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Building airtightness impact on Energy Performance (EP) calculations

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1 Introduction

The energy demand in the building sector is steadily increasing with the world population, the level of desired indoor comfort and the time spent inside buildings, reaching between 20% and 40% of energy consumption in developed countries [1]. This sector has therefore an active role to play in the efforts towards a reduction of the global energy demand.

The energy performance (EP) of a building is the total annual energy consumption of this building, including in particular the heating, cooling and ventilation loads. In some countries an estimation of the EP is calculated prior to the building construction to check the conformity with national requirements. In particular, the European Energy Performance of Buildings Directive (EPBD) introduced in 2002 and revised in 2018 obliges the EU Member States to describe a national building energy performance (EP) calculation methodology.

As it is now a well-known fact that air leakage can significantly impact the building energy performance [2] [3] [4], more and more countries are introducing requirements or recommendations on new buildings' airtightness level [5]. The airtightness performance indicator differs from one country to another, as well as the criteria to determine the airtightness threshold values with for example the type of ventilation systems in Germany; the type of dwellings (single- or multi-family) in France; the compactness of the dwelling in Spain or the climate zone in the USA [6].

One way to encourage good practice and good airtightness levels in new or retrofitted buildings is to include the air infiltration in the EP calculation, with for example penalizing default values (see the example of Belgium paragraph 3.1). The energy loss due to infiltration is calculated based on the envelope air leakage rate and the temperature difference between the inside and the outside, and poor airtightness can jeopardize the possibility to comply with the global energy performance requirements.

For a given building and at a given point in time t, an accurate calculation of the infiltration flow rate under natural operating conditions (q_{inf}) would require to determine the precise distribution of pressure across the envelope (Δp_i depending in particular on the wind, the mechanical ventilation, and the temperature difference) as well as a precise leakage distribution and characterization of each leak i (flow coefficient C_i and flow exponent n_i):

$$q_{inf} = \sum_i C_i \times \Delta p_{i,t}^{n_i} \qquad (1)$$

However, in practice:

- the leakage distribution and the characterization of each leakage path are usually not known: the airtightness is estimated/measured for the whole building envelope;
- the airtightness is usually estimated/measured for a pressure difference of 50 Pa across the envelope whereas the operational pressure difference is rather between -10 and +10 Pa;
- the exact pressure distribution on the envelope, due to wind and stack effect is not known.

As a result, many simplified models have been developed and are used around the world to estimate the infiltration rate for EP calculations, with different levels of accuracy, as described below. For example, the wind velocity can be estimated hourly, monthly or annually; based on the local climate or fixed estimated values; with or without taking into account shielding factors; etc.

The objective of this VIP is to explain these simplified models and give some examples of methodologies applied in various countries.

2 Building airtightness in national energy performance calculations

In countries with Energy Performance (EP) calculations for new and/or retrofitted buildings, the envelope airtightness can be taken into account in various ways described below, and listed in ascending order of accuracy but descending order of simplicity. The model type chosen to estimate the air infiltration rate can also depend on the methodology implemented for the EP calculations, as it may be preferable to have similar levels of simplification.

2.1 *Building airtightness not included in the energy performance calculations*

The building envelope airtightness is not always an input for the EP calculations. In some countries this parameter is not taken into account, as in Switzerland, Sweden (see paragraph 3.1) or in New Zealand for two out of the three methods of compliance (see paragraph 3.2).

2.2 *Leakage-Infiltration Ratio (LIR)*

The first studies attempting to estimate the annual infiltration rate under natural operating conditions (q_{inf} in m^3/h) from the building's airtightness level usually obtained by pressurization tests date back to the 70s. In particular, studies from Kronvall and Persily on Swedish and US homes led to the broadly used "rule of thumb" correlating the air leakage rate at 50 Pa, and the so-called infiltration rate under natural operating conditions [7] [8] (see equation (2). This type of simple linear relationship is called a leakage-infiltration ratio (LIR) [9], expressed here as the ratio between the air change rate by leakage at 50 Pa (n_{50} in h^{-1}) and by infiltration under natural conditions (n_{inf} in h^{-1}).

$$n_{inf} = \frac{n_{50}}{20} \qquad (2)$$

With

$$n_{inf} = \frac{q_{inf}}{V_{int}} \qquad (3)$$

A few years later, Sherman developed a similar model for single-family houses in North America [10], still assuming a linear correlation between the air change rate at 50 Pa and under natural conditions, but replacing the constant coefficient of 20 by an empirical correction factor N:

$$n_{inf} = \frac{n_{50}}{N} \qquad (4)$$

Where N depends on several parameters: local climate, wind shielding, dwelling height and size of air leakage paths.

A study from Dubrul on extensive measurements performed in several European Countries [11], published shortly after, states that the dividing coefficient (N in equation (3)) ranges between 10 and 30. He estimates that a value of 20 can be "regarded as typical", with a lower coefficient in case of high-rise buildings, strong wind exposure and/or uniformly distributed leakage area, and a higher coefficient in case of individual terraced houses, low wind exposure and/or leakage area mainly at high level.

The calculation of a fixed infiltration rate based on a leakage-infiltration ratio is sometimes applied in national building EP calculations. For example:

- In Belgium, v50 (air leakage rate at 50 Pa, divided by the heat loss area) is divided by 25 (see paragraph 3.3)
- In Finland, the leakage-infiltration ratio depends on the number of floors, ranging from 35 for one-floor buildings down to 15 for buildings with five or more floors (see paragraph 3.4)

This infiltration rate is then used to estimate the building steady-state infiltration heat loss, usually applied in semi-steady state calculation methods.

However, one should note that it is a very simplified model for a complex reality [12]. Although it may perform well in yearly average [13] and be useful to have an order of magnitude of infiltration airflow rates, it has fundamental shortcomings since it poorly reflects the influence of critical boundary conditions, in particular, the climate data, building geometry and exposure to wind, as well as the leakage distribution. Jones et al. underline the significant limitations of such leakage-infiltration ratios for English apartments and recommend to limit their use to quick estimations [9].

2.3 *Simple Infiltration Models (SIM)*

In an attempt to improve the estimation accuracy of LIR, some simple infiltration models (SIM) take into account other time-dependent parameters in the calculation. For example, Ng et al. have incorporated the effects of weather, building characteristics and system operation and found infiltration rates in good agreement with the multizone airflow CONTAM simulations (Equilibrium Pressure Model (EPM) calculation, see paragraph 2.4**Error! Reference source not found.**) of v arious types of commercial buildings [14]. Fülöp and Polics have also elaborated a method to calculate the natural infiltration rate based on pressurization test by taking the temperature difference and the wind speed into account [15].

In the EP calculations, simplified models are also sometimes used to estimate the infiltration rate with more accuracy than with a simple leakage-infiltration ratio, but more easily than with an equilibrium pressure model (EPM). For example:

- In the United Kingdom, the leakage-infiltration ratio used is 20 (as in equation (2)), but with monthly correction factors to account for the wind fluctuations (see paragraph 3.7).
- In the United States, the International Energy Conservation Code (IECC) includes stack and wind coefficient in the calculation (see paragraph 3.5).

2.4 *Equilibrium Pressure Model (EPM)*

2.4.1 Approach

A more accurate approach than SIM consists in using an equilibrium pressure model, with the pressure calculated by a mass balance equation. Calculations are performed at a defined time step (dynamic infiltration rate), often hourly, and require an estimation of the pressure and leakage distribution on the building's façades. The fact that the positions of the cracks are unknown in reality make the results still uncertain. The underlying physics behind the airflow models is identical to that used in network airflow models developed in the 1980s and 1990s (such as AIRNET and CONTAM). Nabinger and Persily have proven that, with this method, predictions were in fairly good agreement with the air change rates measured with the tracer gas method [16]. However, this method is also more cumbersome to employ as it requires defining many input parameters and solving an implicit equation to determine the internal pressure. The European standard EN 16798-7:2017 [17] is detailing a calculation methodology, as explained below.

2.4.2 Calculation methodology of standard EN 16798-7

The European Standard EN 16798-7:2017 [17] is part of the set of Energy Performance of Buildings (EPB) Standards which provides a methodology to calculate overall energy performance of buildings supporting the EPB

Directive of the European Union. EN 16798-7 describes two methods to calculate the building ventilation air flow rates for energy performance calculations, heating and cooling loads (for buildings lower than 100 m):

- **Method 1** estimates the air flow rates based on the detailed building characteristics. The model used is the equilibrium pressure, that is to say with the pressure calculated by a mass balance equation, with the sum of all in and out flowing ventilation mass flowrates ($q_{m;V}$) that equals to 0 for each zone (SUP: supply; ETA: extract; comb: combustion appliances; pdu: passive and hybrid duct; arg: airing; vent: vents; leak: leakage):

$$q_{m;V;SUP;dis} + q_{m;V;ETA;dis} + q_{m;V;comb;in} + q_{m;V;comb;out} + q_{m;V;pdu;in} + q_{m;V;pdu;out} + q_{m;V;arg;in} + q_{m;V;arg;out} + q_{m;V;vent;in} + q_{m;V;vent;out} + q_{m;V;leak;in} + q_{m;V;leak;out} = 0 \qquad (5)$$

  Default values can be used for some inputs. In particular, the leakage and opening distributions can have a significant impact, and default values for these distributions can reduce the data collection time and the variations in results.

- **Method 2** specifies the rules to apply a national statistical approach for the air flowrates estimations (including infiltrations). It can be based on the calculations of Method 1 or on measurements. The idea is to provide national data as input for simplification. A statistical analysis is however required to prove the good correlation between the input and output data and the relevance of the methodology.

Method 1 has the advantage of providing more accurate results, while Method 2 is simpler to use. Each European country can choose which method is allowed depending on the local climate, building traditions and user behavior.

2.5 Comparison between SIM and EPM calculations

Happle et al. have estimated the impact of the air infiltration calculation method on the energy demand [18]. They applied two simplified modeling techniques on 24 Swiss buildings of various functions:

- A SIM calculation: static infiltration rate with fixed air change rate (from DIN 1946-6:2009 [19]):

$$q_{inf} = f_{system} \times V_{int} \times n_{50} \times \left(f_{location} \times \frac{\Delta p_{dim}}{50}\right)^{n} \qquad (6)$$

  where $f_{system} = 0.5$, $f_{location} = 1$, $n = 0.66$; a design differential pressure $\Delta p_{dim} = 5$ Pa is suggested for a multi-storey building shielded from wind (DIN 1946-6).
- An EPM calculation: dynamic calculation based on wind pressure and air temperatures, with the infiltration rate calculated according to an iterative procedure described in EN 16798-7.

They concluded that the model choice can drastically affect the energy demand in the individual building level. As illustrated in Figure 1, the annual heating demand was reduced with the EPM for all buildings but one, with an average reduction of 11.6% and a maximum reduction of 65%.

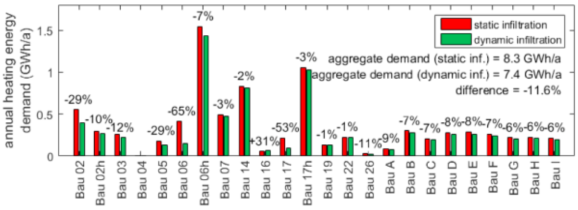

Figure 1 : Annual heating energy demand of buildings simulated with the static and the dynamic infiltration calculation model [18]

3 National examples

In order to illustrate the building airtightness impact on EP calculations, examples of methodologies applied in various countries are detailed in this chapter. The information was mostly collected through papers of the AIVC VIP series on building and ductwork airtightness trends in various countries available at the time of writing (for Spain, Belgium, Czech Republic, France and USA). It was completed by information found in the literature (for the Finnish case) and from other contributors (for UK, New Zealand, Sweden) in order to have a larger number of examples covering all types of models presented in the previous chapter.

The examples are given in the same order as their model in Chapter 2, that is to say in an ascending order of complexity.

Please note that for ease of reading, some national symbols of airtightness indicators have been modified to be consistent throughout this paper. The correspondence with the symbols used in the official national regulations is given in Appendix A (Table A.1)

3.1 *Sweden – Not an input*

In Sweden there are requirements on envelope airtightness, as a part of the requirements for new buildings (building permissions, based on EPBD), and by professional building owners related to renovation projects. However, Energy Performance Certificates are based on measured energy performance and do not use airtightness test values.

For the design phase of new buildings, the building regulation document (BBR) recommends to use standardized input data for climate, building operation, and user behavior from the Swedish program for standardizing and verifying energy performance in buildings (SVEBY), which are average values based on surveys and measurements. The compliance with the energy use requirements should be verified through energy metering afterwards [20].

3.2 *New Zealand – Not included/constant parameter*

3.2.1 Context

In the New Zealand Building Code (NZBC), the outcomes are achieved via performance rather than prescription. Regarding "Energy efficiency", Clause H1 provides ways to establish compliance with the performance requirements. Clause H1, article H1.3.1 states that "The building envelope enclosing spaces where the temperature or humidity (or both) are modified must be constructed to (a) provide adequate thermal resistance; and (b) limit uncontrollable airflow". There is, however, no specific target for the level of airtightness.

Currently, pressurization tests are mainly performed as part of the certification process for passive houses. In 2021, the New Zealand Green Building Council recommended including blower door tests for high-performing dwellings like Homestar levels 9 and 10 [22]. The New Zealand Superhome Movement is also advocating including a blower door test. There is also a government push to build more energy-efficient homes in New Zealand: "The Ministry of Business, Innovation and Employment is monitoring other aspects that impact energy efficiency and a building's internal environment, and will work to resolve any issues in future Building Code updates such as airtightness and thermal bridging."

3.2.2 Airtightness in the energy performance calculation

Under the acceptable solutions/verifications methods scheme (compliance route), there are three methods demonstrating compliance to Clause H1:

1) The Schedule Method is providing minimum construction R-values ($m^2.K/W$) for the six NZ climate zones. This method is applicable under specific conditions on the glazing, skylight and opaque door areas (e.g. glazing areas less than 30% of total wall area).
2) The Calculation Method is based on heat loss equations. This method compares the proposed building to a reference building (insulated following R-value from the Schedule method). To comply, the heat losses of the proposed building must be lower than the heat losses of the reference building. "This calculation method should only be used where glazing area is 40% or less of total wall areas" (H1/AS1).
3) The Modelling Method refers to the use of building energy analysis computer programs as cited in the ANSI/ASHRAE Standard 140 test: ESP-r, Energy Plus, TRNSYS, etc. (reference documents: H1/VM1 for housing and buildings no greater than 300 m^2; H1/VM2 for large buildings). This is a more detailed hourly calculation of the space heating and cooling loads, considering the climate data representing an average year for the site. The results are compared with a reference building of the same shape, dimensions, and orientation as the proposed building. H1/VM1 document states that "*infiltration assumptions for the proposed building and the reference building shall be the same, and shall be reasonable for the building construction,*

location, and use" (H1/VM1). This modelling method involves additional expertise in building energy analysis software and will therefore not be the preferred choice if one of the 2 other methods could be used.

Out of the three proposed methods to demonstrate compliance with the NZBC requirement, the modelling method is the only one that takes into account the airtightness. However, despite a detailed hourly modelling, this is done very roughly with a constant lumped parameter for air exchange in H1/VM1, including both deliberate mechanical ventilation and natural infiltration. The protocol typically assumes a value of 0.5 ACH for this total air exchange rate. Depending on the building, this value can differ, but 0.5 ACH must be used for dwellings. As a result, there is no incentive to reduce air leakage from a compliance perspective.

H1/VM2 allows infiltration to be accounted for. However, the reference building and proposed building shall have the same leakage assumption.

Historically, a lookup table has been used to convert airtightness results to infiltration for modelling purposes using the Annual Loss Factor (ALF) online tool[1]. This did give credit via the building performance index. However, it has been removed from the compliance path in the 5th edition of H1, effective in 2022.

3.3 *Belgium - LIR*

3.3.1 Context

In Belgium, there is no requirement on the minimum airtightness level for new buildings, but the airtightness value is used for the Energy Performance Calculation of the building (E-level). Airtightness testing is strongly encouraged as the default value is very disadvantageous if no test is performed.

In Flanders, one of the three Belgium regions, since January 2018 there is a requirement on the global performance of the building envelope (S-level, taking into account thermal insulation, airtightness, solar gains, etc.). Consequently, airtightness testing has become implicitly mandatory for every new residential building, as using the default airtightness value would jeopardize the chance to comply with this requirement.

More information on building airtightness trends and requirements in Belgium are given in [21].

3.3.2 Airtightness in the energy performance calculation

The airtightness indicator used in the context of Energy Performance Regulation in Belgium is the average of the measured leakage flow at 50 Pa for pressurization and depressurization, divided by the heat loss area A_T (m²), based on the exterior dimensions, and in accordance to the Regulation[2] ($q_{E50,av,ext}$ in m³/(h·m²)). When only the pressurization or depressurization test was in accordance with the regulation (eg. baseline higher than 5Pa, r^2 too low, …), the indicator can be calculated based on the compliant test including a correction factor and the report needs a motivation.

As part of the Energy Performance Calculation, the monthly ventilation heat losses are obtained by multiplying the ventilation heat transfer coefficient by the length of the relevant month and by the difference between the monthly average indoor temperature and the monthly average outdoor temperature. One part of this ventilation heat transfer coefficient is related to in- and exfiltration. The in- and exfiltration flow [m³/h] is calculated as:

$$q_{inf} = \frac{q_{E50,av,ext} \times A_T}{25} \quad (7)$$

According to research, this leakage-infiltration ratio of 25 depends on the wind exposure, but was chosen as an average, conservative value for the built environment in Belgium. If no conform airtightness measurement is available for $q_{E50,av,ext}$, the default values of 12 m³/(h·m²) for heating and 0 m³/(h·m²) for cooling shall be used. This value was based on the average

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[1] ALF 4.0: https://alf.branz.co.nz/

[2] https://www.energiesparen.be/epb-pedia/regelgeving/ministeriele-besluiten/bijlagen20070402#bijlage6

$q_{E50,av,ext}$ value of dwellings in the nineties according to the SENVIVV research[3].

A list of reference documents regarding the regulation in the three Belgium regions and for both residential and non-residential buildings is provided in [21].

3.4 Finland - LIR

According to a publication from Dessalegne and Bhattarai in 2018 [24], in the 2010 version of the Finnish code of building regulations D3 [25], the infiltration rate q_{inf} (m^3/h) is calculated using the following formula:

$$q_{inf} = \frac{q_{E50}}{x} A \quad (8)$$

Where:

- q_{E50} is the average air leakage rate of the building envelope at 50 Pa ($m^3/(h \cdot m^2)$)
- A is the area of the building envelope (base floor included) (m^2)
- X is a floor coefficient (-): 35 for buildings with one floor, 24 for buildings with two floors, 20 for buildings with three and four floors, and 15 for buildings with five or more floors.

The authors are not aware of a potential change in the infiltration rate estimation for the EP calculations in Finland since 2018.

There is no requirement for building airtightness, it is only recommended in part C3 of the national building code to have an air change rate at 50 Pa (n_{50}) close to 1 ACH to guarantee a proper functioning of the ventilation [26].

3.5 USA – Not included/SIM

3.5.1 Context

In the United States, all buildings have to meet the energy code requirements adopted by the cognizant local authority. The International Energy Conservation Code (IECC) is developed nationally and adopted by most States with regional specificities, but there are other model energy codes implemented such as the California Building Standards Commission's Title 24 or the NYC Energy Conservation Code (NYCECC). Most jurisdictions use a prescriptive approach and do not model energy use.

3.5.2 The International Energy Conservation Code (IECC)

Regarding airtightness, the IECC sets an upper limit for leakage: 3 ACH50 (air changes per hour at 50 Pa) except in a few very mild locations where 5 ACH50 is allowed.

The IECC has several compliance paths. The main ones are:

- Prescriptive: No energy calculation is required. Component performance is specified (e.g., insulation levels or window and equipment minimum performance specifications).
- Total Building Performance: Uses an energy calculation (hourly for a year) comparing a proposed design to the prescriptive design. This allows some flexibility while maintaining energy performance.
- Energy Rating Index: Uses the Residential Energy Services Network (RESNET) calculation procedures where a home is compared to a 2006 code compliant home to generate an energy rating index that must be below a value specified according to the climate zone (ranging from 51% to 55%). The hourly air exchange rate for the year is calculated using the models in the ASHRAE Handbook of Fundamentals (HoF) for natural infiltration, and combined with mechanical systems using ASHRAE 62.2.

In RESNET:

If a home does not have whole house mechanical ventilation, the infiltration rate is based on measured envelope leakage using the following equations (but not less than 0.3 ACH).

Natural infiltration should be calculated using the enhanced or simplified model from ASHRAE HoF[4] (in either case the stack and wind components are combined in quadrature).

- Basic model:

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[3] https://www.wtcb.be/publicaties/wtcb-rapporten/04/

[4] It is stated that natural infiltration should be calculated from "ASHRAE HoF 2013, Page 16.25, Equation 51" but the equation reference and page numbers are incorrect. As a result, it is unclear which of the two models should be used.

$$q_{inf} = \frac{A_L}{1000}\sqrt{C_s|\Delta T| + C_w U^2} \qquad (9)$$

Where:

- q_{inf} : infiltration airflow rate (m^3/s)
- A_L: effective air leakage area, which is the result of the airtightness pressurization test (cm^2)
- C_s: stack coefficient - function of the number of stories ($(L/s)^2/(cm^4 \cdot K)$)
- ΔT: average indoor-outdoor temperature difference for time interval of calculation (K)
- C_w: wind coefficient - function of the number of stories and assuming shelter class 4 ($(L/s)^2/[cm^4 \cdot (m/s)^2]$)
- U: average wind speed measured at local weather station for time interval of calculation (m/s)

- Enhanced model:

$$q_s = cC_s \Delta T^n \qquad (10)$$

$$q_w = cC_w (sU)^{2n} \qquad (11)$$

Where:

- q_s: stack airflow rate (m^3/s)
- q_w: wind airflow rate (m^3/s)
- c: flow coefficient ($m^3/(s \cdot Pa^n)$)
- C_s: stack coefficient - function of the number of stories, w/wo flue ($(Pa/K)^n$)
- C_w: wind coefficient - function of the number of stories, w/wo flue ($(Pa \cdot s^2/m^2)^n$)
- s: shelter factor –assuming shelter class 4
- U: average wind speed measured at local weather station for time interval of calculation (m/s)
- ΔT: indoor-outdoor temperature difference (K)
- n: pressure exponent

If a home does have a whole house mechanical ventilation system, the mechanical rate and natural infiltration are combined in quadrature. The mechanical ventilation system flow rate is calculated according to ASHRAE 62.2 (2013):

$$q_{fan} = 0.15 \text{ x } A + 3.5\,(B + 1) \qquad (12)$$

Where:

- q_{fan}: total mechanical ventilation air flow (l/s)
- A: floor area (m^2)
- B: number of bedrooms (-)

For the IECC Energy rating index, the older ASHRAE 62.2 (2010) calculation is used for the mechanical ventilation air flow rate calculation (coefficient on the floor area of 0.05 instead of 0.15) of the reference case, and the specified air flow rate for the home being rated. It is added to the natural infiltration rate using 2001 ASHRAE HoF for intermittent mechanical ventilation. Natural infiltration can be calculated using any of the methods in the ASHRAE HoF as no date or version is given.

3.5.3 The California Building Standards Commission's Title 24

In California there is no requirement for air tightness levels and no mandatory testing, however, the energy code alternative compliance manual uses a multizone combined house/duct airflow network in an hourly energy calculator.

There are prescriptive and software simulation paths to compliance, they both have the same ventilation air flow requirements.

The energy simulation software must be approved by the California Energy Commission. There is an approval process where the software has to provide similar annual energy use as a standardized calculation.

It uses the current ASHRAE 62.2 (2022) method for total ventilation rate (q_{tot}) calculations, which is the sum of the infiltration (q_{inf}) and the fan (q_{fan}) rates. Infiltration rate is based on an annual average calculation:

$$q_{inf} = 0.052 \times q_{50} \times wsf \times \left[\frac{H}{H_r}\right]^{0.4} \qquad (13)$$

Where:

- q_{50}: envelope air leakage rate at 50 Pa from a blower door test (cfm) - limited to not being less than the q_{50} assuming an envelope leakage of 2 ACH_{50} (total air leakage rate, not divided by the surface area)

- wsf: weather and shielding factor (-) (listed in Table 150.0-D of the CEC 2022 Building Energy Efficiency Standard)
- H: vertical distance between highest and lowest above grade points (ft)
- H_r: reference height – 8.2 ft (2.5 m)

The wsf factor is a single annual number, which is correct for an IAQ approach (right effective ventilation rate) but not for energy calculations, as discussed by Turner et al.[23].

The mechanical fan flow sizing then uses the same calculation as current ASHRAE 62.2:

$$q_{fan} = q_{tot} - F\left(q_{inf} \times A_{ext}\right) \qquad (14)$$

Where:

- F = 1 for balanced ventilation systems and Q_{inf}/Q_{tot} otherwise (-)
  A_{ext}: 1 for single-family detached homes, or the ratio of exterior envelope surface area that is not attached to garages or other dwelling units to total envelope surface area (-)
- For multifamily dwelling units $q_{fan} = q_{tot}$.

3.6 *Spain-SIM*

3.6.1 Context

In Spain the energy use and demand of buildings (for both new construction and retrofitting) are regulated by the CTE DB-HE 2019, with recent updates introducing requirement of near-zero-energy buildings.[5]

Since 2019 there is a requirement on the permeability of the envelope for private residential buildings greater than 120 m². The airtightness performance indicator used is the air change rate at a reference pressure difference of 50 Pa, n_{50} [h^{-1}], and the limit values are given depending on the Volume/Area ratio:

- $n_{50} \leq 6\ h^{-1}$ for $V/A \leq 2$
- $n_{50} \leq 3\ h^{-1}$ for $V/A \geq 4$
- limit n_{50}-value for V/A between 2 and 4 can be obtained by interpolation

More information on building airtightness trends and requirements in Spain are presented in [27].

3.6.2 Airtightness in the energy performance calculation

The official unified tool LIDER/CALENER (HULC), or other accepted tools which use the same calculation method, is used to verify the requirements established by regulations (DB HE0 and HE1) and to certify the energy performance of buildings.

The airtightness of the thermal building envelope[6], according to annex H of DB HE1, can be calculated in two ways:

1) Based on pressurization test measurement (according to Method 2 of standard ISO 9972:2019).
2) Estimated according to the building´s parameters together with reference values provided by the regulations:

$$n_{50} = 0.629 \times \frac{C_0 \times A_0 + C_h \times A_h}{V_{int}} \qquad (16)$$

Where:

- n_{50} is the calculated air change rate at 50 Pa [h^{-1}];
- C_0 is the airflow coefficient of the opaque part of the thermal envelope at a reference pressure of 100 Pa [$m^3/(h{\cdot}m^2)$]. Reference values are assigned depending on the assumed airtightness of the building. For new or existing buildings with improved airtightness, C_0 is 16 $m^3/(h{\cdot}m^2)$ whereas for existing buildings a value of 29 $m^3/(h{\cdot}m^2)$ is assumed;
- A_0 is the sum of areas of the opaque thermal building envelope [m^2];
- C_h is the permeability of doors and windows in the thermal building envelope at a reference pressure of 100 Pa [$m^3/(h{\cdot}m^2)$]; threshold levels of maximum permeability are provided depending on the winter climatic area ranging from ≤ 9 to ≤ 27 [$m^3/h\ m^2$] which correspond to

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[5] https://www.planup.eu/en/resources/policies/cte_db_he_2019_(building_technical_regulations/_energy_savings)_%5bspain%5d/901

[6] The thermal building envelope consists of the building parts with heat exchange with the outdoor air. Therefore, internal partitions in contact with adjacent indoor spaces or buildings as well as parts of the envelope in contact with soil, are excluded.

those defined in EN 12207:2017 for classes 3 and 2 respectively.

- A_h is the sum of the area of the doors and windows of the thermal building envelope $[m^2]$.
- V_{int} is the internal volume within the thermal building envelope $[m^3]$. It can be estimated in a simplified way by removing the volume of floor slabs from the volume within the thermal envelope.

Regarding the global energy performance of the building, a dynamic model is applied considering hourly climate data. However, in the case of air infiltration, a simplified calculation method is performed, considering the mean infiltration rate through the envelope calculated in particular with the following parameters:

- two values of wind speed of 0 and 4 m/s
- pressure coefficients: +0.25 for windward façade; -0.50 for downwind façade; -0.60 for roofs (with angle with vertical <= 60°)
- exposure to wind: by default, 50% windward surface; 50% downwind surface
- flow coefficient (n) for both the infiltration through the opaque part and doors and windows: 0.5 for big openings like air inlets and 0.67 for small openings like cracks.
- airflow coefficient (C) for the infiltration through the opaque part (C_o) and doors and windows (C_h): default values given above or alternative values justified,
- ventilation design rate.

More details can be found in Section 6 of [28], and in particular in Table 14 of section 6.6.

3.7 *UK- SIM*

3.7.1 Context

In the UK, the Government's Standard Assessment Procedure (SAP) is followed for the Energy Performance Calculation of dwellings. Since June 2022, the fan pressurization method is no longer the only approved method for measuring the air permeability of dwellings as the low-pressure pulse method is included in the updated SAP 10.2.

3.7.2 Airtightness in the Energy Performance Calculation

The infiltration rate is used in the energy performance calculations to estimate the total ventilation rate, and can be calculated by three different ways (see section 2.3 of SAP 10.2):

1) If a pressurization test is performed: a leakage-infiltration ratio of 20 is used to estimate the air infiltration rate at typical pressure differences (n_{inf} in h^{-1}) from the air permeability at 50 Pa (q_{E50} in cubic meters per hour per square meter of envelope area, floor included):

$$n_{inf} = \frac{q_{E50}}{20} \qquad (17)$$

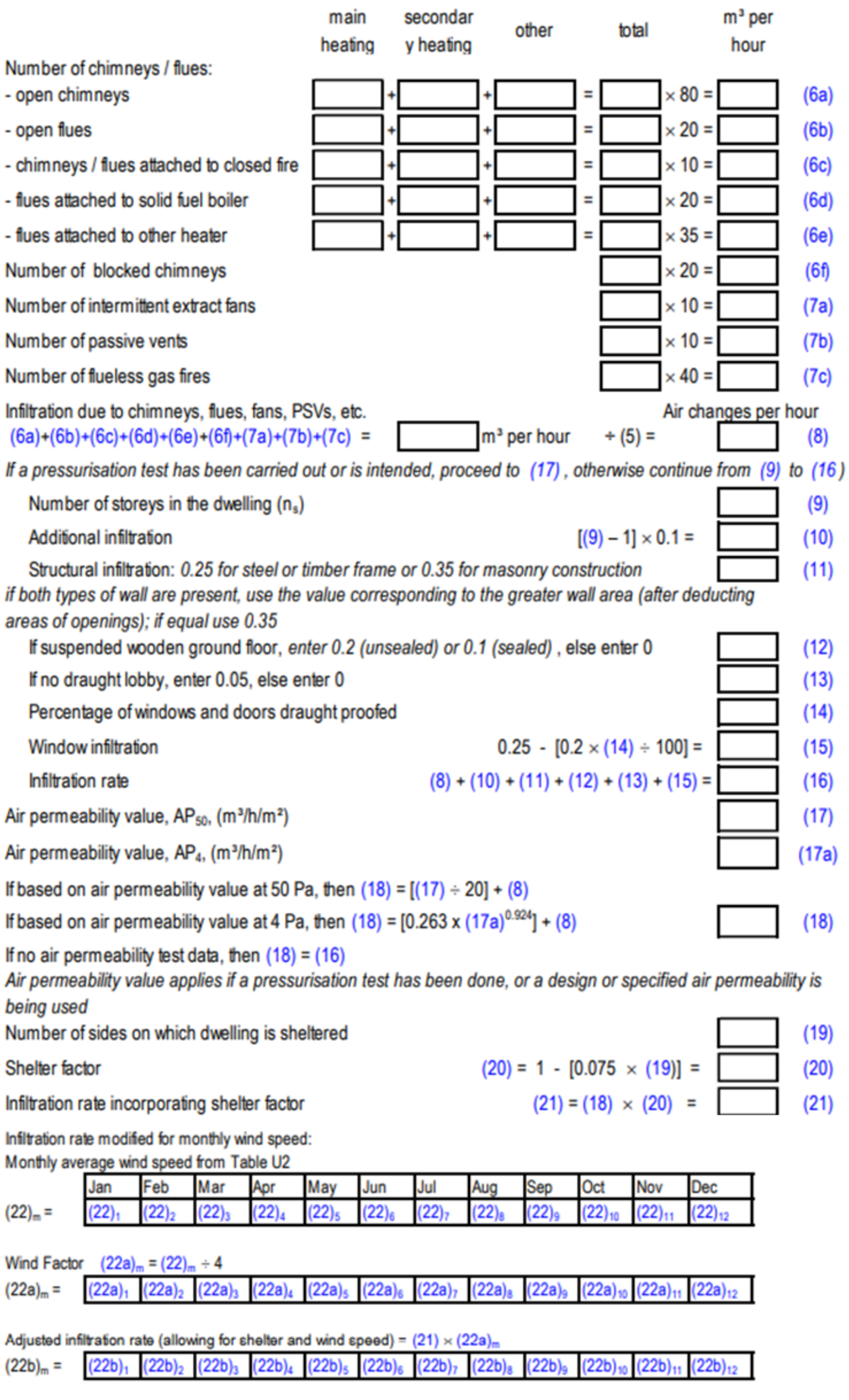
One can note that this ratio of 20 is used here with two different units: n_{inf} is in h^{-1} and q_{E50} is in $m^3/(h.m^2)$. The argument behind is that the UK housing stock has an envelope to volume ratio with a value around 1. This also applies for equation (18) below.

2) If the low-pressure pulse technique is used: the air permeability at 4 Pa (q_{E4} in cubic meters per hour per square meter of envelope area, floor included) is used in the following formula to estimate the air infiltration rate (n_{inf} in h^{-1}) at typical pressure differences:

$$n_{inf} = 0.263 \times q_{E4}^{0.924} \qquad (18)$$

3) In the absence of a pressure test, the infiltration rate can be estimated using the SAP algorithm as defined by (6) to (16) of the worksheet (see Figure 2).

Whatever the method used for its calculation, this infiltration rate due to leakage is added to the estimated infiltration rate through specific openings (chimneys, flues, fans, passive vents, etc.). This total infiltration rate is then adjusted with the shelter factor and the monthly average wind speeds as defined by (19) to (21) of the worksheet (see Figure 2).



	main heating	secondary heating	other	total		m^3 per hour	
Number of chimneys / flues:							
- open chimneys	+	+	=		× 80 =		(6a)
- open flues	+	+	=		× 20 =		(6b)
- chimneys / flues attached to closed fire	+	+	=		× 10 =		(6c)
- flues attached to solid fuel boiler	+	+	=		× 20 =		(6d)
- flues attached to other heater	+	+	=		× 35 =		(6e)
Number of blocked chimneys					× 20 =		(6f)
Number of intermittent extract fans					× 10 =		(7a)
Number of passive vents					× 10 =		(7b)
Number of flueless gas fires					× 40 =		(7c)

Infiltration due to chimneys, flues, fans, PSVs, etc. Air changes per hour

(6a)+(6b)+(6c)+(6d)+(6e)+(6f)+(7a)+(7b)+(7c) = ☐ m^3 per hour ÷ (5) = ☐ (8)

If a pressurisation test has been carried out or is intended, proceed to (17), otherwise continue from (9) to (16)

Number of storeys in the dwelling (n_s)		☐	(9)
Additional infiltration	[(9) – 1] × 0.1 =	☐	(10)
Structural infiltration: *0.25 for steel or timber frame or 0.35 for masonry construction*		☐	(11)

if both types of wall are present, use the value corresponding to the greater wall area (after deducting areas of openings); if equal use 0.35

If suspended wooden ground floor, *enter 0.2 (unsealed) or 0.1 (sealed)*, else enter 0		☐	(12)
If no draught lobby, enter 0.05, else enter 0		☐	(13)
Percentage of windows and doors draught proofed		☐	(14)
Window infiltration	0.25 - [0.2 × (14) ÷ 100] =	☐	(15)
Infiltration rate	(8) + (10) + (11) + (12) + (13) + (15) =	☐	(16)
Air permeability value, AP_{50}, ($m^3/h/m^2$)		☐	(17)
Air permeability value, AP_4, ($m^3/h/m^2$)		☐	(17a)

If based on air permeability value at 50 Pa, then (18) = [(17) ÷ 20] + (8)

If based on air permeability value at 4 Pa, then (18) = $[0.263 \times (17a)^{0.924}] + (8)$ ☐ (18)

If no air permeability test data, then (18) = (16)

Air permeability value applies if a pressurisation test has been done, or a design or specified air permeability is being used

Number of sides on which dwelling is sheltered		☐	(19)
Shelter factor	(20) = 1 - [0.075 × (19)] =	☐	(20)
Infiltration rate incorporating shelter factor	(21) = (18) × (20) =	☐	(21)

Infiltration rate modified for monthly wind speed:

Monthly average wind speed from Table U2

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$(22)_m$ =	$(22)_1$	$(22)_2$	$(22)_3$	$(22)_4$	$(22)_5$	$(22)_6$	$(22)_7$	$(22)_8$	$(22)_9$	$(22)_{10}$	$(22)_{11}$	$(22)_{12}$

Wind Factor $(22a)_m = (22)_m \div 4$

$(22a)_m$ =	$(22a)_1$	$(22a)_2$	$(22a)_3$	$(22a)_4$	$(22a)_5$	$(22a)_6$	$(22a)_7$	$(22a)_8$	$(22a)_9$	$(22a)_{10}$	$(22a)_{11}$	$(22a)_{12}$

Adjusted infiltration rate (allowing for shelter and wind speed) = $(21) \times (22a)_m$

$(22b)_m$ =	$(22b)_1$	$(22b)_2$	$(22b)_3$	$(22b)_4$	$(22b)_5$	$(22b)_6$	$(22b)_7$	$(22b)_8$	$(22b)_9$	$(22b)_{10}$	$(22b)_{11}$	$(22b)_{12}$

Figure 2: Extract from the calculation worksheet of SAP 10.2 to estimate the infiltration rate

3.8 *France - EPM*

3.8.1 Context

In France, the current regulation in response to the EPBD is the Environmental Regulation RE 2020, replacing since 2022 the Thermal Regulation RT 2012, that had introduced a requirement on the minimum airtightness level for residential buildings:

- $q_{E4,fl\_ex} \leq 0.6$ m^3·h^{-1}·m^{-2} for single-family buildings;
- $q_{E4,fl\_ex} \leq 1$ m^3·h^{-1}·m^{-2} for multi-family buildings.
-

Where q_{E4,fl_ex} is the airflow rate at 4 Pa divided by the envelope surface area, but with the lowest floor excluded. Unlike most other countries the reference pressure of 4 Pa was chosen to correspond to the order of magnitude of the pressure difference under natural conditions.

The envelope airtightness has to be justified for new residential buildings, either by a measurement, or by the application of an airtightness quality management approach (QMA).

More information on building airtightness trends and requirements in France are given in [29].

3.8.2 Airtightness in the Energy Performance Calculation

The building airtightness is an input of the energy performance calculation of the French EP regulations. A network zonal model is integrated in the calculation method to estimate the air change rates induced by air infiltration and ventilation in each zone of the building and hence, the associated heat losses. This model is based on an equilibrium pressure method (as proposed in the EPBD standard EN 16798-7 – Method 1), that is to say with the pressure calculated by a mass balance equation.

Regarding the air infiltration, the building envelope airtightness q_{E4,fl_ex}, is used as input.

- For residential buildings: there are no default values but minimum requirements that need to be justified.
- For non-residential buildings: there is no minimum requirement but the airtightness is taken into account either by the default value (1.7 m^3·h^{-1}·m^{-2} or 3 m^3·h^{-1}·m^{-2} depending on the building use), or by a better-than-default value that has to be justified.

For each zone, the method considers two leakages on the leeward walls (at a quarter and three quarters of the ceiling height of the zone), two leakages on the windward walls (at a quarter and three quarters of the ceiling height of the zone), and one leakage on the top if the zone is located under the roof. The flow coefficient of each leakage is estimated from q_{E4,fl_ex} with:

- A flow exponent n of 0.667
- A flow coefficient for each zone proportional to the wall surface in relation to the total surface of the envelope.
- A balanced leakage distribution with ¼ of the façade flow coefficient at each of the 4 leakages considered by the model (illustrated in **Error! Reference source not found.**)
- If the zone is located under the roof, a specific vertical flow coefficient is applied on the ceiling.

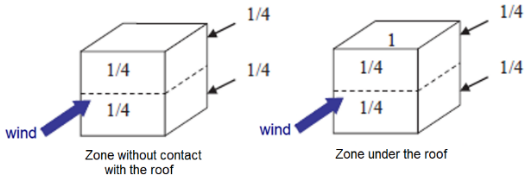


Figure 3 : Leakage distribution for each zone (Fig.22 from the decree of August 4, 2021)

The pressure difference at each leakage is estimated with a mass balance equation, including air mass flowrate due to the envelope permeability but also ventilation and air inlets. The approach, close to Method 1 of EN 16798-7 described in paragraph **Error! Reference source not found.**, is fully described in the decree of August 4, 2021 [30, paragraph 5.6.3.3

3.9 *The Czech Republic - EPM*

3.9.1 Context

In the Czech Republic, the requirements for the energy consumption in buildings are defined in the Ordinance 264/2020 Coll. which is the local implementation of the EPBD. Building envelope airtightness requirements were introduced in the national technical standard ČSN 73 0540-2 in 2002, but they have not been legally binding until now, therefore the check of compliance is still not mandatory. The limit values are defined in function of the building ventilation system and target energy performance (level I considered as minimum; level II for best practice) (Table 1).

The building envelope airtightness indicator used in the Czech regulations is the air change rate at 50 Pa: n_{50} $[h^{-1}]$, calculated as a quotient of the air leakage rate at 50 Pa q_{50} $[m^3/h]$ and the buildings internal volume V_{int} $[m^3]$ (see equations (2) and (3)), both of them determined according to the standard ČSN EN ISO 9972.

Table 1 : Recommended values of the air change rate at 50 Pa, n_{50} according to ČSN 73 0540-2

Ventilation system	Recommended value of the air change rate n_{50} $[h^{-1}]$	
	Level I	Level II
Natural or hybrid ventilation	4.5	3.0
Mechanical ventilation	1.5	1.2
Mechanical ventilation with heat recovery	1.0	0.8
Mechanical ventilation wit heat recovery in buildings with a very low energy use for heating (passive houses)	0.6	0.4

More information on building airtightness trends and requirements in the Czech Republic are presented in [31].

3.9.2 Airtightness in the energy performance calculation

The energy need for heating should be calculated according to the standard ČSN EN ISO 52016-1. As in France, the ventilation and infiltration air flow rates required for the calculation of the energy need should be determined according to Method 1 of the standard ČSN EN 16798-7, with an hourly time step. The air flow rates calculation is therefore similar in the two countries: it is based on iterative solution of the simplified mass balance equations for the ventilated zone (EPM). Hourly wind speeds and temperatures data are used to estimate the pressure difference at each time step and for each leakage induced by the wind and stack effect. The pressure coefficients Cp are taken from Annex B of ČSN EN 16798-7.

The leakage coefficients are calculated out of the n_{50} value. The default value for the flow exponent given in the standard is 0.667, and the default leakage distribution is the one used in France and illustrated in **Error! Reference source not found.**. The present regulations do not set any default n_{50} values penalising the energy consumption calculation results in order to stimulate a systematic airtightness testing. The recommended n_{50} values at level I according to ČSN 73 0540-2 (see Table 1) can be used as an estimate of the final building airtightness for the purpose of energy consumption calculation (e.g. in the design phase) unless the measured n_{50} value is available. This is the common practice among the building energy advisors, since the energy consumption is usually calculated at the design phase, before the building construction starts and the airtightness could be measured.

One can note that standard ČSN 73 0540-2 is being revised, and modification of the airtightness requirements, as well as penalising default values for energy performance calculations are foreseen.

4 Conclusion

As a conclusion, various approaches are used in Energy Performance Calculations regarding airtightness. Some countries simply do not take this parameter into account while other countries estimate a fixed infiltration rate with either a simple leakage-infiltration ratio or a model including building's and/or climate parameters. For a more accurate calculation, the alternative is to use a multi-zone airflow modeling software based on an equilibrium pressure method. The model type chosen to estimate the air infiltration rate can also depend on the methodology implemented for the EP calculations, as it may be preferable to have similar levels of simplification. National examples were provided for these various approaches and a summary is presented in Table 2.

Country	Airtightness in EP calc.?	Method	Comments
Sweden	No	-	Energy Performance Certificates are based on measured energy performance
New-Zealand	It depends	- / const.	Airtightness not included for 2 methods of compliance; included for the 3rd one through a constant air exchange lumped parameter (mechanical ventilation & infiltration)
Belgium	Yes	LIR	Based on pressurization test measurement
Finland	Yes	LIR	Based on pressurization test measurement Fixed infiltration rate (annual) with a leakage-infiltration ratio depending on the number of floors
USA	It depends	- / SIM	Most jurisdictions use a prescriptive approach and do not model energy use IECC: SIM; dynamic infiltration rate California: SIM; fixed infiltration rate
Spain	Yes	SIM	Based on pressurization test measurement or estimated according to the building's parameters and default values - Fixed infiltration rate (annual)
UK	Yes	SIM	Based on pressurization/pulse technique test measurement or estimated according to the building's parameters Monthly infiltration rates (according to the wind)
France	Yes	EPM	Based on method 1 of EN 16798-7:2017 Dynamic infiltration rates (hourly)
Czech Republic	Yes	EPM	Based on method 1 of EN 16798-7:2017 Dynamic infiltration rates (hourly)

Table 2 : Summary of the national approaches regarding airtightness in the EP calculation

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7 Appendix A: national symbols for air permeability indicators

For ease of reading, some national symbols of airtightness indicators have been modified to be consistent throughout this paper. The indicators used in the official national regulations are listed below.

Table A.1 – Correspondence between the air permeability symbols used in this paper and the official national symbols

Paper symbol	**Unit**	**Country**	**Official symbol**	**Definitions and national specificities**	
q_{E50}	$m^3/(h.m^2)$	UK	AP_{50}	Airflow rate at 50 Pa divided by envelope surface area	• internal dimensions used • lowest floor included
		Finland	q_{50}		• internal dimensions used • lowest floor included
$q_{E50,av,ext}$		Belgium	v_{50}		• average pressurization and depressurization • external dimensions used • lowest floor included
q_{E4}		UK	AP_4	Airflow rate at 4 Pa divided by envelope surface area	• internal dimensions used • lowest floor included
q_{E4,fl_ex}		France	$Q_{4PaSurf}$		• internal dimensions used • lowest floor included
q_{50}	cfm	USA	Q_{50}	Airflow rate at 50 Pa	
	m^3/h	Czech R.	q_{50}		
q_{inf}	m^3/h	Belgium	$V_{in/exfiltration}$	Estimated infiltration rate under natural conditions	
		Finland	$q_{v,vuotoilma}$		In m^3/s
	m^3/s	USA	$Q; Q_{inf}$		
n_{50}	h^{-1} (ACH)	Spain	n_{50}	Airflow rate at 50 Pa divided by the internal volume	
		Czech R.			
n_{inf}	h^{-1} (ACH)	UK	-	Estimated infiltration rate under natural conditions divided by the internal volume	

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