research question being investigated	Duplicated studies, e.g., where a conference paper became a journal paper
The full text provides quantitative evidence for the research question being investigated	Focuses on a single building component rather than whole house infiltration.

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 [13] (Figure 1).

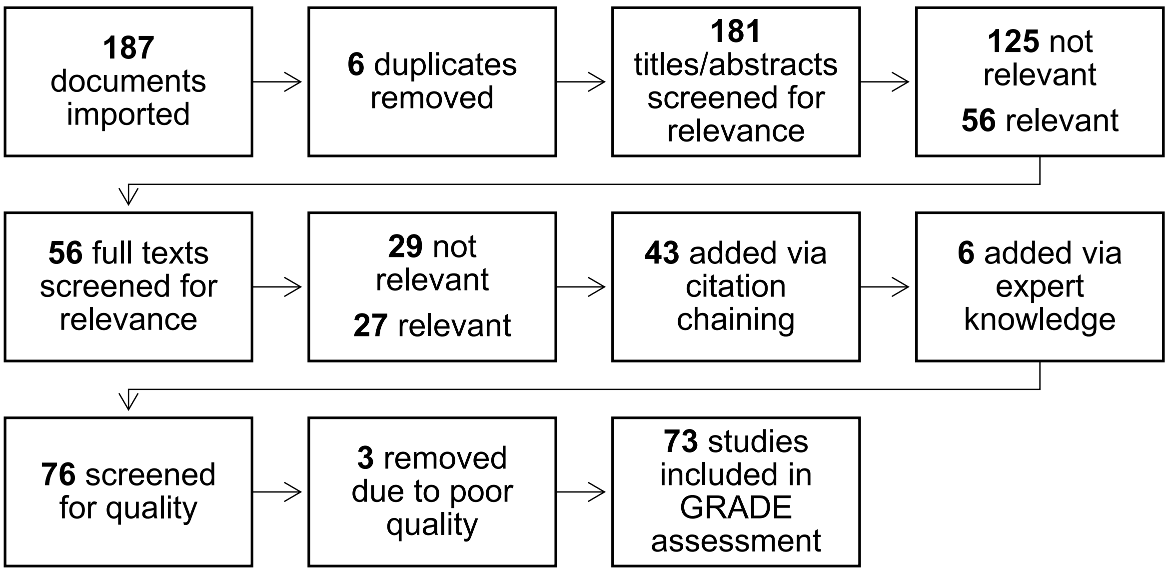

Figure 1: PRISMA diagram, after Page et al. [13].

RQ1a: What is the divide-by-20 rule of thumb?

Key findings:

The divide-by-20 rule of thumb is a leakage-infiltration ratio that calculates infiltration rate from a pressure test result for a single-zone. Divisors other than 20 have been suggested from 10 to 58 depending on the dwelling, location, and weather conditions. The method forms the basis for the SAP infiltration estimation method.

GRADE quality assessment rating:

There is high-quality evidence which describes the divide-by-20 rule of thumb.

The origins of the method

The divide-by-20 rule of thumb is one of several infiltration estimation methods and among the most simplistic, being a “pressure test reduction” [14] which treats the dwelling as a single zone. Being a leakage-infiltration ratio, it simply requires a measured air leakage rate from a dwelling (at 50 Pa) and a numerical divisor to estimate the infiltration rate. A leakage-infiltration ratio represents a linear relationship between air leakage rate[3] (N_{50}) and infiltration. The most common divisor used is 20, and thus it is named the “divide-by-20 rule of thumb”. Alternative names include: the rule-of-20, Sherman’s ratio, or the Kronvall-Persily (K-P) method [15] – due to being frequently, but incorrectly, attributed to work done by Kronvall [16] and Persily [17].

The origins of the divide-by-20 infiltration estimation method are often thought to be unclear [15]. In reanalysis of the results of Kronvall [16] in Swedish dwellings, Jones et al. [15] show that a linear relationship between infiltration rate ($\bar{N}$) and air leakage (N_{50}) exists and is $\bar{N} = 19.96N_{50}$ – i.e. close to the frequently mentioned 20. However, the results were not originally presented in this way, so it is impossible to say if the divisor of 20 originated from the work of Kronvall. Jacobson et al. [3] incorrectly attribute the divide-by-20 model to Kronvall [16] and Persily [17], but include reanalysis of the data from both studies – 26 dwellings in Sweden and several dwellings in New Jersey, USA to derive a divisor of 18, not 20. Jones et al. [15] highlights that the governments of Finland and UK subsequently use the number 20 in their building codes[4] and energy performance assessment models. Germany, however, uses a value of 14.3 [18]. The Danish national energy code uses $(AP_{50} \times 0.06) + 0.04$ which is based on an empirical relationship between airtightness and infiltration in Canadian dwellings [19]. The UK Government is proposing alternative divisors based on number of storeys and sheltering [20]. Johnston and Stafford [21] suggested 13.3 to 24.9 in four houses[5]. Keig et al. [22] suggested 23 to 29 in four dwellings. Others have suggested that the divisor should range from 10 to 30 depending on number of storeys [23], or higher, 37 [4], or higher still, 58, for

[3] Although air permeability (AP_{50}) is usually applied in the UK.
[4] For three- and four-storey dwellings, which is reduced in accordance with the number of storeys.
[5] Infiltration rates were only made in the living room and one or two bedrooms, then averaged for the whole house. Whole house infiltration, measured as a single zone might be different.

summertime conditions when wind- and stack-driven ventilation is low [2]. In Spanish apartments, a divisor of 13.59 is suggested [24].

It seems that the origins of the divide-by-20 method, and the choice of 20 as a divisor, remain unclear. What is known, however, is that this work was originally done almost 50 years ago, probably in a relatively small number dwellings in Sweden and USA, where the climate and building practices are different from the UK and have changed in the last half a century.

Other single-zone infiltration estimation methods

Other single-zone infiltration estimation methods exist and have done for at least 45 years. Some are based on the divide-by-20 method and require a pressure test from a dwelling. Most use at least some output from a pressure test, besides AP_{50} and N_{50}, these include flow coefficient, flow exponent, and equivalent leakage area. Others require details of the number of storeys in the dwelling, information on the wind sheltering, and average weather conditions. Roberts et al. [2] provide an extensive tabular summary of the variety of required inputs for each infiltration estimation method.

The ASHRAE Basic method [25] is based on work by Sherman and others on the Lawrence Berkeley Laboratory (LBL[6]) method [26–28] and is called the Effective Leakage Area model in EnergyPlus dynamic thermal modelling software. The ASHRAE Enhanced method [25] is derived from the Alberta Infiltration Model (AIM-2) [29,30], and is called the Flow Coefficient model in EnergyPlus dynamic thermal modelling software. The SAP method is used in UK dwelling energy assessments and is based on the divide-by-20 method with additional inputs such as local wind speed, the number of sheltered sides the dwelling has, the number of storeys and chimneys [31]. There is a variant of the SAP method which uses an algorithm to calculate airtightness in place of a pressure test, should one be unavailable. Proposals for a new infiltration estimation method for the DESNZ Home Energy Model (HEM) describe a selection of divisors which account for number of storeys and sheltering alongside an input for wind speed [20]. The limitation of any infiltration estimation method is that they are extremely sensitive to the accuracy of the input data, which is often difficult to determine [32].

Complex single- and multi-zone models

More complex methods (infiltration models) exist including AIDA [33], CONTAM (e.g., [34]), and DOMVENT [35,36]. Multi-zone models have advantages over single-zone in that they can determine infiltration rates for individual rooms, as well as the whole building, and so are useful for predicting inter-room air movement for air quality, smoke, fire spread, and energy calculations [37]. However, they require substantial input data to describe the flow network and additional computational time [ibid.]. Further consideration of complex models is out of the scope of this review which focuses on the “divide-by-20” and other simple single zone infiltration estimation methods. Other methods, e.g., a heat balance approach [38], are also noted for future consideration, but out of scope in this review.

[6] The LBL model is now, strictly, the LBNL (Lawrence Berkeley *National* Laboratory), but is called the LBL model in the cited publications.

RQ1b: How is the divide-by-20 method used?

Key findings:

The divide-by-20 rule of thumb is the most commonly used single-zone infiltration estimation method in the literature. Most studies estimate infiltration for the purposes of overheating modelling.

GRADE quality assessment rating:

There is high-quality evidence to describe the application of the divide-by-20 method.

The divide-by-20 method is the most widely used infiltration estimation method found in the review of the literature (Figure 2 and Table 4 in Appendix 1)[7],[8],[9]. This is attributed to its ease of use [39].

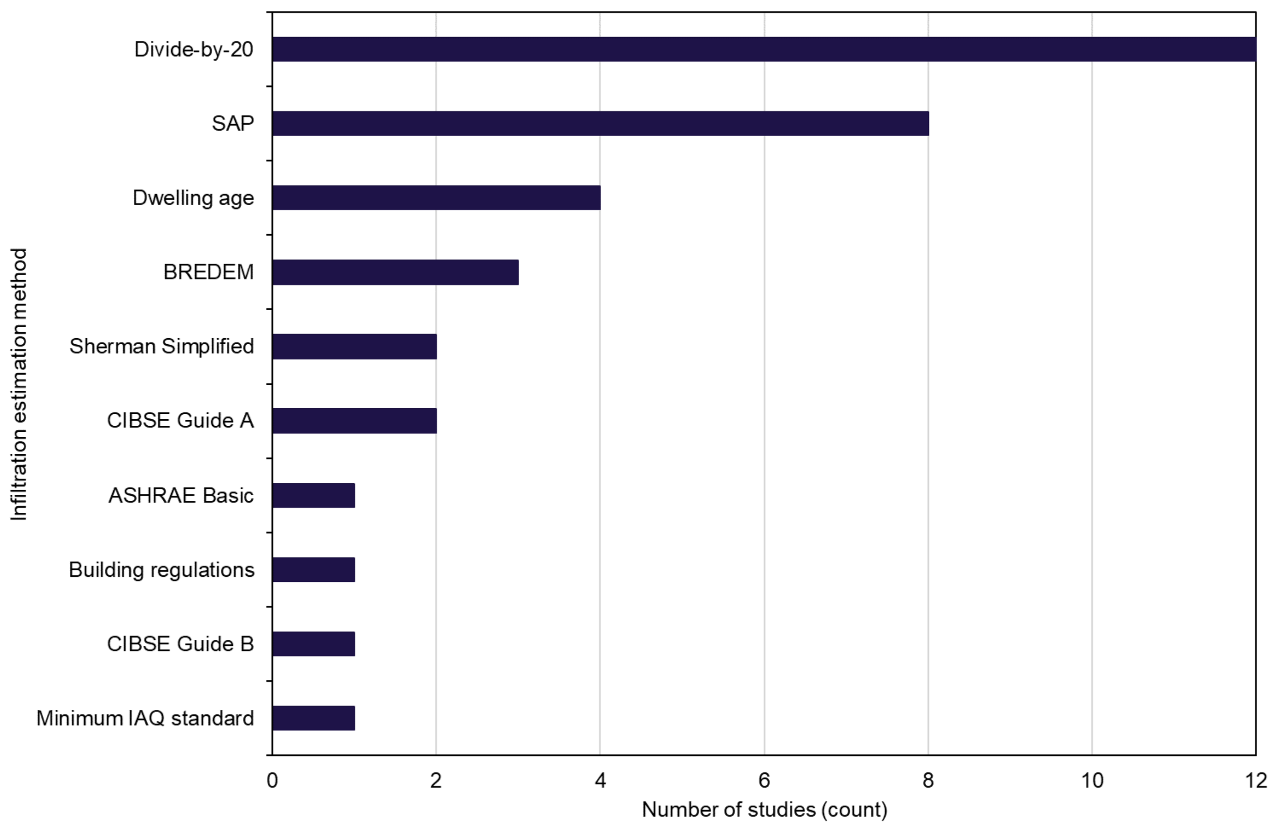

Figure 2: The number of studies using infiltration estimation methods grouped by method.

[7] Descriptive tables with each author listed are in Appendix 1.
[8] In practice, it is likely that the SAP method is most widely due to the large number of SAP assessments.
[9] All studies estimating infiltration using dwelling age relied on Stephen [116].

RQ2: What are the limitations of the divide-by-20 rule of thumb?

Key findings:

The divide-by-20 rule of thumb has drawn criticism for being an unreliable estimator of infiltration rate. This is perhaps undue because the method is intended for low-precision heating season estimates. Two of the two most prominent UK validation studies have used the method to estimate point-in-time infiltration rates under summer weather conditions and suggest that the divide-by-20 method does not reliably predict infiltration under these conditions. For spring/summer weather conditions, errors of 64-590% have been found using different estimation methods in different dwellings. There is a literature gap regarding the reliability of these estimation methods under UK winter weather conditions.

GRADE quality assessment rating:

There is high-quality evidence to suggest that current infiltration estimation methods produce unreliable estimates of infiltration rates in English two-storey dwellings when validated using point-in-time measurements tested with small indoor-outdoor temperature differences.

There is low-quality evidence to indicate the reliability of a divisor of 20 to estimate mean heating season infiltration in UK dwellings.

Divide-by-20

The divide-by-20 method has drawn criticism for being an unreliable estimator of infiltration at specific point-in-time measurements and so should only be used for low precision estimates of infiltration rate [40]. However, low-precision average heating season estimates are exactly what the divide-by-20 method was intended for; dwelling- and location-specific results are only approximations [15]. Therefore, researchers and practitioners are, perhaps, expecting the divide-by-20 method to make reliable predictions of infiltration under conditions for which it was never designed to operate. Nonetheless, the limitations of the divide-by-20 rule of thumb are reported in several studies [2–4,21,22,41–43].

Jacobson et al. [3] highlighted that two different infiltration estimation methods, divide-by-20 and LBL, did not estimate similar post-retrofit infiltration reductions. Sherman, in a written discussion to the authors Jacobson et al. [3] notes that the LBL method was not intended to be used on attached (semi-detached) dwellings and criticised the use of spot tracer measurements which are unrelated to the average infiltration rates estimated by the LBL method.

Everett [44], conversely, showed that the winter season average infiltration rate was close to 1/20th of the pressure test result with an N_{50} of 8.9 ach @ 50 Pa and an infiltration rate of 0.41 ach. The infiltration rate was measured over successive weeks but can vary by ±30% in individual tests. The study does warn that average infiltration rates are difficult to attribute to a pressure test value because of differences in house orientation and sheltering. Two houses with similar airtightness in the same terrace were shown to have an average infiltration rate of 0.28 ach if sheltered by the terrace and 0.41 ach if facing the prevailing wind without sheltering from other houses [44].

Keig et al. [22] suggested a divisor of 23 to 29 when normalised to an indoor-outdoor temperature difference of 11.5°C, which would be close to spring and autumn weather conditions in the UK. The study was an empirical validation of the method in four dwellings: a single-storey detached, two two-storey mid-terraced, and one three-storey end-terraced dwelling.

Farmer et al. [45] reported that using 20 as the divisor for N_{50} greatly overestimated the measured infiltration, and they recommend a much higher divisor for the dwelling being tested but does not indicate a specific value. Some authors are firm in their criticisms of leakage-infiltration ratios, saying it is not possible to normalise ventilation measurement data to airtightness [46]. It has been found that infiltration varies between <0.2 and 1 ach with wind speed [47] and so it is unsurprising that a single divisor is an unreliable estimator of infiltration.

Roberts et al. [2] reported the divide-by-20 method to be the least reliable of 11 different infiltration estimation methods that were empirically evaluated with overestimations of up to 0.54 ach. Similarly, Pasos et al. [4] in an empirical validation study of 21 dwellings note that infiltration was mostly overestimated using 20 as the divisor, but it was found that the ratio was close to 20 in five of the dwellings. However, both studies were conducted under mostly summertime weather conditions and so the findings cannot be necessarily translated to considerations of the winter heating season.

Johnston and Stafford [21] measured infiltration rate during the winter heating season, but there may be problems with their infiltration rate measurement methodology. The tracer gas tests were conducted in the living room and one or two bedrooms, rather than the whole house. Whether the infiltration rate of a single room can be transferred to the whole house without introducing errors is not discussed. Nonetheless, the study found the divide-by-20 method overestimated infiltration rate in two dwellings and underestimated it in two others. They suggest alternative divisors of 13.3, 16.7, 23.4, and 24.9, rather than 20.

Until now, this review has focused solely on infiltration. Some methods, however, can also account for ventilation. A pilot study measured ventilation (which included infiltration using the “divide-by-20” method) and air permeability in five occupied dwellings using the Building Research Establishment Domestic Energy Model (BREDEM[10]). It found that measured ventilation rates were around 50% lower than estimated [41]. The unreliability of the underlying divide-by-20 infiltration model is compounded here by uncertainties in ventilation use. Predicting ventilation is likely to be even more challenging than infiltration.

[10] This method is shared by the Standard Assessment Procedure (SAP).

Other single zone infiltration estimation methods

Pasos et al. [4] present one of the largest empirical validations to be conducted in English dwellings (in terms of number of dwellings). The study validated the SAP[11] infiltration estimation method using one point-in-time measurement of infiltration in 21 two-storey houses in the East Midlands of England. The study found that the SAP infiltration estimation method overestimated the infiltration rate in all dwellings, and errors were greater than 590%[12] in some cases, especially in more airtight dwellings [4]. A limitation of the work was that only a single tracer gas test was done in each house, so the varying nature of wind and temperature could not be detected in any single dwelling[13]. Furthermore, the indoor-outdoor temperature differences under which the tracer gas tests were conducted were small, less than around 6°C in all but two of the tests, and so not representing the normal conditions of the winter heating season.

Roberts et al. [2] provides one of the most comprehensive empirical validations of infiltration estimation methods, investigating 11 different methods. The study does so in a single test house in England and conducted multiple tests (15) which allows for the effect of varying wind and temperature on infiltration to be investigated. Of the 11 methods tested, the ASHRAE Enhanced method provided the most accurate estimation of infiltration (mean bias error (MBE) = 0.16 ach, or mean 64% higher than the measured value). As previously stated, the "divide-by-20" method was the least reliable (MBE = 0.51 ach, or mean 208% higher than the measured value). The SAP infiltration estimation method, using wind measured during the test, was more accurate than divide-by-20 (MBE = 0.36 ach). The study had a similar limitation to Pasos et al. [4], however. The indoor-outdoor temperature differences for the tracer gas tests were, again, small (mean = 6.6°C) and so the methods were only validated under summertime conditions. Yet, estimation errors of 64-208% were found. Similar trends were observed in another study, this time, using a controlled test cell[14] rather than a full-scale test house. An MBE of 0.58 ach was found between the divide-by-20 method and the measured infiltration rate [48].

Taken together, the findings of Pasos et al. [4] and Roberts et al. [2] suggest that infiltration estimation methods are less reliable than previously thought – although these were both based on point-in-time measurements under, generally, summer weather, and only in English two-storey houses. In other countries, for example, Shaw's validation of his method from 25 Canadian dwellings in 1981 found that estimated infiltration fell within 25% of the point-in-time measurements [49]. Empirical validation of the LBL method found the estimates to be within 20% of the measured value over the long-term [50]. Walker and Wilson [51] found only 10% error in three models but had a vast dataset of 1491 hours of constant concentration tracer gas air infiltration measurements. The reason that prior studies may have detected lower errors may be because the two UK studies were conducted under summertime infiltration. Estimates of infiltration rate may be least accurate in the summer season, with one relevant study

[11] The same study also validated the "divide-by-20" as mentioned in the previous section.
[12] This error was detected using the SAP annual average in a dwelling with a SAP annual estimated N_{50} of 0.6883 ach and a measured N_{50} of 0.0998 ach [4].
[13] Everett [44] warns against the reliance of a single small number of tests to build a picture of infiltration rate as the effect of wind is unlikely to be equal in all direction.
[14] A test cell is a single zone building, which differs from a test house or real dwelling which has multiple zones.

showing that the difference between measured and estimated infiltration rates (Sherman Simplified model) were greater in summer and smaller in the winter [52].

In tests conducted during winter, Everett [44] showed there to be at variation of ±0.15 ach (±15%) between measured infiltration and infiltration predicted by an estimation method attributed to Etheridge without citation[15]. The study demonstrated a clear associated between wind and infiltration, and the indoor-outdoor temperature.

Summary 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 high-quality evidence which describes the divide-by-20 rule of thumb and its frequency and topic of use. The divide-by-20 rule of thumb is the most used single-zone infiltration estimation method due to its simplicity and ease of use.
- There is high-quality evidence to suggest that current infiltration estimation methods produce unreliable estimates of infiltration rates in English dwellings when validated against summertime point-in-time measurements. This is because the method was only designed for low-precision average heating season estimates. Further research should measure the infiltration rates in a diverse range of dwelling types, locations, and weather conditions.
- There is low-quality evidence regarding the reliability of a divisor of 20 as an estimator of mean heating season infiltration in UK dwellings. The studies which exist may contain methodological errors with respect to the way infiltration was measured and others focus on a small, homogeneous sample of case study dwellings or a test cell.

[15] The method appears to be the ASHRAE Basic method [25], but no citation is given.

Empirical validation and inter-model comparison of existing infiltration estimation methods

Introduction

This section addresses RQ2: What are the limitations of the divide-by-20 rule of thumb? The divide-by-20 method is compared to measurements of infiltration (empirical validation) and compared to other methods (inter-model comparison), including the SAP method and the new method proposed in the DESNZ Home Energy Model (HEM) consultation [20].

Methodology

A dataset of measured infiltration rates, identified from the Rapid Evidence Assessment, was used to empirically validate the estimates of infiltration rate of 12 different methods. In a semi-detached house, infiltration was measured in 15 separate tests using tracer gas alongside measurements of the indoor and outdoor temperature, and local wind speed. A full building survey alongside blower door tests provided the necessary input data for the estimation methods. Analysis was conducted to identify the difference between measured and estimated infiltration, to quantify the accuracy and precision of each method, and finally to identify the input parameters common to the most reliable methods.

Available datasets for empirical validation

The Rapid Evidence Assessment (REA) revealed a paucity of infiltration measurements in dwellings with companion airtightness tests. In the UK, the most prominent datasets in terms of sample size are Pasos et al. [4] and Roberts et al. [2]. The latter study measured infiltration rates at 15 different times in the same dwellings which allows for variations in temperature and wind to be investigated via empirical validation, but only for one house. The former took single test measurements in 21 dwellings, and so is less useful for detecting the variable nature of infiltration against the more static airtightness but provides results for more than one house. There was a need to understand how the infiltration rate varied with the weather and to identify the methods which best accounted for this. As such, the Roberts et al. [2] dataset was selected as the most appropriate for use in the empirical validation exercise. Both the infiltration datasets presented in Pasos et al. [4] and Roberts et al. [2] were identified in the REA as being recorded under a limited range of indoor-outdoor temperatures and with those temperatures being akin to summertime conditions. This is a key limitation of both datasets given that most infiltration estimation methods were developed for use in the heating season.

The Roberts et al. [2] dataset comprises 15 tracer gas tests with purpose-provided openings closed, thus measuring infiltration. Alongside infiltration, the dataset contains 34 blower door tests which measured the dwelling air permeability and provides many of the required inputs for several infiltration estimation models such as flow coefficient, flow exponent, and equivalent leakage area. Finally, other data are available about the dwelling's geometry, construction, and surrounding environment which are required by some infiltration estimation methods [53,54].

Measurement of infiltration, airtightness, indoor temperature, and weather in a test house

The measurements were made in one of the Loughborough Matched Pair test houses, which are owned and operated by Loughborough University in Loughborough, UK (Figure 3). The weather conditions (wind speed, wind direction, outdoor dry bulb temperature) at a local weather station and indoor dry bulb temperatures in every room were measured during the tracer gas and blower door tests[16]. The measurements provide a value for the whole-house infiltration rate. Data from this house is also used in subsequent sections of this report on the effect of infiltration on energy use and overheating in dynamic thermal and SAP models.

(a) (b)

Figure 3: The test house from (a) the front, and (b) the rear.

Estimating infiltration

Infiltration was estimated using 12 methods. All the methods, except for the SAP algorithm method, required data from an airtightness test, be that AP_{50}, N_{50}, flow coefficient, flow exponent, or equivalent leakage area (Table 3). The "divide-by" methods required the least input data: just a single value for AP_{50} or N_{50} against a divisor of 20 (see [15]) or 30 (see [23]). The SAP methods [31] required additional information about the dwelling, e.g., number of

[16] For full details see [2].

storeys and the local wind speed[17]. The Home Energy Model (HEM)[18] [20] was similar to SAP but also needed to know whether the dwelling was a house or a flat. The ASHRAE Basic [25], ASHRAE Enhanced [25], LBL[19] [27,28], Sherman Simplified [55] also required indoor-outdoor temperature difference (ΔT) as an input. The HEM and SAP methods also allow for ventilation to be estimated in addition to infiltration, but for the purposes of this work, only infiltration was calculated.

The application of the methods, except the HEM method, is summarised in Roberts et al. [2] and described in full in their respective original sources. The HEM [20] uses "divide-by" as a basis, but rather than the commonly used divisor of 20, uses modified divisors suggested in CIBSE Guide A [56] with sheltering categories derived from BS EN 5925 [57]. For this two-storey test house, in a "very sheltered" location, the proposed divisor for N_{50} [20] is 34. This value is multiplied by a modified wind speed, which is modified in the same way as in SAP. In this case wind speed is divided by 4 to account for the difference between wind speed measured on a mast at a weather station at a height of 10 m from the ground compared to the wind speed experienced by the dwelling at ground level. In this empirical validation, the wind speed and indoor-outdoor temperature difference (ΔT) was averaged over the duration of each individual tracer gas test[21]. In practice, the HEM would require an hourly wind speed calculation from a weather file suited to the location of the dwelling in question.

[17] But not wind direction.
[18] As of 2023, the HEM infiltration estimation method is undergoing consultation, and subject to change.
[19] The LBL model is now, strictly the LBNL (Lawrence Berkeley National Laboratory), but is called the LBL model in the cited publications.
[20] The HEM method uses N_{50}, whereas SAP uses AP_{50}.
[21] Test duration ranged from 01:37 hours to 12:26 hours with a mean of 06:41 hours [2].

Table 3: Infiltration estimation methods and model inputs. The numbered headings indicate the method: (1) ASHRAE Basic, (2) ASHRAE Enhanced, (3) divide-by-n, (4) HEM, (5) LBL, (6) SAP Algorithm, (7) SAP with pressure test, (8) Sherman Simplified.

Input	1	2	3	4	5	6	7	8
Flow coefficient		✓						
Flow exponent		✓						
Equivalent leakage area (ELA)	✓				✓			
AP_{50} or N_{50}			✓	✓			✓	✓
Crack factor								✓
Dwelling volume	✓	✓			✓			
Dwelling type (house or flat)				✓				
Storeys	✓	✓		✓	✓	✓	✓	✓
Shelter / shielding class	✓	✓		✓	✓			✓
Sheltered sides						✓	✓	
Terrain coefficient					✓			
Flue		✓						
Chimney, fans, etc.						✓ *	✓	
Wall type						✓		
Floor type		✓				✓		
Draught lobby						✓		
Window draught proofing						✓		
Ventilation method						✓	✓	
ΔT (°C)	✓	✓			✓			✓
Wind speed (m/s)	✓	✓		✓	✓	✓	✓	✓
TOTAL INPUTS	6	9	1	5	7	9	6	6

* The SAP methods included inputs for chimneys, fans, and flues, but these were sealed during both the pressure test and the infiltration measurements.

Ranking of the infiltration estimation methods

For each individual measurement of infiltration, a corresponding estimate of infiltration rate was made using each of the 12 methods using the weather measured at the time of the tracer gas test used in the infiltration estimation method, if applicable. There were 15 infiltration measurements in total. Each of the infiltration estimation methods was ranked in the order of their accuracy compared to the measured value. The precision and trueness (accuracy) metrics of CVRMSE[22] and NMBE[23] were used for this purpose. These two error metrics are

[22] CVRMSE is Coefficient of Variation of the Root Mean Square Error with the units “%”.
[23] NMBE is the Normalised Mean Bias Error with the units “%”.

commonly used for evaluating model predictions, e.g., the BEIS SMETER evaluation [58] and the DESNZ Home Energy Model validation [59]. They are standard metrics recommended for evaluating building energy models within ASHRAE Guideline 14 [60]. The CVRMSE is a comparative measure of precision, with a lower percentage value indicating a more precise prediction [58]. The NMBE quantifies the magnitude and direction of the average bias in the model's estimate, i.e., the accuracy or trueness. Precision (CVRMSE) and accuracy (NMBE) differ because precision describes how close each value is to each other whereas accuracy described how close the predicted value is to the true value. Thus, it is possible for a model to be both precise and inaccurate if multiple predictions are close together but far from the true value. The perfect model would be both precise and accurate with CVRMSE and NMBE values of zero. The equations for CVRMSE (Equation 1) and NMBE (Equation 2) are below, where: E = the error in the prediction (estimate minus measurement M) for a particular test t, and n is the number of infiltration rates being compared.

$$CVRMSE\ (\%) = \frac{\sqrt{\left(\frac{\sum_{t=1}^{n}(E_t)^2}{n}\right)}}{\bar{M}} \times 100$$

Equation 1: CVRMSE

$$NMBE\ (\%) = \frac{\left(\frac{\sum_{t=1}^{n} E_t}{n}\right)}{\bar{M}} \times 100$$

Equation 2: NMBE

Results

Ranking infiltration estimation methods by accuracy and precision

All the infiltration estimation methods estimated a mean infiltration rate that was higher than measured (Figure 4). The mean measured infiltration rate was 0.25 ach. The HEM method estimated infiltration to be, on average, 0.06 ach higher[24] (0.31 ach), which was closest to the measured value of all the estimation methods. The next closest was the ASHRAE Enhanced method (mean of 0.41 ach and mean difference of 0.16 ach). The estimated infiltration furthest from the measured mean was the $N_{50}/20$ method (mean of 0.77 ach and mean difference of 0.52 ach). The HEM infiltration estimation method was the most accurate and precise, with the lowest CVRMSE and NMBE (59 and 24%) (Figure 5). The least accurate and precise was the $N_{50}/20$ method, with the highest CVRMSE and NMBE (both 201%).

Each of the 15 measured infiltration rates were plotted against the corresponding infiltration estimate for each method (to ensure same weather and indoor temperature and comparing like-for-like). Examination of correlation coefficients showed that the HEM method's infiltration estimates were *not* well correlated with the measured values (R = 0.14), despite being

[24] The mean bias error (MBE).

previously shown the most accurate method. The causes of this are later considered in the discussion section. Other methods showed stronger correlations with the measured value. The ASHRAE Basic, LBL, ASHRAE Enhanced, and Sherman Simplified methods were all positively correlated with the measurements (R = 0.50, 0.50, 0.48 and 0.31 respectively).

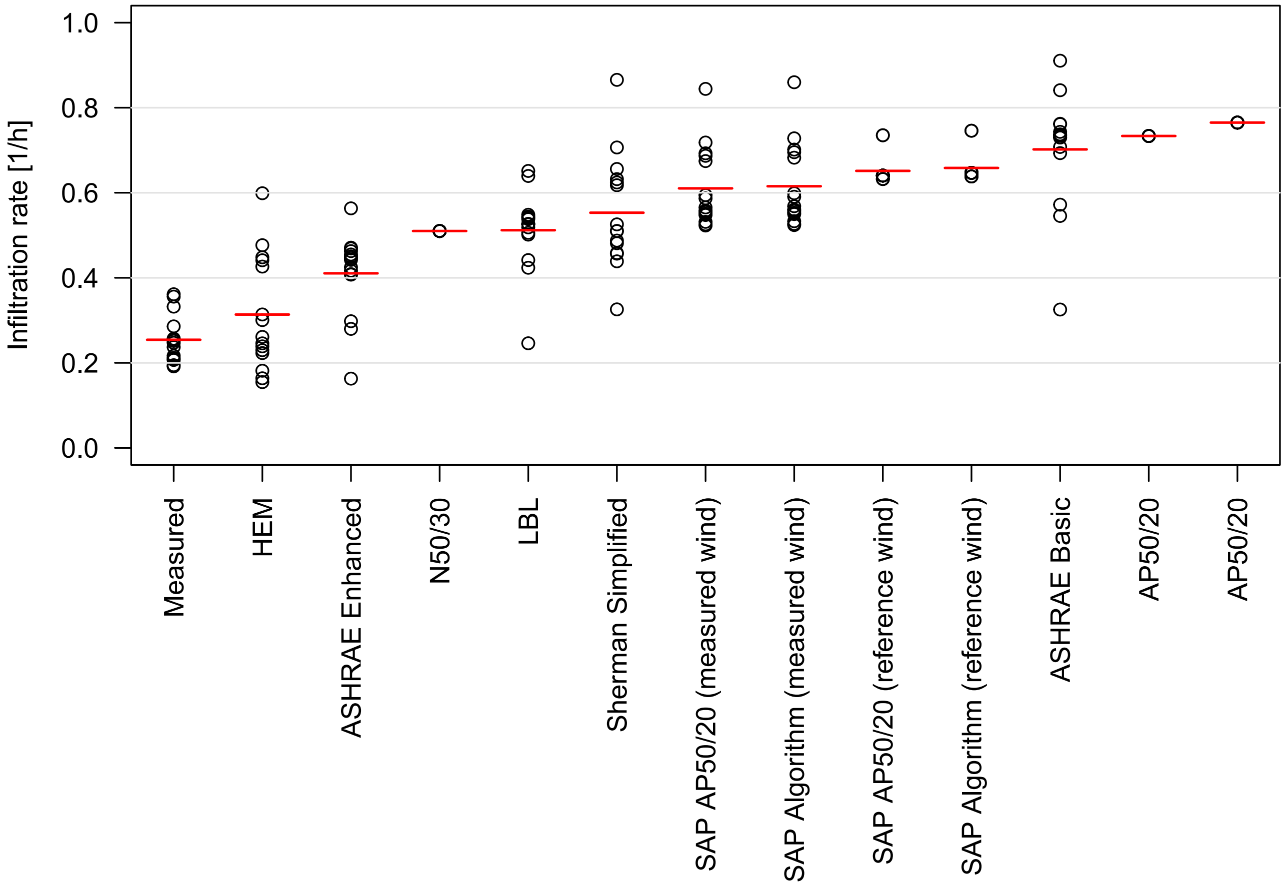

Figure 44: Individual infiltration rates for the measurements and for each of the estimation methods. Each data point represents a single measured or estimated value. The red horizontal bars are the mean infiltration rate. Arranged in order of ascending mean infiltration rate. Note that the “divide-by-n” methods do not vary around the mean as they do not account for wind speed and ΔT, so always estimate one value for any given pressure test.

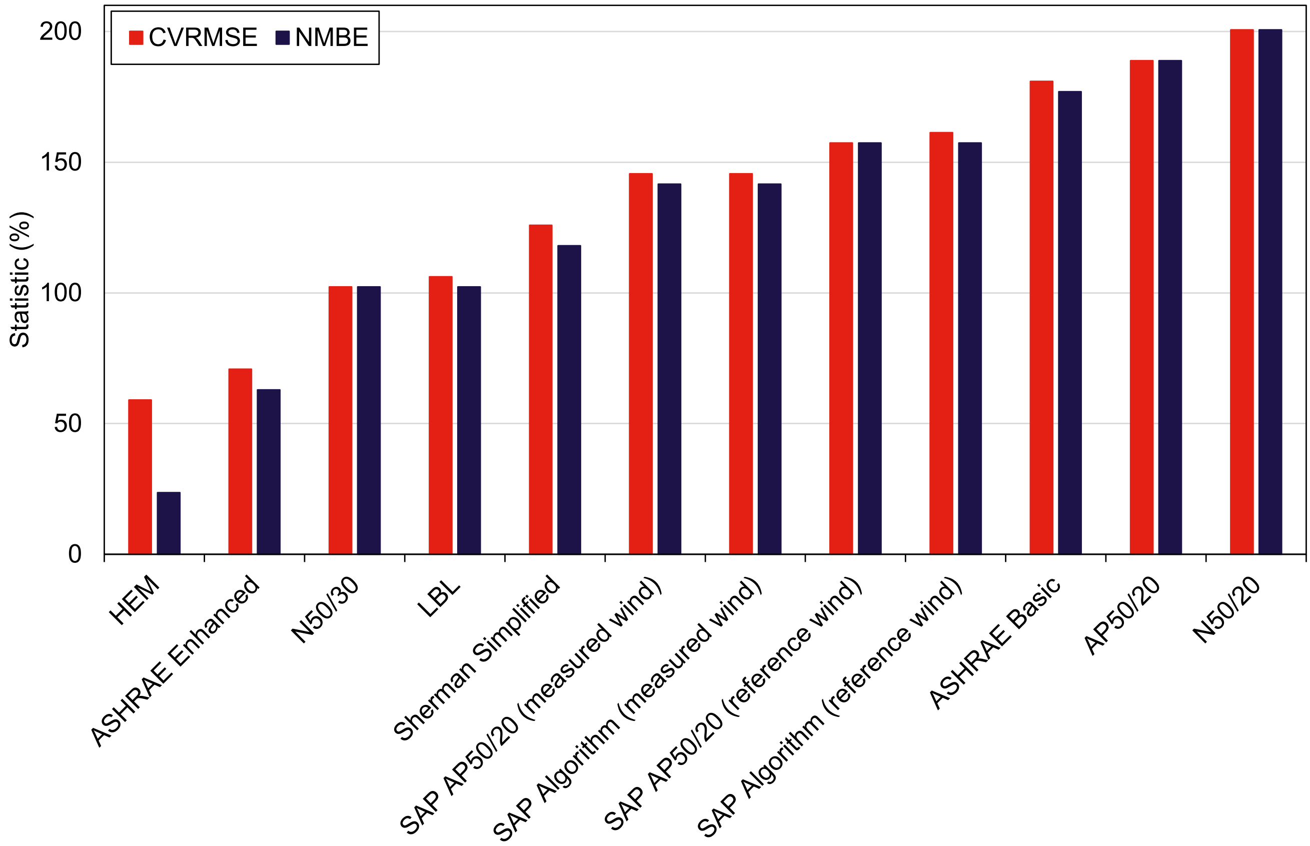

Figure 55: Bar chart of CVRMSE and NMBE for each infiltration estimation method. Ranked in ascending order from lowest CVRMSE value.

Does a method with more inputs achieve higher accuracy?

Statistical analysis of the relationship between the number of inputs to the method compared to the accuracy and precision of the infiltration estimation revealed no relationship between the two. Therefore, a method with more inputs does not achieve higher accuracy.

What inputs are most important to achieve reliable infiltration estimation?

By regressing the estimated infiltration rate against the measured infiltration rate for all 15 test cases it is possible to compare the estimated variation in infiltration rate with the measured values. It can be seen (Figure 6) that, as noted above, all the methods overestimate the infiltration rate and, of course, the three methods that simply scale the measured air tightness test value cannot reproduce any inter-test variability (thus the regression line is horizontal).

The other methods do provide an indication of the overall trend in the test values, with the two ASHRAE models, the LBL, and the Sherman Simplified methods indicating similar overall variability to measured values. These four methods include wind speed in their calculation method. Both SAP Algorithms and the HEM algorithm show a similar but less well-aligned inter-test trend in infiltration to the measured values. These methods too have wind speed as an input, but the HEM method does not include ΔT. The HEM regression line intersects the line of equality at around 0.35 ach on the x-axis (Figure 6) but the slope of the line is shallower than, e.g., the ASHRAE Enhanced model, indicating that when stack-driven infiltration dominates, predictions of infiltration are poorer with the HEM infiltration estimation method.

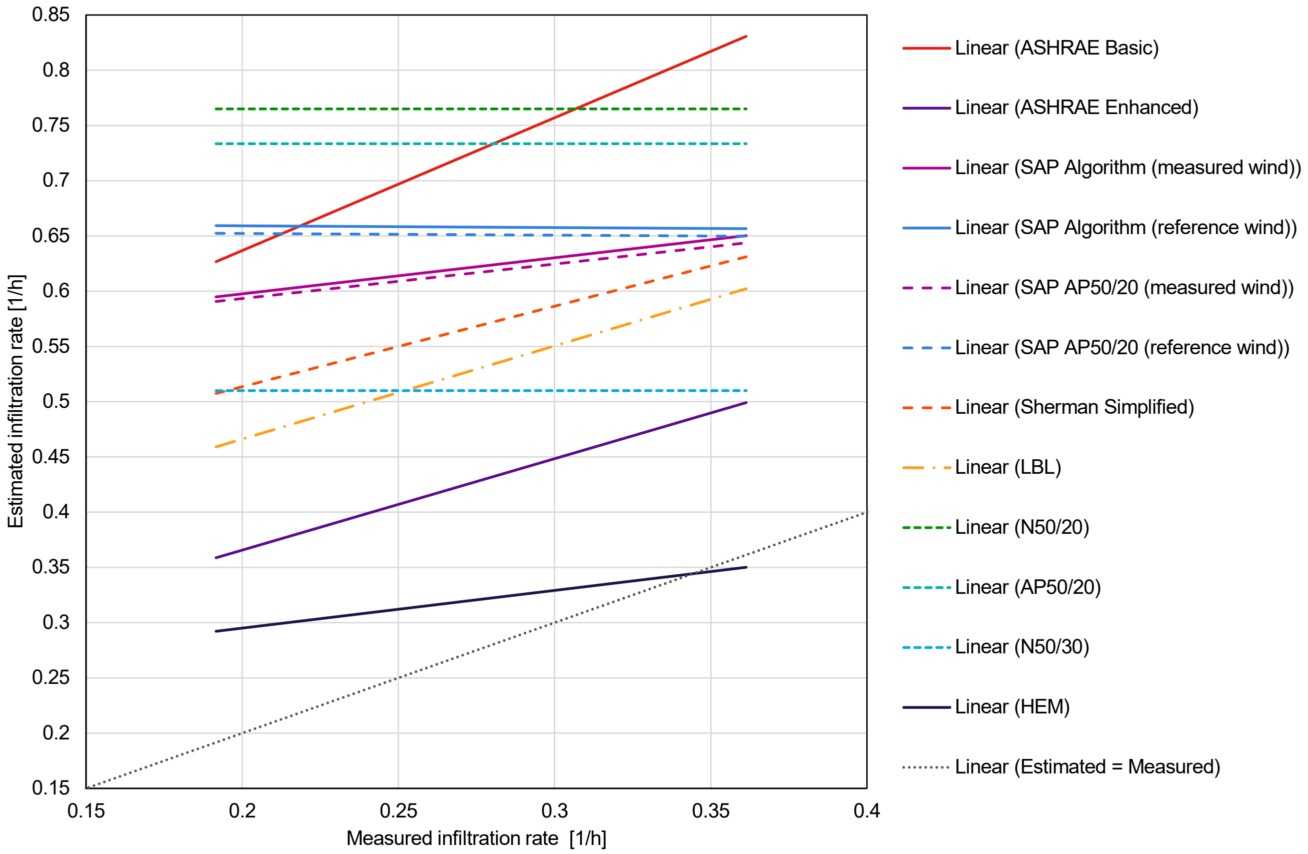

Figure 6: Regression lines for estimated infiltration rate against measured infiltration rate for all 15 tracer gas tests and equivalent infiltration estimation.

Discussion and conclusions

Improving the Home Energy Model (HEM) method

The analysis has shown that the total number of inputs to an infiltration estimation method does not, as least for the single dataset used, lead to a more accurate or precise estimate of infiltration. It is the inclusion of two key inputs, wind speed and the inside to outside temperature difference (ΔT), that is important for a reliable estimation of infiltration.

The HEM infiltration estimation method was, overall, the most accurate and precise estimator of measured infiltration in this single case study dwelling[25]. However, the correlation coefficient was considerably lower for the HEM method than for some other methods, which suggests that HEM estimates are perhaps not responding to boundary conditions as well as other models' estimates. The methods which had a higher correlation coefficient contained both the

[25] Additional case studies with multiple infiltration measurements under a variety of weather conditions are needed to improve the confidence in this result.

difference between indoor and outdoor temperature (ΔT) and wind speed as an input, whereas the HEM only includes wind speed.

When wind speeds are low, stack ventilation is the dominant driver of infiltration [23]. The highest measured infiltration rate coincided with the highest wind speed [2] and the HEM method regression line intersects the line of equality at 0.35 ach, where a wind-dominant regime was present. The HEM method deviated most from the measured values at lower infiltration rates where a stack-driven infiltration regime is likely to dominate. It is acknowledged that a possible weakness of the HEM model is not including stack ventilation [20] and that appears to be supported with this evidence.

The SAP algorithm

In this case study dwelling, it is interesting that the SAP algorithm method (which does not require a pressure test) was of similar accuracy and precision to the SAP method with a pressure test available. If sufficient information about a dwelling is available, then this method may be an ideal choice based on simplicity and cost. There is clear scope for improvement in terms of its reliability of infiltration estimation, however it should not be discounted due to the range of benefits a no-pressure-test method provides. Further study in a variety of dwelling types under a greater range of weather conditions is, of course, needed to increase the confidence in this conclusion.

Limitations

The Roberts et al. [2] dataset has several limitations, despite being among the highest quality currently available. Firstly, the measurements of infiltration were taken mainly in spring and summer, and so a narrow range of weather conditions surrounds the 15 tests. Secondly, all tests were done in a single house. Whilst this is useful to capture a range of weather conditions acting on the same building, it does not give the opportunity to test the methods in other building types. The other available dataset [4] also focused on similar building types (mainly semi-detached houses). New data are needed to explore the reliability of infiltration models on a diverse range of building types and weather conditions.

The infiltration estimation methods which required a pressure test result used a blower door test as input. An alternative method, the low-pressure pulse test, was not examined here. Additionally, the effect of inter-dwelling leakage, which is perhaps (pending further evidence) induced by a pressure test [12], was not accounted for as there is currently insufficient evidence to quantify the magnitude of such air leakage.

Several of the methods presented account for the use of openings that might be sealed during a pressure test but open during occupancy, and so better represent in-use infiltration. Such openings include chimneys, flues, and flueless gas fires. The effect of these could not be validated with the existing data. Other research has examined this, however [20].

Future work

There is a lack of infiltration data from across the variety of dwellings in the UK housing stock, and indeed from countries other than England. Future studies must do multiple tests, under different weather conditions, in a variety of dwelling types. With such data, the existing infiltration estimation methods can be further empirically validated.

As both the blower door test and the low-pressure pulse test are authorised under UK building regulations, these should both be used to derive estimations of infiltration in further work.

Quantifying the effect of infiltration rate on summertime overheating and wintertime heating demand

Introduction

This section addresses Objective 2.3: Quantify the effect of infiltration on heating energy demand and overheating using a steady-state and dynamic thermal model, which relates to RQ4. To quantify the effect of infiltration on overheating and heating demand, a parametric study was conducted under both steady-state (SAP[26]) and dynamic conditions (EnergyPlus[27]). A steady-state energy model was built using SAP to predict heating energy demand. A dynamic thermal model was built using EnergyPlus to predict heating energy demand and overheating. In each of the models the infiltration rate was varied from 0 ach to 1 ach at 0.1 ach increments to investigate how changing the infiltration rate changed the heating demand or predicted overheating in the models. An infiltration rate of 0.25 ach was measured in summer [2]. The heating season infiltration rate was unknown, but would be expected to be ~0.75 ach. A value as low as 0 ach or as high 1 ach would not be expected in either summer or winter, but this exercise is purely a sensitivity analysis to see how the models respond. The same case study dwelling was used for both models – the Loughborough Matched Pair test houses. These are the same test houses as used in the previous section on empirical validation.

Methodology

Case study for modelling

Two identical adjoining semi-detached two-storey houses in Loughborough, UK, served as the case study homes: the test houses. Built in the 1930s, they have south- and north-facing windows, external cavity brick walls, and ventilated suspended timber ground floors (except the kitchens, which are concrete). The test houses are described in full, with geometry and construction elsewhere [53,54].

Dynamic thermal model to predict overheating and heating energy demand

A model of the two test houses was created in EnergyPlus and calibrated against indoor temperature data measured in the test houses during July 2021 [61,62]. During this month, in the West house windows remained closed, and no internal gains were generated, while in the East house synthetic occupancy operated in line with CIBSE TM59 guidance [63] and windows were always open in the bedrooms and during occupied hours in the living room. A custom weather file was constructed utilising weather data collected at Loughborough University

[26] SAP 2009 (version 9.90).
[27] EnergyPlus (version 23.1).

during the period May to September inclusive, and data from the UK Met Office MIDAS database (Nottingham-Watnall weather station) for the remaining months of 2021. The calibrated model performed reasonably well in terms of predicting indoor air temperature with the coefficient of determination (R2 value) being up to 0.97 in the living room of the unoccupied house. For the parametric analysis, both houses were occupied and operated in line with TM59 including window opening [63]. In the dynamic thermal model the infiltration rate was varied from 0 ach to 1 ach at 0.1 ach increments in the occupied zones, while it remained unchanged in the unoccupied spaces (e.g. subfloors and roof spaces).

A zonal network method (the AirflowNetwork (AFN) in EnergyPlus) was used to predict infiltration/ventilation. Since the aim of this parametric study was to investigate the impact of infiltration on overheating and heating demand, the AFN was replaced with simple infiltration/ventilation objects where infiltration could be varied in a controlled manner. The "Zoneinflitration:DesignFlowRate" object (which accepts scheduled values) was with respect to infiltration. For the unoccupied zones (i.e. subfloors and roof spaces), the average infiltration rate over 2021 predicted by the AFN in the calibrated model was ascribed to the model. The average infiltration yielded to 6 ach (subfloors) and 8 ach (unoccupied roof spaces). Ventilation due to open windows was predicted through the "Zoneventilation:WindandStackOpenArea" object which estimates ventilation as a function of windows' area, orientation, and schedule of windows' operation, as well as wind speed and direction. Heating demand was predicted using the "HVACTemplate:ZoneIdealLoadsAirSystem" object; heat is added or removed at 100% efficiency. The thermostat setpoint was a constant 20°C in the living room, kitchen, and all three bedrooms. There was no heating in the dining room, hall, landing, and bathroom.

Overheating was assessed in line with CIBSE TM59 [63]; living rooms, kitchens, and bedrooms were assessed against Criterion A, and bedrooms were also assessed against Criterion B.

Criterion A: Sum of hours that $\Delta T \geq 1°C$ is less than 3% of occupied hours[28] between May to September inclusive; this criterion is applicable to living-rooms, kitchens and bedrooms.

Criterion B: sum of hours that $T_{op} > 26°C$ is less than 1% of annual hours between 22:00 and 07:00; this criterion is applicable only to bedrooms in order to assess sleep quality.

Where,

$\Delta T = T_{op} - T_{max}$.

T_{op} is the operative temperature of the assessed room.

$T_{\mathrm{max}} = 0.33T_{rm} + 21.8$.

T_{rm} is the weighted running mean temperature; an exponential equation where days that are closer to the present day have a greater impact on it.

[28] Living rooms and kitchens are assumed to be occupied between 09:00 and 22:00, and bedrooms 24 hours per day.

The heating performance was assessed by computing the annual heating demand[29] for the winter period defined in SAP (October to May inclusive).

Steady-state model to predict heating energy demand

The heating energy demand was also assessed in accordance with SAP 2009 (version 9.90) using a spreadsheet developed by the Building Energy Research Group at Loughborough University [64]. Again, the dwelling's geometry and construction were taken from existing sources [53,54]. Infiltration was varied in the same way as in the EnergyPlus model by altering the SAP effective air change rate at 0.1 ach increments between 0 and 1 ach[30]. The temperature setpoint was the SAP default according to room type. The mean whole house setpoint was equal to 17.9°C while the corresponding value in the dynamic model was 20.0°C.

Results

Dynamic thermal model

Overheating

Figure 7 shows how the outcome of the overheating assessment against Criterion A and B varies with infiltration rate in the East house (TM59 occupied with window opening). The increase of infiltration alleviates overheating in all rooms. For example, overheating reduces from 21.9% (0 ach) to 5.5% (1 ach) in the living room (Figure 7). Similarly, overheating reduces from 11.0% (0 ach) to 3% (1 ach) in the front bedroom (Figure 8).

The outcome of the assessment remains unchanged in most cases: for all infiltration rates the threshold value is exceeded. An exception to this observation is the kitchen and rear bedroom assessed under Criterion A (Figure 7) where the assessment is passed when infiltration rate gets equal or exceeds 0.7 ach (rear bedroom) and 0.9 ach (kitchen). It can also be observed in both figures that the rate of overheating reduction is exponential.

[29] Infiltration modifies the SAP heat transfer coefficient, which then impacts the heat loss used to calculate the heating demand.
[30] This hypothetical range of values was investigated by modifying the effective air change rate in the SAP model spreadsheet. SAP predicts heat loss using effective air change rate, rather than infiltration rate. However, this required the effective air change rate to be overridden because SAP assumes a minimum effective air change rate of 0.5 ach. The overridden effective air change rate in SAP is referred to as infiltration in this report.

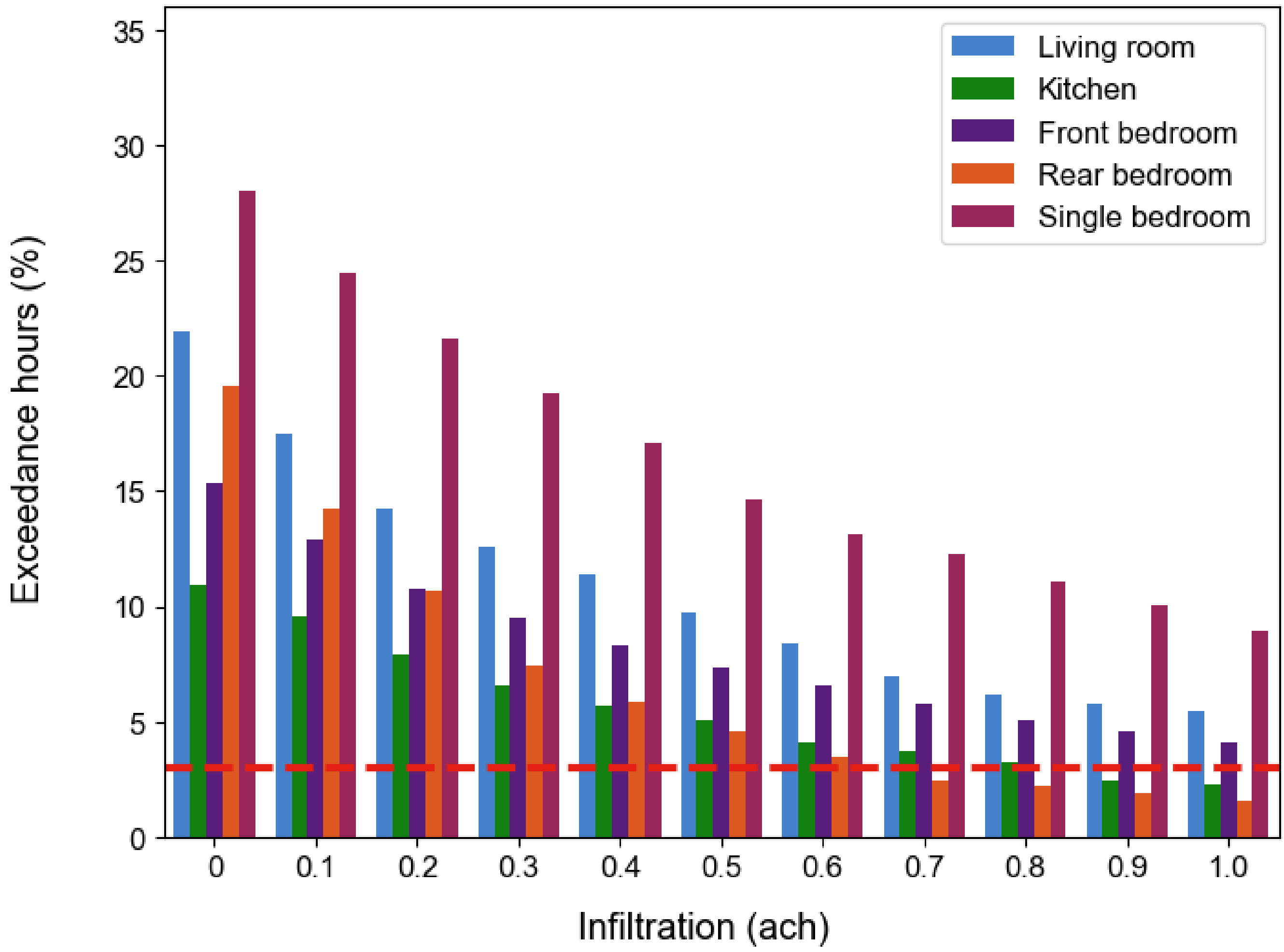

Figure 76: Modelled overheating assessment in East House (TM59 window opening and internal heat gains) for various infiltration rates against TM59 Criterion A. The mean measured infiltration rate in the case study dwelling during summer was 0.25 ach.

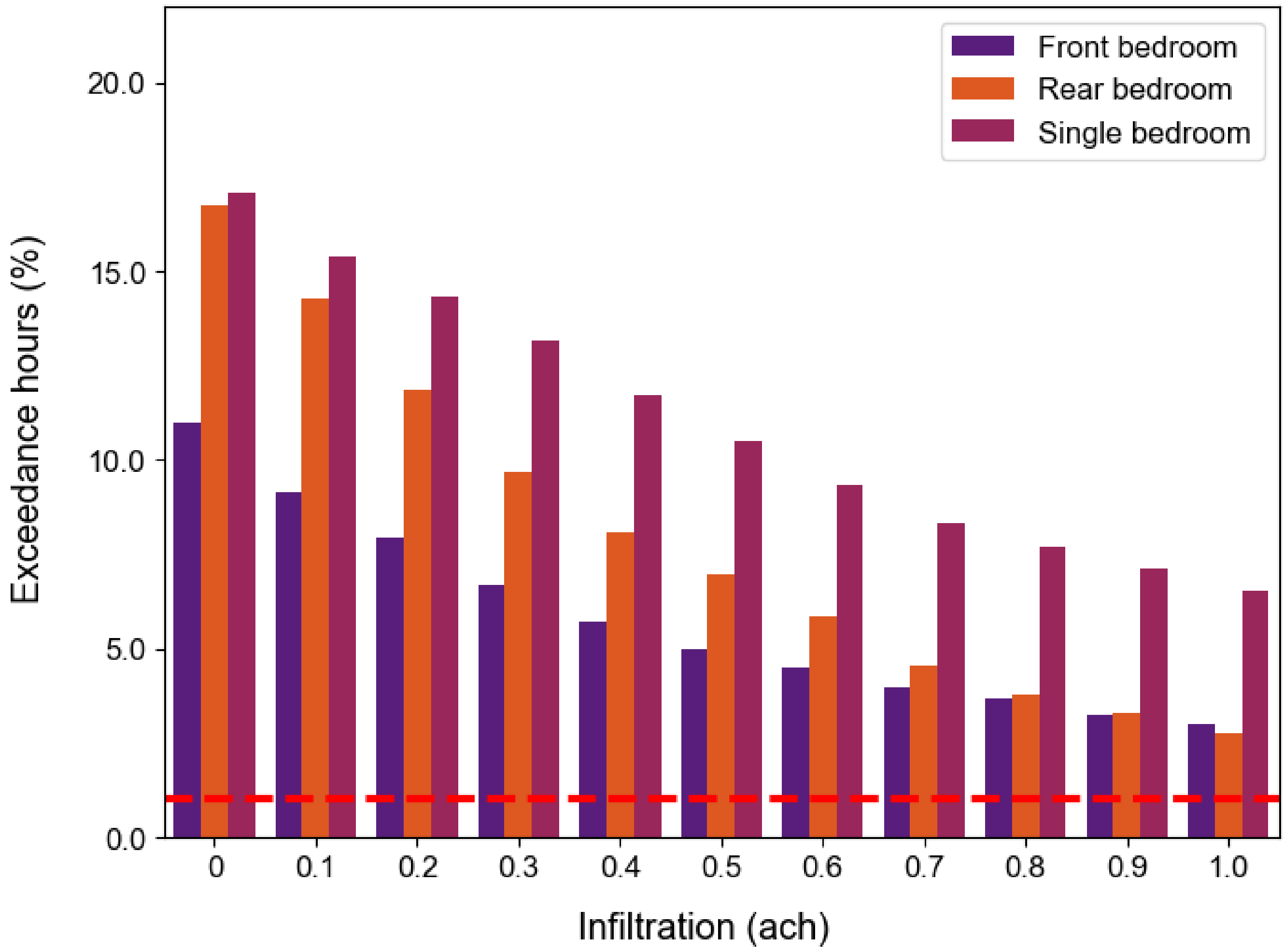

Figure 87: Modelled overheating assessment in East House (TM59 window opening and internal heat gains) for various infiltration rates against TM59 Criterion B. The mean measured infiltration rate in the case study dwelling during summer was 0.25 ach.

Heating energy demand

Figure 9 shows how heating energy demand varies with infiltration in the EnergyPlus model. As expected, heating energy demand increases linearly as infiltration rate increases. To assess any impact of the infiltration in the subfloor and loft spaces (attics) on the heating energy demand, three scenarios were additionally assessed where infiltration values of 3 and 13 ach in the subfloors, and an infiltration rate of 3 ach in the roof spaces, were also tested. Figures 11-13[31] display these additional scenarios, but there is negligible difference heating energy demand. Very small differences are observed among these scenarios and hence, the infiltration rates assumed in the unoccupied zones exert marginal impact on the outcome of this assessment.

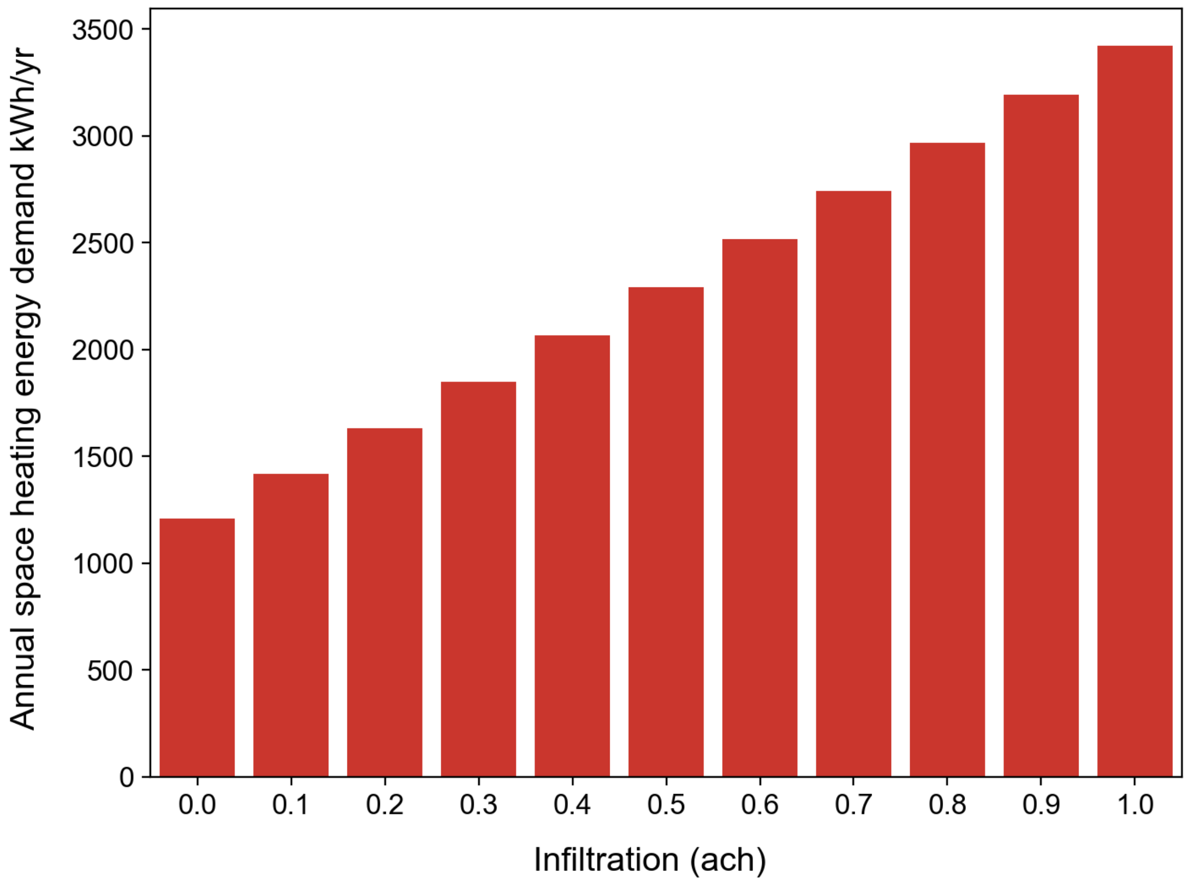

Figure 98: Modelled heating energy demand in the test house for various infiltration rates according to the EnergyPlus model. Infiltration rate is constant in the subfloors (6 ach) and roof spaces (8 ach). The mean measured infiltration rate in the case study dwelling during summer was 0.25 ach, but a higher infiltration rate of ~0.75 ach would be expected during the heating season.

[31] See Appendix 3.

SAP model

Heating energy demand

Figure 10 displays the variation of heating energy demand with infiltration rate utilising this time the SAP model. Although the two models (i.e., EnergyPlus and SAP models) are not directly comparable due to different boundary conditions (both external and internal) it is apparent from this figure that the SAP model is less sensitive to infiltration rate changes in comparison to the the EnergyPlus model.

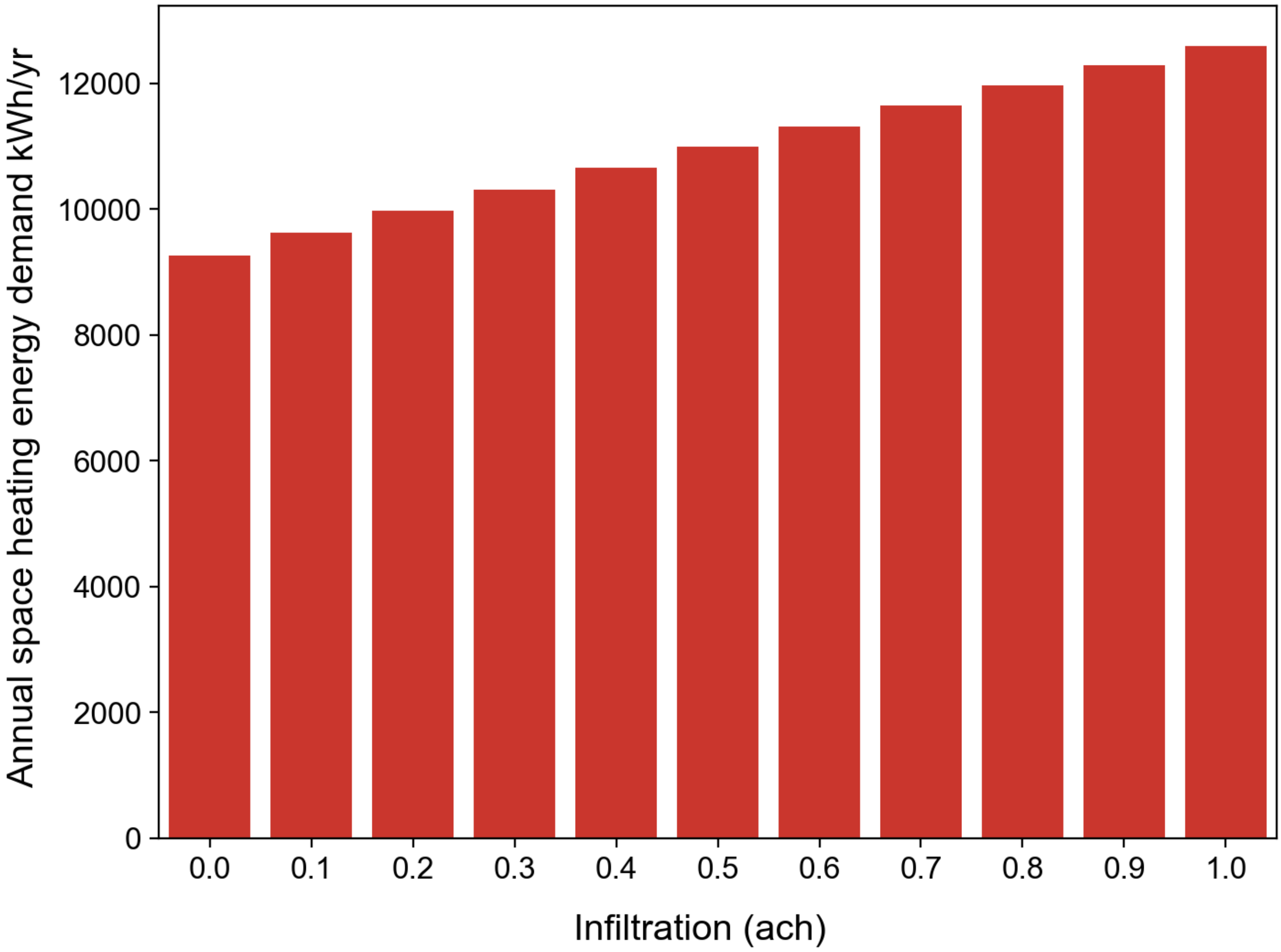

Figure 10: Modelled heating energy demand in the test house for various infiltration rates according to the SAP model. The mean measured infiltration rate in the case study dwelling during summer was 0.25 ach, but a higher infiltration rate of ~0.75 ach would be expected during the heating season.

Discussion and conclusions

Dynamic thermal model predictions of summertime overheating and wintertime energy demand of a calibrated model of a test house revealed overheating and heating demand to be influenced by infiltration rate. The incidence of overheating decreases as infiltration increases. The heating energy demand increases as infiltration increases. A steady-state model of the same test houses predicted heating demand with similar trends: increasing with infiltration.

Overheating

In the earlier section on empirical validation of infiltration estimation methods[32] it was shown that, under summertime weather conditions, infiltration was measured to be 0.25 ach and estimated by the divide-by-20 method to be 0.77 ach. To put this estimation error into the context of the effect on predictions of overheating, Criterion A overheating hours were reduced from 5.8 to 2.3% in a bedroom when the value of infiltration was increased from 0.3 ach (the measured infiltration rate) to 0.8 ach (as estimated by the divide-by-20 method). This means the house would be compliant with Building Regulations on Overheating (Part O) using the estimated infiltration rate, but not compliant if the real, measured, value for infiltration was used in the model[33]. Thus, incorrect estimation of infiltration in dynamic thermal models can allow a building to pass or fail depending on which method is used. Porritt [65] found a similar trend in dynamic thermal modelling of overheating. Increasing infiltration rate by 0.5 ach (from 0.5 to 1 ach) decreased overheating by 7%. It has previously been stated that modellers conducting overheating assessments “input infiltration into the [dynamic thermal] model and forget about it” [66]. On the basis of these findings, careful consideration should be given to the value of infiltration rate for overheating predictions, such as those for Part O Building Regulations compliance. An important caveat to note, however, is that Part O overheating compliance assessments would generally be conducted on dwellings which are considerably more airtight, and so have a lower infiltration rate, than the case studies used here. In a more airtight dwelling, the proportion of air entering a dwelling by infiltration would be less in relative terms than that via ventilation. This makes these types of models less sensitive to infiltration but makes it more important for the ventilation algorithms to respond reliably.

Heating demand

The increase in heating demand with increasing infiltration in the dynamic thermal model was greater in percentage terms than the increase in the steady-state model. The difference in heating demand at a continuous infiltration rate of 0 ach compared to 1 ach was 182% (1,211 to 3,422, range 2,211 kWh) in the dynamic model compared to 35% (9,269 to 12,599, range 3,330 kWh) in the steady-state, indicating that the dynamic thermal model was more sensitive to the effect of infiltration[34]. However, the dynamic and steady-state model are not directly

[32] See Section “Empirical validation and inter-model comparison of existing infiltration estimation methods” which starts on page 17.
[33] Note that CIBSE TM59 window opening routines were used in this case study.
[34] The range of the measured infiltration rate in this test house (during spring/summer weather conditions) was 0.17 ach. Whilst the winter infiltration rate is unknown at present, it is likely that the variation in infiltration rate in the real home would be considerably less than has been modelled.

comparable due to having different input assumptions and boundary conditions. Nonetheless, there is evidence to suggest that if input assumptions are kept similar, i.e., using a reduced data dynamic model and a reduced data steady-state model (e.g., RdSAP) there is a tendency to for the dynamic models to predict lower space heating demand than the steady-state models [67,68].

Equally, the changes in wintertime heating energy demand in Report 1 [69] should not be directly compared to the findings here for several reasons. Firstly, the analysis in this report focuses on a single case study dwelling whereas in Report 1 the entire GB housing stock is considered. Secondly, different weather (boundary conditions) was applied to the two models here and the analysis in Report 1 [12]. Thirdly, Report 1 varies airtightness[35], whereas Report 2 varies infiltration rate. Fourthly, the values listed in Report 1 pertain to heating energy demand due to infiltrative losses, whereas Report 2 is total heating energy demand.

[35] Although infiltration is captured in the underlying equation.

Improving the SAP infiltration estimation method

This section addresses RQ3: How should the SAP methodology for estimating infiltration rates be changed or improved?

Improving methods and models

The sources of error in infiltration estimation methods are several and include uncertainties that are present regardless of weather conditions: the flow equation, leakage at the reference pressure (4 or 50 Pa[36]), and shape of leakage characteristic, i.e., the size and shape of openings [70]. Also, uncertainties that scale according to the weather conditions: pressure coefficient, wind speed, air temperature, leakage distribution (walls), leakage distribution (ceilings), neglect of pressure fluctuations [70]. Wind is turbulent and causes fluctuating infiltration rates [71] and so any point-in-time measure of infiltration rate may be affected by this and is difficult for a single-zone infiltration estimation method to predict.

Although Etheridge [70] states that the wind speed introduces uncertainty into estimation of infiltration, it is likely that exclusion of this input altogether is more damaging to estimation method reliability, as shown in this report. Infiltration rate is inherently linked to wind speed, indoor-outdoor temperature difference [72], and to the degree of wind sheltering [73]. Any method which does not account for this is at a disadvantage, e.g. the divide-by-20 method.

Several infiltration estimation methods, including that used in SAP [31] and the proposed HEM method [20], do not account for indoor or outdoor temperature. This could be problematic because when wind speeds are below 3.5 m/s, infiltration occurs almost entirely due to indoor-outdoor temperature difference only [49]. The HEM proposal acknowledges this limitation and instead suggests a nodal infiltration model whereby each airflow path is considered independently, and a mass balance equation principle applied to derive an internal pressure from which infiltration rate can be determined [20]. Feustel and Kendon [74] state that single zone infiltration estimation methods, such as SAP and HEM, will be less reliable as they do not account for airflows within the dwelling. The trade-off is that more complex, multi-zonal models come with greater data input requirements and computation time [75]. As methods become more complex, they require greater numbers of geometric inputs [48]. This may not be a significant additional undertaking if these are already being collected for the HEM model.

Jones et al. [75,76] criticise estimation methods that do not account for inter-dwelling air leakage, which further decreases their reliability. In other work, Jones et al. [15] suggest the notion of infiltration-leakage *relationships* – not ratios – as more useful ways to estimate infiltration.

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[36] This reference pressure would depend on which of the two pressure tests authorised for use in UK compliance testing is used; 4 Pa for the low-pressure pulse test and 50 Pa for the fan pressurisation (blower door) test.

Improving airtightness testing for infiltration estimation

When airtightness is measured for UK Building Regulations compliance testing, a dwelling is prepared by closing purpose provided ventilation openings (e.g. windows and trickle vents with a flap closure) and sealing other purpose provided ventilation openings that cannot be closed (e.g., extractor fans, chimney flues, passive vents such as airbricks, and trickle vents without a flap closure). This is called Method 3 in BS EN ISO 9972:2015 [77] and CIBSE TM23 [78], Method B by the Air Tightness Testing and Measurement Association (ATTMA) [79] and the “closed” method by the American Society for Testing and Materials (ASTM) [80].

This may be a useful way to test the as-built or post-retrofit performance of a building, to detect the integrity of the airtightness barriers, and to highlight issues mid-construction that should be rectified before completion. However, it is apparent that there is often a difference between the conditions under which airtightness (sealed) is measured compared to infiltration (unsealed).

This issue has been noted in the literature, e.g. [19], and this act is likely to decrease the reliability of infiltration estimated from pressure tests. To overcome this issue, the SAP method [31] includes amendments to increase airflow depending on the number and type of openings that are sealed in a pressure test, but unsealed when a building is in-use. Any uncertainties in these input data and the airflows they account for will alter the reliability of the estimation.

The BS 40101 on Building Performance Evaluation suggests that where infiltration is to be estimated from a pressure test, the test should be performed without the usual sealing required for compliance testing [81]. The ASTM E1827−11 standard similarly encourages airtightness tests to be performed in “occupied” mode by default if there is not a compelling reason[37] to choose the “closed” method [80]. A simple improvement could simply to be that airtightness tests are undertaken under the same conditions that infiltration is being estimated for.

A previous review has shown that evidence indicates that seasonal variation, degradation over longer time periods, and inter-dwelling air leakage affects airtightness, but the effect has not yet been quantified [12]. Airtightness is not a single, unchanging value. This, therefore, affects the reliability of infiltration from a pressure test. Quantifying these effects could improve estimation method reliability, especially in attached dwellings[38] (inter-dwelling air leakage) and if airtightness is measured in one season and infiltration is estimated in another (seasonal variation).

[37] Such as Building Regulations compliance testing.
[38] Attached dwellings could include semi-detached and terraced houses and bungalows, and flats.

Report summary

RQ1: What is the divide-by-20 rule of thumb and how is it used?

The divide-by-20 rule of thumb is a leakage-infiltration ratio which converts a pressure test result (at 50 Pa) into a value for infiltration rate. It provides a single average value for heating season infiltration rates. It forms the basis for other single zone infiltration estimation methods such as SAP and LBL. It is the most used single zone infiltration estimation method. Most estimation methods of this type are used as an input for overheating modelling, based on the number of academic studies published. This may differ in practice.

RQ2: What are the limitations of the divide-by-20 rule?

The simplicity of the divide-by-20 rule of thumb is a blessing and a curse. It is easy and quick to implement, but is not a reliable predictor of a single point-in-time infiltration rate, and is often misused outside of its intended purpose as a low-precision heating season average estimate. Further research into the matter is needed. Available datasets for empirical validation are scarce and do not capture a diverse range of dwelling types, locations, and weather conditions. Under summer weather conditions in a typical English semi-detached two-storey house, the divide-by-20 was the least accurate and least precise infiltration estimation method with a mean bias error of 0.51 ach. The proposed Home Energy Model (HEM)[39] method was the most accurate, with a mean bias error of 0.06 ach. However, the HEM method was less accurate at lower wind speeds, when the dominant driving for of infiltration is the stack effect (related to indoor-outdoor temperature difference and dwelling height). An important limitation of this work was that only a single case study dwelling was used and the variations in weather across the test were atypical of the winter heating season for which the infiltration estimation methods were designed to operate.

RQ3: How should the SAP methodology for estimating infiltration rates be changed or improved?

The answer is not necessarily increasing the number of model inputs. Rather inclusion of the most influential inputs. For the divide-by-20 method, this is wind speed, and has been done via the Sherman Simplified method. The HEM infiltration estimation model could be improved with the inclusion of ΔT to account for the stack effect, which is the dominant driving force of infiltration at low wind speeds, to improve the reliability of this model, which otherwise performed well in terms of accuracy and precision against a measured infiltration rate.

[39] The consultation version was used in this analysis.

Infiltration estimation methods were historically designed to predict mean wintertime (heating season) infiltration rates. However, they are now frequently used for overheating modelling. The influence of infiltration on overheating has been demonstrated. Future infiltration estimation method development needs to be suitable for estimating annual infiltration.

RQ4: How does infiltration impact heating energy demand and overheating in steady-state and dynamic thermal models?

Steady-state and dynamic thermal model predictions for wintertime energy demand are influenced by infiltration rate. Both models predicted that the heating energy demand increased as infiltration increased. The dynamic thermal model was more sensitive to changes in infiltration rate but ultimately predicted a lower annual space heating energy demand than the steady-state model. Whilst the steady-state and dynamic models should not be directly compared, there is evidence from the literature to suggest that dynamic models have a tendency to predict lower heating demands than steady-state models when the model inputs are tightly controlled and matched [67,68].

Dynamic thermal modelling of summertime overheating using a calibrated model of two test houses revealed that the incidence of overheating was sensitive to infiltration rate. Criterion A overheating hours were reduced from 5.8 to 2.3% in a bedroom when the value of infiltration was increased from 0.3 ach (the measured infiltration rate) to 0.8 ach (as estimated by the divide-by-20 method). This means the house would be compliant with Building Regulations on Overheating (Part O) using the estimated infiltration rate, but not compliant if the real, measured, value for infiltration was used in the model. Thus, incorrect estimation of infiltration in dynamic thermal models can allow a building to pass or fail depending on the method used.

Further work

The following further work is suggested, and is discussed in more detail in Report 4 [82].

- Creation of a dataset which allows for empirical validation of infiltration estimation methods, including those used in SAP and proposed for HEM, which captures a diverse range of dwelling types, locations, and weather conditions.
- Development of a series of leakage-infiltration relationships (not necessarily ratios) for various dwelling types which account for seasonal variation.
- Quantification of the extent and effect of inter-dwelling air leakage using a field trial and experiments in a full-scale test facility during a blower door test, low pressure pulse test, and normal conditions (ambient pressure differences). This would allow policymakers to understand how stock level airtightness (see [12]) relates to stock level infiltration (currently estimated with large uncertainty) and so make more accurate estimates of potential changes to energy demand with more airtight dwellings.
- Quantification of the difference between airtightness and infiltration as measured with vents sealed and unsealed in a range of dwellings.

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Appendices

Appendix 1: Studies using infiltration estimation methods

Table 44: Studies using different air infiltration estimation methods group by topic and method used. Adapted and added to from Roberts et al. [2]**.**

Reference	Topic	Method used
[83]	Energy performance evaluation	Divide-by-20
[84]	Mechanical ventilation	BREDEM reduction
[85]	Airtightness	Divide-by-20
[86]	Emissions modelling	Minimum IAQ standard
[87]	Mechanical ventilation	Divide-by-20
[88]	Infiltration	Divide-by-20
[89]	Overheating modelling	BREDEM reference
[90]	Energy performance evaluation	Divide-by-20
[91]	Overheating modelling	Dwelling age *
[92]	Overheating modelling	Dwelling age *
[93]	Overheating modelling	BREDEM reference
[94]	Overheating modelling	Dwelling age *
[95]	Overheating modelling	Dwelling age *
[96]	Overheating modelling	SAP reduction
[97]	Heating controls	Divide-by-20
[98]	Overheating modelling	SAP reduction
[99]	Infiltration	Divide-by-20
[100]	Infiltration and ventilation heat loss	Divide-by-20
[101]	Infiltration and ventilation heat loss	ASHRAE Basic †
[102]	Overheating modelling	SAP reduction
[103]	Overheating modelling	SAP reduction
[104]	HTC testing	Divide-by-20
[105]	Overheating modelling	Estonian building regulations
[106]	Energy performance evaluation	Sherman Simplified ‡
[107]	Airtightness	SAP reduction
[108]	Energy modelling	Divide-by-20
[109]	Infiltration and ventilation heat loss	Divide-by-20
[110]	Overheating modelling	CIBSE Guide B §
Continued overleaf		

[111]	Overheating modelling	CIBSE Guide A ‖
[112]	Overheating modelling	SAP reduction
[66]	Overheating modelling	Divide-by-20
[113]	Energy modelling	CIBSE Guide A
[114]	HTC testing	SAP reduction
[115]	Thermal comfort modelling	Sherman Simplified ‡ ¶

Note: Excludes studies which use the methods for comparison/validation purposes.

* Using guidance from [116].

† [25]

‡ [55]

§ [117]

‖ [56]

¶ In this case derived from low-pressure pulse test, not the fan pressurisation test as the Sherman Simplified method was originally tested on [55].

Appendix 2: Tabular summaries of overheating assessments

Table 5: East house overheating exceedance hours with constant infiltration in subfloor (6 ach) and roof spaces (8 ach) – TM59 Criterion A. Shaded boxes indicate a value that is higher than the overheating threshold value of 3%.

Infiltration (ach)	Overheating exceedance hours (% of total hours)				
	Living room	Kitchen	Front bedroom	Rear bedroom	Single bedroom
0	21.9	11	15.4	19.6	28
0.1	17.5	9.6	12.9	14.3	24.5
0.2	14.3	7.9	10.8	10.6	21.6
0.3	12.6	6.5	9.5	7.5	19.2
0.4	11.4	5.7	8.3	5.8	17.1
0.5	9.7	5	7.4	4.6	14.7
0.6	8.4	4.1	6.6	3.5	13.1
0.7	6.9	3.7	5.8	2.5	12.2
0.8	6.1	3.2	5.1	2.2	11.1
0.9	5.8	2.4	4.5	1.9	10
1.0	5.5	2.3	4.1	1.6	9

Table 6: East house overheating exceedance hours with constant infiltration in subfloor (6 ach) and roof spaces (8 ach) – TM59 Criterion B. Shaded boxes indicate a value that is higher than the overheating threshold value of 1%

Infiltration (ach)	Overheating exceedance hours (%)		
	Front bedroom	Rear bedroom	Single bedroom
0	11	16.7	17.1
0.1	9.1	14.2	15.4
0.2	7.9	11.8	14.3
0.3	6.7	9.6	13.2
0.4	5.7	8.1	11.7
0.5	5	6.9	10.5
0.6	4.5	5.8	9.3
0.7	4	4.6	8.3
0.8	3.7	3.8	7.7
0.9	3.3	3.3	7.1
1.0	3	2.8	6.5

Appendix 3: Graphs of heating energy consumption with different assumptions of subfloor and loft space ventilation

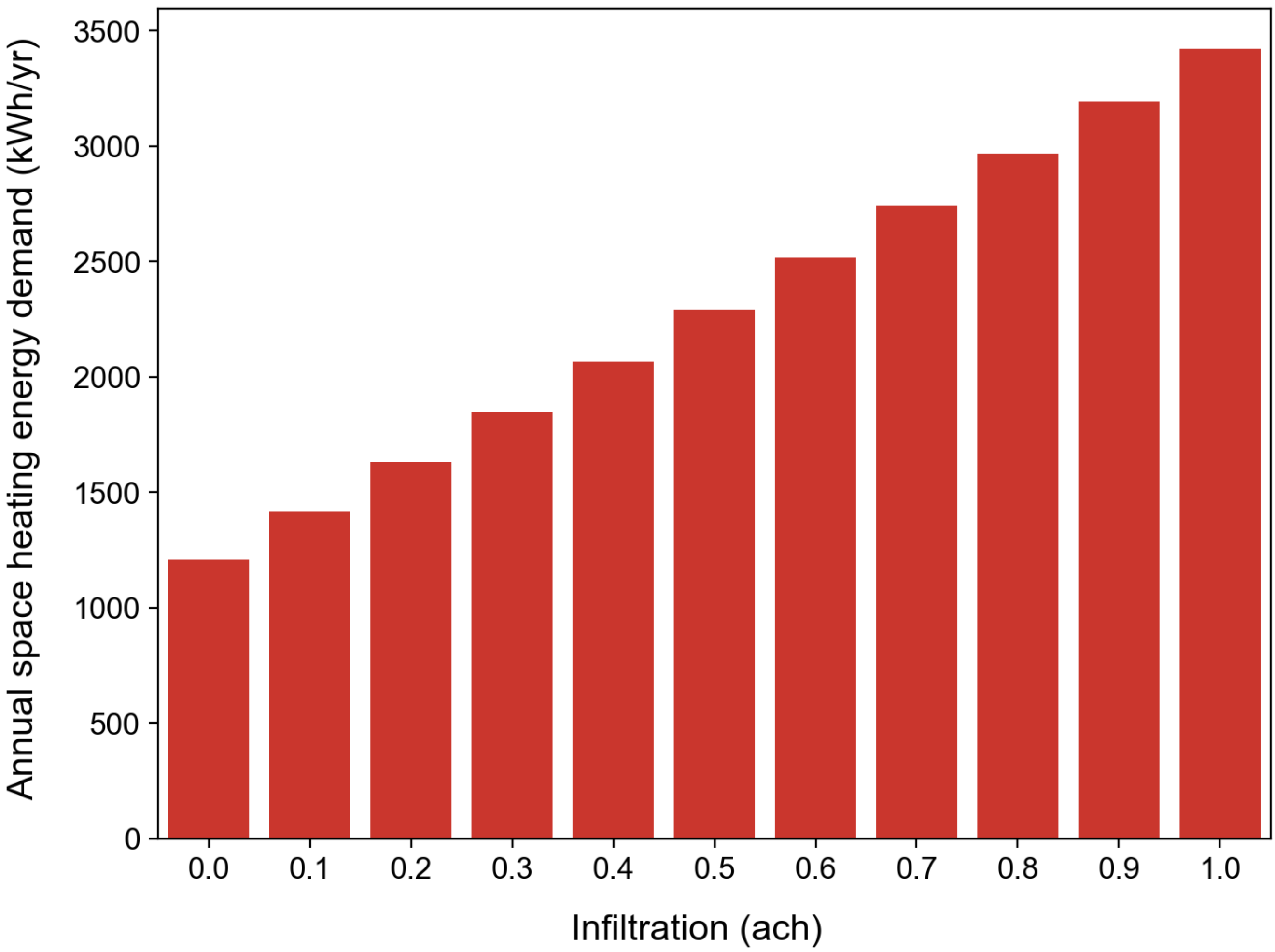

Figure 119: Modelled heating energy demand in the test house for various infiltration rates according to the EnergyPlus model. Infiltration rate is constant in the subfloors (3 ach) and roof spaces (8 ach).

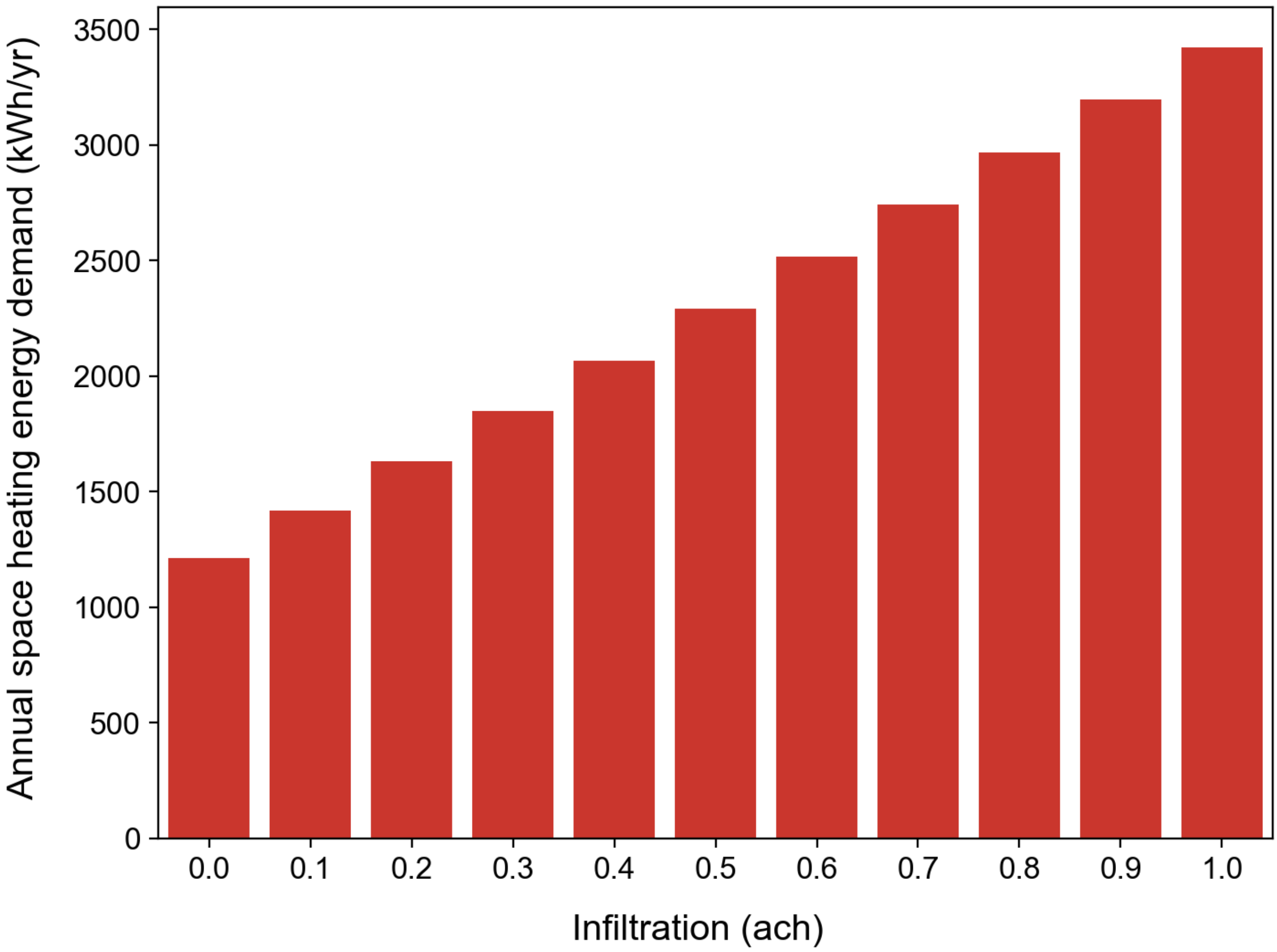

Figure 1210: Modelled heating energy demand in the test house for various infiltration rates according to the EnergyPlus model. Infiltration rate is constant in the subfloors (6 ach) and roof spaces (3 ach).

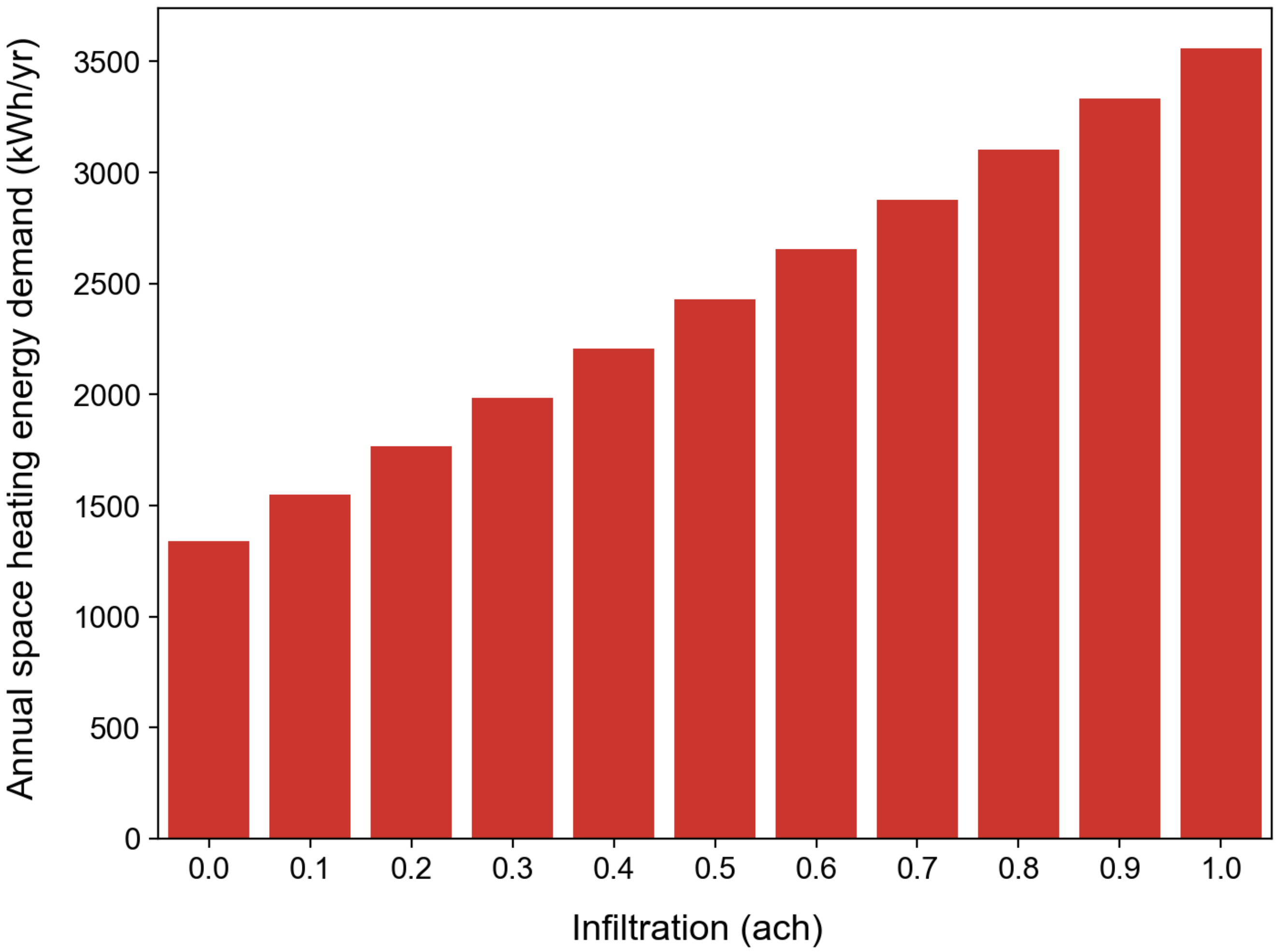

Figure 1311: Modelled heating energy demand in the test house for various infiltration rates according to the EnergyPlus model. Infiltration rate is constant in the subfloors (13 ach) and roof spaces (8 ach).

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