ANNEX **5**

EBC
Energy in Building and
Communities Programme

AIVC Technical Note 73
Overview of the trends in building and ductwork airtightness in 16 countries

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Main Authors
Nolwenn Hurel, Cerema, France
Valerie Leprince, Cerema, France

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Participating countries in the EBC: Australia, Austria, Belgium, Brazil, Canada, P.R. China, Denmark, Finland, France, Germany, Ireland, Italy, Japan, Republic of Korea, the Netherlands, New Zealand, Norway, Portugal, Singapore, Spain, Sweden, Switzerland, Turkey, United Kingdom and the United States of America.

www.iea-ebc.org

essu@iea-ebc.org

Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international cooperation among the 30 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes (TCPs). The mission of the IEA Energy in Buildings and Communities (IEA EBC) TCP is to support the acceleration of the transformation of the built environment towards more energy efficient and sustainable buildings and communities, by the development and dissemination of knowledge, technologies and processes and other solutions through international collaborative research and open innovation. (Until 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.)

The high priority research themes in the EBC Strategic Plan 2019-2024 are based on research drivers, national programmes within the EBC participating countries, the Future Buildings Forum (FBF) Think Tank Workshop held in Singapore in October 2017 and a Strategy Planning Workshop held at the EBC Executive Committee Meeting in November 2017. The research themes represent a collective input of the Executive Committee members and Operating Agents to exploit technological and other opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy technologies, systems and processes. Future EBC collaborative research and innovation work should have its focus on these themes.

At the Strategy Planning Workshop in 2017, some 40 research themes were developed. From those 40 themes, 10 themes of special high priority have been extracted, taking into consideration a score that was given to each theme at the workshop. The 10 high priority themes can be separated in two types namely 'Objectives' and 'Means'. These two groups are distinguished for a better understanding of the different themes.

Objectives: The strategic objectives of the EBC TCP are as follows:

– reinforcing the technical and economic basis for refurbishment of existing buildings, including financing, engagement of stakeholders and promotion of co-benefits;
– improvement of planning, construction and management processes to reduce the performance gap between design stage assessments and real-world operation;
– the creation of 'low tech', robust and affordable technologies;
– the further development of energy efficient cooling in hot and humid, or dry climates, avoiding mechanical cooling if possible;– the creation of holistic solution sets for district level systems taking into account energy grids, overall performance, business models, engagement of stakeholders, and transport energy system implications.

Means: The strategic objectives of the EBC TCP will be achieved by the means listed below:

– the creation of tools for supporting design and construction through to operations and maintenance, including building energy standards and life cycle analysis (LCA);
– benefitting from 'living labs' to provide experience of and overcome barriers to adoption of energy efficiency measures;
– improving smart control of building services technical installations, including occupant and operator interfaces;
– addressing data issues in buildings, including non-intrusive and secure data collection;
– the development of building information modelling (BIM) as a game changer, from design and construction through to operations and maintenance.

The themes in both groups can be the subject for new Annexes, but what distinguishes them is that the 'objectives' themes are final goals or solutions (or part of) for an energy efficient built environment, while the 'means' themes are instruments or enablers to reach such a goal. These themes are explained in more detail in the EBC Strategic Plan 2019-2024.

The Executive Committee

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme by (☼):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: ☼ Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: ☼ Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: ☼ Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: ☼ Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)

Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy and CO_2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO_2 Equivalent Emissions for Building Construction (*)
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62: Ventilative Cooling (*)
Annex 63: Implementation of Energy Strategies in Communities (*)
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles (*)
Annex 65: Long-Term Performance of Super-Insulating Materials in Building Components and Systems (*)
Annex 66: Definition and Simulation of Occupant Behavior in Buildings (*)
Annex 67: Energy Flexible Buildings (*)
Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings (*)
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings (*)
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale (*)
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements (*)
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings (*)
Annex 73: Towards Net Zero Energy Resilient Public Communities (*)
Annex 74: Competition and Living Lab Platform (*)
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables (*)
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Annex 89: Ways to Implement Net-zero Whole Life Carbon Buildings
Annex 90: EBC Annex 90 / SHC Task 70 Low Carbon, High Comfort Integrated Lighting
Annex 91: Open BIM for Energy Efficient Buildings
Annex 92: Smart Materials for Energy-Efficient Heating, Cooling and IAQ Control in Residential Buildings

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings (*)
Working Group - Cities and Communities (*)
Working Group – Building Energy Codes

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1. General Introduction

The current trend in most Western countries regarding building ventilation is to follow the “build tight, ventilate right” strategy. New energy efficient buildings are indeed getting more and more airtight to avoid energy losses through uncontrolled air leakages. Instead of relying on natural infiltration, ventilation systems are installed to ensure a good indoor air quality (IAQ) with controlled ventilative air flowrates.

In some European countries, minimum requirements for building airtightness are included in Energy Performance (EP) regulations, with sometimes a mandatory justification required by testing or applying certified approach, such as in France, Ireland and United Kingdom (Leprince et al., 2017). As a result, building airtightness tests are getting commonly performed on new buildings in many countries to quantify and limit air leakage through the envelope. While there are many voluntary programs for increased airtightness in buildings, such as the Passivhaus label or the R-2000 certification in Canada, this report focuses on mandatory/regulatory requirements.

In addition, even if the significant impact of leaky ventilation ductworks on energy use and IAQ has been well established in the literature (Leprince et al., 2020), the awareness on this issue is raising more slowly.

In 2008 a series of Ventilation Information Papers (from VIP 17 to VIP 27) were published by the AIVC, detailing the “Trends in the building ventilation market and drivers for changes” for 10 countries. Regulations have however evolved a lot in most countries since then. A new series of 16 VIPs is being published to get an update on the current regulations in various countries around the world regarding building and ductwork airtightness. They include for both, when relevant, information on:

- national requirements and drivers: airtightness metrics, requirements in regulations, energy programs, airtightness justifications, sanctions, etc.
- if it is included in the energy calculations and how;
- the airtightness test protocol: qualification for the testers, guidelines, requirements on measuring devices;
- tests performed: tested buildings/ductwork, database, evolution with time;
- guidelines to build airtight buildings/ductworks.

The objective of this report is to give an overview of the trends in building and ductwork airtightness in these 16 countries around the world (Figure 1), summarising and comparing the information. More details about specific countries can be found in the corresponding published VIPs which are publicly available on the AIVC website[1].

Abbreviation	Country	Flag
BE	Belgium	
CH	Switzerland	
CN	China	
CZ	Czech Republic	
DE	Germany	
EE	Estonia	
ES	Spain	
FR	France	
GR	Greece	
JP	Japan	
KR	Korea	
LV	Latvia	
NL	Netherlands	
NO	Norway	
NZ	New Zealand	
US	United Stated of America	

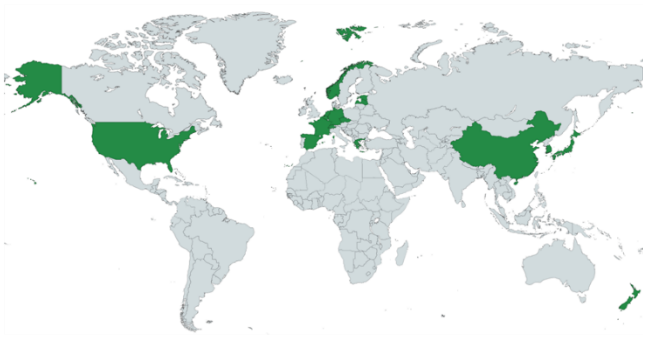

Figure 1: List of the countries included in this overview

[1] https://www.aivc.org/resources/collection-papers/volume/ventilation-information-papers-0

2. Building airtightness

2.1. Introduction

The air permeability of the envelope is one of the crucial parameters to reduce the energy demand in the building sector. It characterises the building's ability to permit air leakage which is the unintended air flow through the envelope due to a pressure difference between the inside and outside. Up to 53% of the ventilation heating energy in buildings is indeed lost due to uncontrolled air leakage (Logue et al., 2013) and a bad airtightness can lead to a 25% over-consumption of energy for high performance buildings (Carrié et al., 2006).

The airtightness issue affects not only the heating load but also the indoor air quality since it can disrupt the proper functioning of mechanical ventilation, and the air can introduce outdoor pollutants or pick them up when passing through the wall (Carrié et al., 2006; Hurel, 2016). Air leakage can also lead to moisture damages, increasing the heat transfer and threatening the longevity of the building itself (Sandberg and Sikander, 2005), as well as affect the acoustic insulation regarding to outside noise (Iordache and Catalina, 2012).

As a result, standards for highly efficient buildings such as Passivhaus, Minergie-P and Effinergie generally include a minimum airtightness level, and minimum performance standards and regulations are also requiring airtightness limits. Because energy savings are the main motivation for building airtightness regulation, the countries with cold climates tend to be ahead on this issue. Norway was probably one of the first to introduce national requirements on building airtightness in the 1980s. This has been followed by more countries in the intervening years, often with progressively stricter requirements. Building airtightness has historically not been a major concern in countries with low heating loads. While this is changing in some of them, such as in Spain, airtightness is still not really considered in others such as in Greece.

This section aims to provide an overview of the national trends in building airtightness in 16 countries, and show in particular the variety of national requirements, recommendations and incentives.

2.2. Airtightness metrics

The first step for a country to define requirements or recommendations on building airtightness is to define an airtightness metric to quantify the permeability level of building envelopes.

A variety of metrics have been implemented by different countries, with sometimes several of them used by the same nation (see an overview Table 1 and a detailed summary Table 2).

The two main metrics aim to normalise measured leakage by parameters associated with building size:

- **the leakage flowrate divided by the envelope area** in $m^3/(h.m^2)$. The floor is generally included in this area (except in France), and internal dimensions are usually used (except in Belgium).
- **the leakage flowrate divided by the building volume** in h^{-1} (also called ACH for Air Change per Hour). Internal dimensions are usually used.

These metrics are almost always calculated for a pressure difference between the inside and the outside of the building of 50 Pa, because testing at high pressures is more repeatable, with less sensitivity to wind effects during the testing, except in France where a pressure of 4 Pa is used because it corresponds to the order of magnitude of the pressure difference under natural conditions.

Some other metrics are used by few countries:

- **the specific leakage area** which is the area of an orifice that would produce the same amount of leakage as the building envelope at the reference pressure, divided by the square footage of the conditioned space. It is used in the USA, with a reference pressure of 4 Pa, and in Japan with a reference pressure of 9.8 Pa (historically: 1 mmAq).
- **the leakage flowrate** at 10 Pa is used in the Netherlands (m^3/s or dm^3/s), sometimes divided by the floor area ($m^3/(h.m^2)$). As this metric does not ease the airtightness level comparison between buildings of different sizes, other international metrics can also be used.

Germany has the specificity of using two metrics in the regulation, depending on the volume of the building. Historically, the leakage flowrate divided by the building volume (nL50) was used, but in 2014 a new metric with the leakage flowrate divided by the building area (qE50) was introduced for buildings with an internal volume greater than 1500 m³. This was done as nL50 is usually automatically low in large buildings due to the low surface-to-volume ratio.

This diversity of metrics makes it difficult to directly compare national requirements, as the conversions are not straightforward because conversion factors change depending on building geometry.

Table 1: Airtightness metrics based on leakage flowrate measurements in the various countries

Flowrate at pressure:	Divided by:			
	Envelope area ($m^3/(h.m^2)$)	Building volume (h^{-1})	Both used ($m^3/(h.m^2)$) ; (h^{-1})	- (m^3/s or dm^3/s)
50 Pa				
10 Pa				
4 Pa				

Table 2: Airtightness metrics in the 16 countries, with details on the national symbols and specificities

Pressure	Unit	Definitions	Country	Official symbol	National specificities
50 Pa	$m^3/(h.m^2)$	Airflow rate at 50 Pa divided by envelope surface area	BE	v_{50}	– average pressurisation and depressurisation – external dimensions used – lowest floor included
			CH	q_{a50}	-
			EE	q_{50}	-
			LV	q_{50}	– Internal dimensions – n_{50} sometimes also used
	(h^{-1})	Airflow rate at 50 Pa divided by the internal volume	CZ		According to ISO 9972 :2019 (internal volume)
			ES	n_{50}	
			GR	n_{50}	Not an official metric (no regulation)
			KR	ACH50	-
			NO	n_{50}	Internal dimensions
			NZ	ACH50	– Internal dimensions – q_{50} sometimes also used
	(h^{-1}) ; $m^3/(h.m^2)$	Airflow rate at 50 Pa divided by the internal volume or by the envelope surface area	CN	N_{50} ; Q_{50}	-
			DE	V<1500m^3: n_{L50} ; V>1500m3: q_{E50}	– n_{L50} : Internal dimensions – q_{E50}: envelope area acc. to ISO 9975:2015
	(h^{-1}) ; CFM/ft²		US	ACH50; CFM50/ft²	Specific leakage area at 4 Pa also used
4 Pa	$m^3/(h.m^2)$	Airflow rate at 4 Pa divided by envelope surface area	FR	$Q_{4PaSurf}$	– internal dimensions used – lowest floor excluded
10 Pa	m^3/s or dm^3/s	Airflow rate at 10 Pa	NL	q_{v10}	– sometimes divided by the floor area – n_{50} / ACH50 also used
9.8 Pa	cm²/m²	Specific effective leakage area per the floor area at 9.8 Pa (1 mmAq)	JP	ELAF9.8	-

2.3. Requirements and drivers

Mandatory building airtightness requirements

The most direct way for countries to ensure good building airtightness is to define mandatory requirements with maximum allowable air leakage.

Among the 16 countries presented in this report, this has been implemented by 7 of them, among which 3 countries have requirements for all buildings (Norway, Germany and the Netherlands), and the 4 others (France, Spain, Latvia and the USA) have requirements for certain types of buildings only, with in general a focus on residential buildings (see Table 3 and Figure 2). One can note that in the USA, the regulation depends not only on the type of buildings but also on the State.

The maximum air permeability values are defined depending on different parameters according to the countries: single/multi-family buildings in France; dwellings/other buildings in Norway; the envelope area in Spain; the type of ventilation systems in Germany and Latvia; the building volume in the Netherlands and the location (different value for very mild climates) in the USA.

One can note that Japan is the only country that had a mandatory requirement on building airtightness (since 1999) and decided to remove it in 2009 based on the judgment that the airtightness of housing was widely known and construction was being carried out accordingly.

To ensure that the airtightness requirements are met, a mandatory justification is asked for only 3 countries: France, Norway and the USA. The official view in Norway is that all new buildings shall be tested, but there are many indications that much less measurement is carried out in practice, and several contractors have procedures for limited statistical random sampling. In the USA, all single-family homes are tested in some States that have adopted the IECC energy codes, and there are usually sampling procedures for multifamily buildings. In France there are two options to justify the building airtightness level used as an input in the EP calculation:

- an airtightness test of each building (with sampling rules for apartments in multi-family buildings and housing developments described in FD P50-784 [2]), performed by a qualified tester; or
- the application of a certified quality management approach (QMA) on the building airtightness (Annex VII of the regulation), that allows to test only a sample of buildings.

In Spain, there is also officially a mandatory justification of the airtightness level of the building envelope but this can be done with a very simple formula that can hardly reflect the reality of individual buildings, and in practice only few tests are performed:

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

Where: n_{50} is the calculated air permeability at 50 Pa (h^{-1}); V is the internal volume within the thermal building envelope (m^3); C_0 is the airflow coefficient of the opaque part of the thermal envelope at a reference pressure of 100 Pa ($m^3/(h.m^2)$) (29 $m^3/(h.m^2)$ for existing building; 16 $m^3/(h.m^2)$ for improved airtightness); 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 ($m^3/(h.m^2)$), according to laboratory testing results provided by the manufacturer; A_h is the sum of the area of the doors and windows of the thermal building envelope (m^2).

Table 3: National mandatory requirements regarding building airtightness currently in force in the 16 countries

Mandatory requirements?					
NO	YES				
	Country	Mandatory justification?	Mandatory for:	Values: Indic.	Values: Max. values
	FR	YES (by test or certified quality management approach)	Residential buildings (sampling allowed)	$q_{4PaSurf}$ (m³/(h.m²))	– 0.6 for single-family – 1 for multi-family
	NO	YES (by test)	All buildings (sampling allowed)	n_{50} (h^{-1})	– 1.5 for all buildings – target of 0.6 for dwellings
	US	YES (by test)	Residential buildings in some states that have adopted the IECC energy codes (sampling allowed)	ACH50	– 3 nationally – 5 in few locations with very mild climates
	ES	By test or calculation with a formula: $n_{50} = 0.629 \frac{C_0 \times A_0 + C_h \times A_h}{V_{int}}$	Residential build. > 120 m², with mandatory controlled mech. or hybrid vent. system	n_{50} (h^{-1})	– 6 if Vol//Env. Area <2 – 3 if Vol//Env. Area >4 – Interpolation in between
	DE	NO	All buildings	n_{L50} (h^{-1}) for V<1500m³; else: q_{E50} (m³/(h.m²))	– With ventilation system: $n_{L50} \leq 1{,}5$; $q_{E50}<2{,}5$ – Without ventilation: $n_{L50} \leq 3$; $q_{E50}<4{,}5$
	LV	NO	Residential houses, homes for the elderly, hospitals, kindergartens, and public buildings	q_{50} (m³/(h.m²))	– 3,0 for natural vent. – 2,0 for mech. vent – 1,5 for heat recov. – 4,0 for industrial build.
	NL	NO	All buildings?	q_{v10} (dm³/s)	– 200 up to 500 m³, pro rata above – Stricter in EPC: about 0,6 /m² of floor

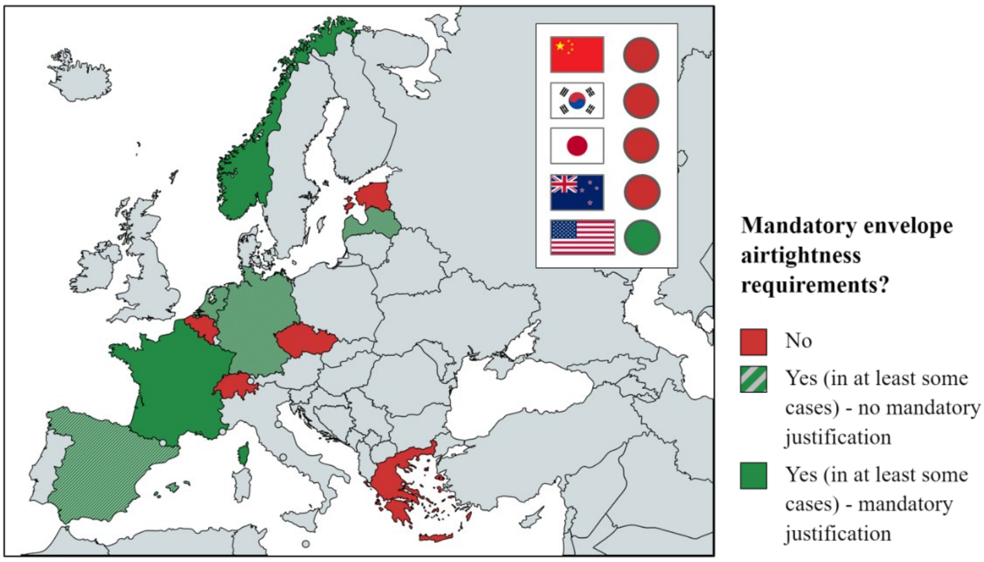

Figure 2: Building airtightness requirements and justification in the 16 countries

Other incentives for building airtightness

The fact that the other countries (Germany, Latvia, and the Netherlands) have no mandatory justification weakens the impact of their airtightness mandatory requirements. For these countries, as for the 9 countries with no mandatory requirements, a good building airtightness is often promoted by other means:

- The energy performance (EP) calculation (see paragraph 3.4):
  - BE: the energy performance requirements towards Nearly Zero Energy Buildings became more and more difficult to meet without the result of an airtightness test to replace the disadvantageous default value in the EP calculation.
  - EE: as in Belgium, the building airtightness is driven mainly by EP requirements, with disadvantageous default values that can be replaced only with an on-site test justification.
  - KR: a building applying for EP certification must satisfy an airtightness criterion, with a mandatory on-site test for residential buildings.
- Regulation on the airtightness performance of building components:
  - CN: the airtightness of doors and windows is regulated according to the national standard GB/T 7106-2019.
  - KR: the airtightness of certain building components (in particular doors and windows) is specified in the Energy Conservation Design Criteria for Buildings and the Construction Standard for Energy-Saving Eco-Friendly residential buildings.
  - ES: minimum airtightness requirements for windows and doors for new and retrofitted buildings are given regarding the winter climate zone where the building is located.
- Recommendations in (non-mandatory) standards or other documents:
  - CN: maximum air permeability values are given in standards for low-energy and zero energy building.
  - CZ: requirements are given in national technical standard ČSN 73 0540-2 since 2002 (with mandatory tests).
  - LV: airtightness tests are recommended for the commissioning of all public buildings larger than 5000 m^3 since 2001.
  - NZ: BRANZ (an independent construction industry research organisation funded via a levy on construction activity) recommends a maximum permeability of 3 ACH at 50 Pa.
  - CH: There are standards such as SIA 180 recommending airtightness tests.
- Labels which include airtightness requirements:
  - Passive Houses requirements (BE, DE and NZ in particular): Airtightness shall not exceed 0.6 ACH at 50 Pascal and shall be verified by on-site air permeability measurement (depressurisation and pressurisation).
  - FR: the EP-labels of French association Effinergie (BEPOS, and BEPOS+ Effinergie 2017) set higher requirements for residential buildings and require an airtightness measurement for non-residential building with an area below 3000 m².
  - CH: Minergie label.
- Financial subsidies (voluntary schemes):
  - CZ: the New Green Savings (NGS) is the most impactful long-term energy performance programme, aiming to reduce the energy consumption in the residential sector by reinvesting the revenues of the European allowance units into the construction of energy efficient buildings (with mandatory tests).
  - DE: for all measures funded by Kreditanstalt für Wiederaufbau (KfW) regarding the building envelope an airtightness concept is required.
  - JP: local governments set standards for building airtightness, with subsidises construction costs (with mandatory justification).
  - LV: since January 2022, the city of Riga gives a 90% discount on property taxes with conditions on the energy performance involving airtightness tests.
  - NL: BREEAM (Building Research Establishment Environmental Assessment Method), with savings on taxes (maximum deduction of taxes is €10milion for the 'outstanding' rating).
  - NZ: the New Zealand Green Building Council's Homestar v5 scheme provides a mechanism to incentivise airtightness in its assessment framework (section EHC5). If a blower door test is undertaken, credit is given.
  - USA: tax credits starting in 2023 for homes that meet Energy Star Program requirements, including air leakage. Many energy conservation programs include rebates and incentives for home air sealing, however, most of them do not require blower door testing and rely on checklists.
- Certification schemes
  - CZ: manufacturers of the wooden houses involved in the certification scheme of the association ADMD have to test a specified portion of their production on a regular basis.

2.4. Building airtightness in the energy performance calculation

As mentioned above, one way to promote building airtightness is to include this parameter in the energy performance (EP) calculation, which is the case for all countries but Japan. This is particularly impactful if very penalising default values are set, and an airtightness test is required to implement better values, as in Belgium and Estonia.

On the other hand, in Latvia the default values are the mandatory requirements, with no justification asked. This means that even though this country sets legal requirements and includes the airtightness in the EP calculations, there is in practice no strong constraint on the level of building airtightness.

One can note that the envelope airtightness can be taken into account in various ways in the EP calculation, listed in Table 4 in ascending order of accuracy but descending order of simplicity:

- Constant value (CH, NZ): regardless of the airtightness performance of the envelope (not promoting building airtightness).
- Tabulated values (GR): fixed tabulated air infiltration rates given for different types of windows and doors; for chimneys and ventilation boxes.
- Leakage-infiltration ratio (BE, DE, EE, ES, KR, NO): assuming a linear correlation between the air change rate at 50 Pa and under natural conditions, with a coefficient either identical for all buildings or calculated according to a number of parameters (type of ventilation; number of stories; wind exposition).
- Equilibrium pressure model (CZ, FR): pressure calculated by a mass balance equation at a defined time step (dynamic infiltration rate), often hourly. This calculation requires an estimation of the pressure and leakage distribution on the building's façades.

These models are further explained in a dedicated AIVC Ventilation Information Paper (VIP 46) (Hurel and Leprince, 2023).

One can note that not all 16 countries are included in Table 4. This is because details of the type of model used to include airtightness in the EP calculation (CN, LV, NL) are unknown, as illustrated in Figure 3. In addition, the USA is not included as the way airtightness is taken into account or not depends on the State and on the method of compliance chosen, but most jurisdictions use a prescriptive approach and do not model energy use.

Table 4: Building airtightness in the Energy Performance calculations: type of models and default values

Level of accuracy and complexity

Type of model	Country	Details	Default values: Used?	Default values: Values	Default values: Comments
Constant value	CH	Not a variable: fixed additional outside air volume flow of 0.15 $m^3/(h.m^2)$ (net floor area reference) regardless of the quality of the envelope (not possible to use test values)			
	NZ	Airtightness not included for 2 methods of compliance; included for the 3rd one through a constant air exchange lumped parameter (mechanical ventilation & infiltration)			
Tabulated values	GR	Fixed tabulated air infiltration rates (m^3/h) given for different types of windows and doors; for chimneys and ventilation boxes (not possible to use test values)			
Leakage-infiltration ratio	BE	$v_{inf} = 0.04 * v_{50} * A_T$	YES	**VERY penalising** v_{50}: 12 $m^3/(h{\cdot}m^2)$ for heating; 0 for cooling	Test not officially mandatory but almost necessary for the EP calculation (better v_{50})
	DE	With ventilation system: $n_{inf} = n_{50}.e_{wind}$ (with $\mathbf{e_{wind}}$ typically = 0,07) Without: $n_{inf} = n_{50}\, e_{wind} \left(1 + f_{V,mech} \frac{t_{V,mech}}{24\,h}\right)$	YES	Penalising n_{50} (h^{-1}): 4; 6 or 10 depending on the building (typically 4)	If a test will be performed: maximum mandatory requirements are the default values
	EE	$q_{inf} = q_{50}.A/X$ A: area of the building envelope (m^2) X: factor depending on the **number of stories** (ranging from 15 to 35)	YES	Penalising q_{50} ($m^3/(h.m^2)$): – detached house: 4 (6 for minor renovation) – - other buildings: 2,5 (4)	Other possibilites: – Use 1.5 $m^3/(h{\cdot}m^2)$ to be justified by test later – Use of a calculated "declared air leakage rate"
	ES	Fixed infiltration rate estimated from n_{50} with hypotheses (wind speed: 2,8 m/s, Cp values; n=0,67; etc.)	YES	Calculation of n_{50} by a formula: $n_{50} = 0.629\, \frac{C_0.A_0 + C_h.A_h}{V_{int}}$	-
	KR	According to ISO 13789: $n_{inf} = \frac{n_{50} \times e}{1 + \frac{f}{e}\left(\frac{\dot{V}_1 - \dot{V}_2}{V \times n_{50}}\right)^2}$ f, e: **shielding factors**; V_1, V_2: sup. and exh. **airflows**	YES	Penalising for residential: 6 ACH50 non-residential: 1,5 ACH50	Mandatory test for residential building: the measured value is used in the final certification
	NO	Common case: $n_{inf} = n_{50}.0{,}07$ but depends **on number of facades exposed** and **degree of exposure to wind**	NO	-	Requirements can be used prior to the test
Equilibrum pressure model	CZ	Method 1 of the standard EN 16798-7, with an hourly time step (pressure calculated by a **mass balance equation**)	NO	-	Common practice: use recommended n_{50} values at level I according to ČSN 73 0540-2
	FR		YES	Non-residential: $Q_{4PaSurf}$: 1.7 or 3 $m^3/(h{\cdot}m^2)$ depending on the building use	No default values for residential buildings: minimum requirements to be justified

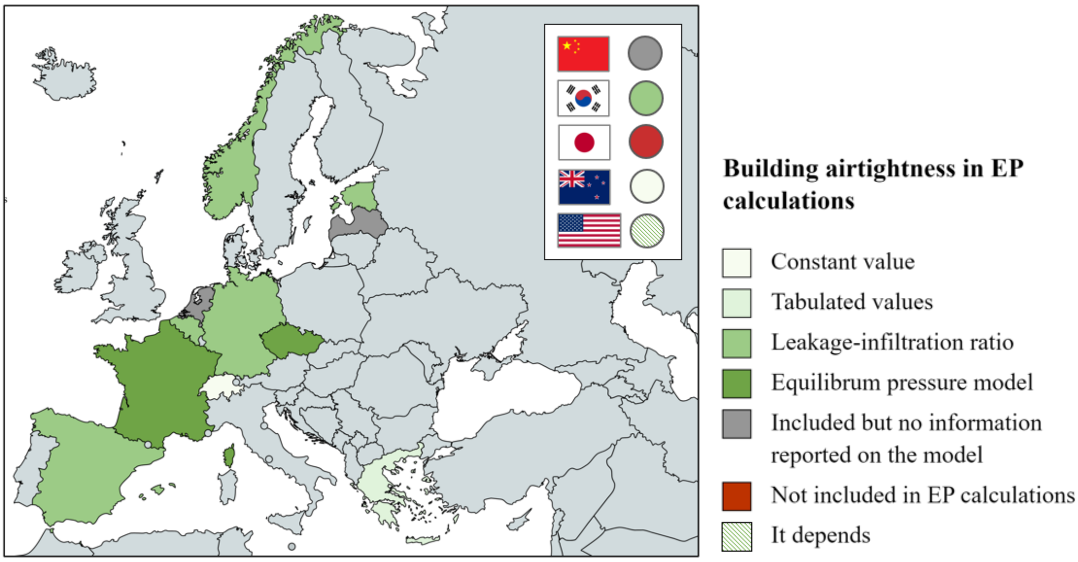

Figure 3: Building airtightness in the Energy Performance calculations in the 16 countries

2.5. Building airtightness test protocol

The most common way to measure the airtightness performance of a building is to perform a pressurisation test, as described for example in standard ISO 9972 (ISO, 2015).

To ensure that these tests are performed properly, with in particular a consistent building preparation and accurate measurements and calculations, more than half of the 16 countries have developed local qualifications for testers, as detailed in Table 5. In the countries with no local qualifications, some testers get qualified abroad, as in Switzerland, Latvia and the Netherlands.

These qualifications are mandatory in 2 countries only:

- BE (Flanders only): the quality framework for airtightness testers of both BCCA (Belgian Construction Certification Association) and SKH are approved by the Flemish government. They comply with the new requirements (from 2020) on a quality framework for airtightness testers which specify in particular:
  - The qualification procedure must include at least an optional training and a mandatory theoretical and practical exam.
  - The quality of the airtightness measurements must be guaranteed by running desk and onsite audits combined with effective enforcement (90% of the testers are audited at least once a year)
- FR: airtightness tests must be performed by a third-party tester, qualified by the certification body, Qualibat. To be qualified, a tester has to undergo state-approved training, pass the theoretical and practical training examination and provide proof of sufficient testing experience with a minimum of 10 tests performed. Once qualified, every tester is subjected to yearly follow-up checks, organised by the certification body.

In addition, if standard ISO 9972 is used by most countries (especially in Europe) to perform the airtightness tests, some countries have developed local guidelines to give further guidance on how to perform these tests. These local guidelines are also listed in Table 5. They include national specificities, such as for example the obligation to perform both a pressurisation and a depressurisation tests (BE, DE, NL) or sampling rules (KR).

Table 5: Building airtightness tests: national qualifications for testers and national guidelines

Country	National qualification for testers				National guidelines		
	Existing?	Mandatory?	Name	Number or %	Existing?	Name (year)	Specificities
BE	YES (Fl.)	YES	By BCCA and SKH	150 – 190 (Fl.)	YES	STS-P 71-3 (2014), mandatory only in Fl.	Tests in p^+ and p^- (or correction if not possible)
CH	NO	NO	qualified with FLiB	2 (~2%)	YES	Minergie airtightness guideline (RiLuMi)	Building and test prep. (ISO 9972 used)
CN	NO	-	-	-	YES	T/CECS 704 (2020)	Tracer gaz method allowed
CZ	YES	NO	A.BD_CZ (mandatory for members)	15 (30-35%)	YES	annex of TNI 73 0330	Method for testing multi-family buildings
						New Green Savings (NGS) guidelines	For buildings in this energy perf. program
DE	YES	NO	program by FLiB e. V.	~ 500	YES	National annex of DIN EN ISO 9972:2018-12	Tests in p^+ and p^-
EE	NO	NO	-	-	NO	-	-
ES	NO	NO	Trainings by manufacturers	?	NO	In accordance with UNE-EN ISO 9972:2019	
FR	YES	YES	Qualibat	842	YES	FD P50-784	Application guide of EN ISO 9972
GR	YES	NO	Seminars by Aerosteganotita	10	NO	-	-
JP	YES	NO?	by IBECs	~ 500/yr	YES	JIS A 2201	
KR	YES	NO	Several existing; main one: KIAEBS	~ 200	YES	building airtightness measurements manual	Sampling rules for multi-unit residential buildings (ISO 9972 used)
LV	NO	NO	Some qualified with Retrotec, FliB, ATTMA	11	NO	In accordance with LVS EN 9972:2016	
NL	NO	NO	Some qualified by SKH	10-15%	YES	NEN 2686	Tests in p^+ and p^- (in upcomming update: in line with ISO 9972)
NO	NO	NO	-	-	YES	There are simplified methods in use not complying entirely with ISO 9972	
NZ	YES	NO	?	?	NO	ISO method adopted as AS/NZS ISO 9972:2015	
US	YES	NO?	Energy auditor certification (ABNSI/BPI-1100-T-2014) by BPI	?	YES	Standard ASTM E779	For multipoint measure.
						Standard ASTM E1827	For single point measurements (50 Pa)
						More commonly used (simpler): ANSI/RESNET 380 or blower door manufacturer's instructions	

2.6. Building airtightness tests performed

The various national regulations and/or incentives on building airtighntess in the 16 countries result in different percentages of tested buildings, as detailed in Table 6 and illustrated in Figure 4.

The following main conclusions can be drawn from this data:

- **There is no country testing all new buildings**
- **Only Flanders in Belgium has almost all new residential buildings tested** (no data for Wallonia and Brussels): this is driven by the very disadvantageous airtightness default value in the EP calculation, as there are officially no requirements on airtightness performance.
- **Non-residential buildings are rarely tested**: less than 10% of non-residential buildings are tested in all countries except in Belgium where there is also a penalising default value for EP calculations (no data available, but probably a similar percentage of tests as for residential buildings), perhaps in Germany where the authors only indicated a "large number of air permeability measurements" without distinguishing the type of buildings and in Latvia where there is a national recommendation to test all public buildings.
- **Mandatory requirements AND justification of airtightness level increase the number of tests but does not guarantee systematic testing**:
  - FR: the justification can be made either by testing of by applying a certified quality management approach. Around 30% of all new constructed houses, and 6% of all new constructed multi-family dwellings are being tested each year (lower for multi-family dwellings as the measurement by sampling is widely used).
  - NO: the author estimated that only about 10% of new buildings were tested, which is at least partly explained by the sampling rules
  - USA: it is difficult to estimate the overall percentage but the authors indicated that about 10-15% of new homes are tested as part of the Energy Star for Homes program. In addition, nearly half of new residential buildings (single and multifamily) are tested as part of the RESNET rating program. 43 states that have adopted some form of the IECC, indicating that the majority of new homes are air leak tested (with possible overlap in states that use RESNET ratings to show compliance with the IECC).
  - ES: as previously discussed in paragraph 2.3, justification of airtightness performance is also mandatory in Spain but it can be done through a very simple formula. As a result, the authors mentioned that the testing movement "has made a small step forward but still it is far behind to what is happening in other European countries" (percentage unknown).

National public up-to-date databases gathering the results of airtightness tests are helpful to have a good overview of the building airtightness in the country, and of its evolution with time. It can also be helpful to analyse the impact of particular parameters on the airtightness level such as the type of materials or the year of construction (McWilliams and Jung, 2006). For example, the French database has shown that there is a priori no seasonal effect on airtightness performance (Moujalled et al., 2021). However, as detailed in Table 6, only a few countries have public up-to-date database (BE, CZ, FR, GR and KR) and only France and Belgium (Flanders) have comprehensive database collecting results of 100% of the tests performed. In some countries (ES, JP, NZ and US), data was collected and published through research projects, but as a one-time effort with a limited number of tests included.

One can note that these tests are usually performed just after the completion of the buildings, but studies have shown that airtightness performance is not robust, and tends to deteriorate with time, especially during the first year of the building's life (Leprince et al., 2022).

Table 6: Airtightness tests: percentage of buildings tested and public database

Country	Residential buildings	Non-residential buildings	Public database: Existing?	Public database: In charge:	Public database: % of tests
BE (Flanders)	New: alm. 100%	Probably similar as residential build.	YES	Flanders: VEKA	100%
	Deep retrofit: ~ 25%			Quality frameworks like BCCA	All from this QF
CH	~ 5%		NO	Survey of Minergie	
CN	Unknown	-	NO	-	-
CZ	<15%	-	YES	A.BD_CZ	~ 3%
DE	Large number of measurements		NO	-	-
EE	~ 25%	-	NO	-	-
ES	Unknown		NO	One-time effort: 400 cases (INFILES Project)	
FR	Single-family: 30% Multi-family: 6%	Very few	YES	Qualibat (since 2007)	100%
GR	Very very few	-	YES	Aerosteganotita	?
JP	Common	Rare	NO	Some data by researchers	
KR	<10% (mostly large multi-family buildings)	Rare	YES	Building Airtightness Information Platform (BAIP)	? (1280 tests)
LV	5-15%	Public: 70-80%	NO	-	-
		Industrial: 5-10%			
NL	5-10%		NO	Data gathered (Retrotec's rCloud, SKH scheme, Uni. of Twente, etc.) but not published	
NO	~ 10%		NO	-	
NZ	Very few		NO	Some data gathered (Research and industry databases)	
US	>50% (depends on the states)	-	NO	Old one from LBNL (150 000 entries)	

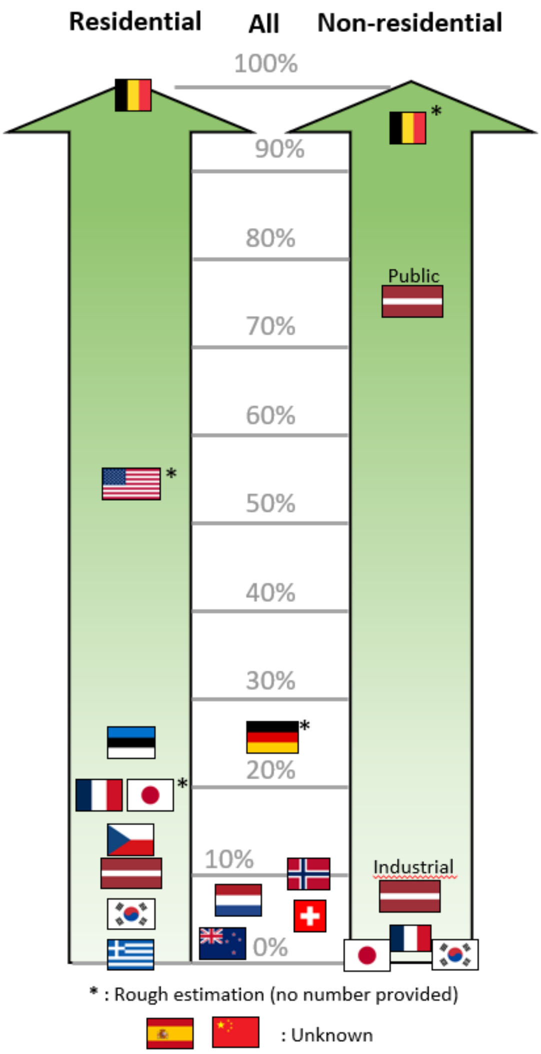

Figure 4: Percentage of new buildings (residential and non-residential) with an airtightness test performed according to the country

2.7. Guidelines to build airtight

In order to give guidance on how to meet more and more stringent building airtightness requirements, and more generally to limit air leakage and its impact on energy use, IAQ, moisture and noise, guidelines to build airtight have been developed in most countries (BE, CH, CN, CZ, DE, ES, FR, KR and US) either as an official national standard or document, or by specific institutions (see Table 7 and Figure 5). Such guidelines are in preparation in two additional countries (EE and JP), so in total there are only 5 out of the 16 countries with no guidelines existing or in preparation (GR, LV, NL, NO and NZ). This underlines the general interest on this issue in most countries.

Table 7: Details on the local guidelines to build airtight in the 16 countries

Country	Guidelines to build airtight		
	Existing?	Name	Details/Comments
BE	YES	Technical Guidance on building airtightness (by Buildwise)	Technical Information Note: recommended principles for constructing airtight buildings
CH	YES	SIA 180, SIA 4001, …	Standards that relate to specific components (roof, wall, window….)
		RiLuMi for Minergie	
CN	YES	Guideline T/CECS 826 (2021)	Applies to the design construction, and acceptance of airtight materials for building construction
CZ	YES	Standard ČSN 74 6077	Recommends several technical solutions for an airtight design of the window-to-wall interface
DE	YES	DIN 4108-7 (most important one)	Also: FLiB e.V.; DIN 4108-2 ; DIN EN 12152 ; DIN EN 12426 ; DIN 18015-5 ; The FLiB book Building Airtightness Volume 1 and 2 ; FLiB Research Report - Leakage Assessment
EE	In prep.		Estonian national standard under development
ES	YES	Basic Document for the Energy Saving in Buildings (DB HE1)	Construction solutions and workmanship of the building envelope for good airtightness
		UNE 8529:2016	Joints and discontinuities on the thermal envelope
FR	YES	Carnets Mininfil (2010)	Design and implementation guide for designers, craftsmen and construction companies
GR	NO	-	-
JP	In prep.		AIJ is currently formulating academic standards to improve building airtightness; a consortium study group on building airtightness of non-residential buildings has been established
KR	YES	National R&D study; practical guidelines by Korea Land & Housing Corporation (LH)	National study (with research institutes and construction companies): with the goal of establishing a national building airtightness performance standard and developing measurement methods.
LV	NO	-	-
NL	YES	SBR Handbook for airtight buildings : Luchtdicht bouwen - theorie-ontwerp-praktijk (2013)	Theory, design and practice of airtight construction, for residential and non-residential buildings Some manufacturers of buildings also provide guideline
NO	NO	-	Airtightness issues are important in the Norwegian building research details database
NZ	NO	-	Only scattered recommendations and articles
US	YES	Guidelines in many individual programs, usually in the form of checklists. Examples: ENERGY STAR Qualified Homes, Version 3 (Rev. 04), Inspection Checklists for National Program Requirements; IECC Air Barrier and Insulation Inspection Checklist; BPI Technical Standards for Certified Shell Specialists.	

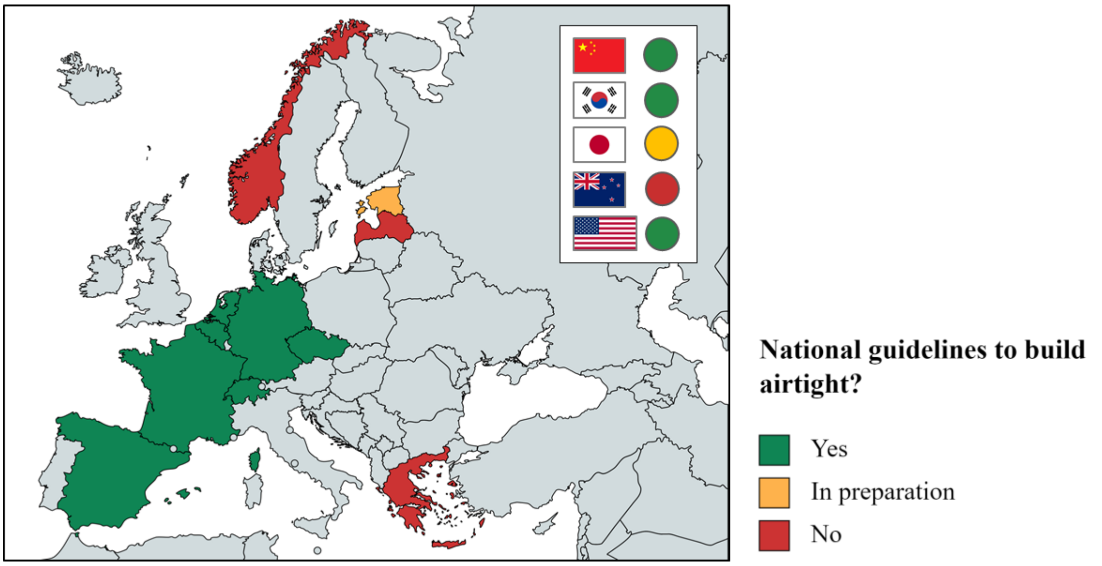

Figure 5: Existence of local guidelines to build airtight in the 16 countries

2.8. Conclusion

To conclude, there is a general growing interest on the building airtightness performance in the 16 countries of this overview. This is promoted by various ways, with different levels of constraint and of effectiveness. Some countries have implemented mandatory requirements with a maximum air leakage flowrate per envelope area or building volume to not overpass, but unfortunately not always with a mandatory justification required. Other countries rely on a disadvantageous airtightness default value in the EP calculation to encourage airtightness testing. Building airtightness is also promoted through other incentives: local or national subsidies; high-performance building labels (such as Passive House label); national standards or recommendations and certification schemes.

A summary of the information provided in this section about building airtightness in the 16 countries is presented in Table 8.

The authors have all underlined the significant progress regarding building airtightness in their country in the past decades, with the exception of Greece. Some of them have also mentioned foreseen new developments in the next years with an overall knowledge and quality of workmanship that is expected to increase (EE, CN); more demanding requirements and concerning more types of buildings (ES), more tests expected (CN, JP) in particular for non-residential buildings (FR, KR), local guidelines or standards under development (CZ, EE, JP, KR) or expected (NZ) and possible new implementation of airtightness requirements (California).

With the global increasing need for energy savings, one can expect that more and more countries over the world will develop incentives to promote building airtightness, and that countries with already existing requirements or recommendations will continue their efforts in the future.

Table 8: Summary of the building airtightness status in the 16 countries

Country	Mandatory requirements?	Mandatory justifications?	Included in EP calculations?	National qualif. for testers?	Mandatory qualification?	National guidelines for tests?	Tests performed in new buildings		Public database?	Guidelines to build airtight?
							Residential	Non-residential		
BE	NO	NO	YES	YES (Fl.)	YES	YES	alm. 100%	alm. 100%?	YES	YES
CH	NO	NO	YES	NO	NO	YES	~ 5%		NO	YES
CN	NO	NO	YES	NO	NO	YES	Unknown	-	NO	YES
CZ	NO	NO	YES	YES	NO	YES	<15%	-	YES	YES
DE	YES	NO	YES	YES	NO	YES	Large number		NO	YES
EE	NO	NO	YES	NO	NO	NO	~ 25%	-	NO	In prep.
ES	YES	formula	YES	NO	NO	NO	Unknown		NO	NO
FR	YES	YES	YES	YES	YES	YES	Singe-f.: 30% Multi-f.: 6%	Very few	YES	YES
GR	NO	NO	YES	YES	NO	NO	Very very few	-	YES	NO
JP	NO	NO	NO	YES	YES?	YES	Common	Rare	NO	In prep.
KR	NO	NO	YES	YES	NO	YES	<10%	Rare	YES	YES
LV	YES	NO	YES	NO	NO	NO	5-15%	Public: 70-80%; Indust.: 5-10%	NO	NO
NL	YES	NO	YES	NO	NO	YES	5-10%		NO	YES
NO	YES	YES	YES	NO	NO	YES	Very few		NO	NO
NZ	NO	NO	YES	YES	NO	NO	~ 10%		NO	NO
US	YES	NO	YES	YES	NO ?	YES	>50%	-	NO	YES

3. Ductwork airtightness

3.1. Introduction

We have underlined in the previous section focusing on building airtightness trends (2), the large number of incentives to promote a good airtightness of the envelope, proof of a growing interest on this issue in the past decades.

Less concern is however given regarding ductwork airtightness in most countries, despite a number of studies demonstrating the significant impact of ductwork leakage on energy consumption and on the IAQ, that have been summarised in a review published by the AIVC (VIP 40) (Leprince et al., 2020). Simplified models have been developed to quantify this impact and raise awareness (Hurel et al., 2023; Hurel and Leprince, 2022), but more time will probably be necessary to see a real and more global raise of awareness on this issue.

The aim of this section is to give on overview of the trends regarding ductwork airtightness in a similar way than the information presented for building airtightness in chapter 2. Only 15 countries are studied here as no information in ductwork airtightness has been provided yet for Switzerland.

One can note also, that several airtightness VIP authors wrote only a few sentences on the ductwork airtightness trends in their country to specify that ductwork airtightness has not been really considered or regulated yet (GR, JP, NO, NZ and LV). This is a good illustration of the gap between building and ductwork airtightness as on the other hand, all these authors wrote several pages on building airtightness.

3.2. Airtightness metrics

As the ductwork airtightness is less regulated than the building airtightness, there is less need to develop metrics, and some countries do not have an official one (GR, JP, NO and NZ). The metrics used in the other countries are listed below.

In **European countries**, as well as in **Korea**, the air leakage factor f ($m^3/(s.m^2)$) is used, which corresponds to the leakage flowrate divided by the ductwork area. Airtightness classes are defined by maximum f values in European standards[2]. Until 2017 the airtightness classes were ranging from A to D, with class A being the leakiest one, and a factor of 3 between the maximum f values of two consecutive classes. In 2017, EN 16798-3 introduced new names for ductwork airtightness classes; ranging now from classes ATC 1 to ATC 7, ATC 1 being the tightest one, ATC 6 the leakiest one, and ATC7 referring to non classified ductworks. The equivalence between the old and new names for airtightness classes and the corresponding maximum f values are given in Table 9.

Table 9: Classification of ductwork airtightness

Airtightness classes		Air leakage limit (fmax) according to the test pressure (p_t) ($m^3/(s.m^2)$)
Previous name	New name	
	ATC 7	Not classified
(2.5 A)	ATC 6	$0,0675 \times p_t^{0,65} \times 10^{-3}$
A	ATC 5	$0,027 \times p_t^{0,65} \times 10^{-3}$
B	ATC 4	$0,009 \times p_t^{0,65} \times 10^{-3}$
C	ATC 3	$0,003 \times p_t^{0,65} \times 10^{-3}$
D	ATC 2	$0,001 \times p_t^{0,65} \times 10^{-3}$
	ATC 1	$0,00033 \times p_t^{0,65} \times 10^{-3}$

In **Belgium**, the authors specified that the national regulations use specific metrics according to the type of ducts:

- For natural exhaust ducts, the total leakage flow for all ducts is expressed as Vleak,stack,zone [m³/h] at a reference pressure of 2 Pa (in accordance with NBN EN 14134:2019).

[2] EN 16798-3 for ductwork systems; EN 12237 for circular ductwork; EN 1507 for rectangular ductwork and EN 17192 for non-metallic ductwork; EN 1751 and EN 15727 for technical ductwork components

- For mechanical supply ducts, the total leakage flow for all ducts is expressed as Vleak,supplyduct,zone [m³/h] at the operational pressure of the ventilation system (in accordance with NBN EN 14134:2019).
- For mechanical exhaust ducts, the total leakage flow for all ducts is expressed as Vleak,extr.duct,zone [m³/h] at the operational pressure of the ventilation system (in accordance with NBN EN 14134).

In the **USA**, the awareness on this issue started early in the 1990s, as heating and cooling through air distribution is common in this country. For residential buildings, the most commonly used metric is to specify leakage as a fraction of total air flow through the duct. Another metric is the leakage flowrate at 25 Pa divided by the floor area (CFM25/ft²) (simplifying assumption relating system total air flow to floor area). There are other metrics that separate supply and return leaks or test at operating conditions rather than fixed pressures. For commercial buildings, leakage tests are normally only performed for high pressure duct sections and are normalised by duct surface area.

Finally, in **China** the metric used is the leakage flowrate divided by the ductwork area ($m^3/(h.m^2)$), but the tested pressure difference is not clearly defined.

3.3. Requirements and drivers

Mandatory requirements

Unlike for building airtightness with almost half of the countries (7) having mandatory requirements, only 4 countries have similar requirements for ductwork airtightness (EE, ES, CN and US), as detailed in Table 10 and illustrated in Figure 6.

Spain has the strongest requirements, with a maximum ductwork permeability of ATC 4 for all new and retrofitted buildings according to “Reglamento de instalaciones térmicas de los edificios” (RITE) since 2007, with a mandatory justification by test according to UNE-EN 12599:01 to prove compliance. However, the authors mentioned that in practice “there is not much concern among construction agents”, ductwork are not always tested and there are no sanctions if a ductwork does not comply with the requirements.

Three other countries have mandatory requirements, but without mandatory justifications: Estonia, China and the USA.

In Estonia, the requirements for ventilation systems in buildings require class ATC 4 (class B) or better for the whole system and recommend ducts and components of Class C or better. The requirements for the airtightness class of the ventilation ductwork are usually set by the ventilation designer based on the specific requirements of the building or room. the airtightness test is not always mandatory, and it depends on the customer's requirements and designer’s requirements in HVAC Project

In China, the ductwork airtightness is regulated for all types of buildings. The permitted air leakage rate is given according to the design pressure, as the leakage impact is more significant at high pressure, and to the type of ductwork: rectangular/circular (probably because rectangular ductwork can be harder to seal). The requirements are given in Table 11, with the equivalent airtightness class according to European standards (ATC). One can note that requirements are not very stringent below 500 Pa, especially for rectangular ductwork: 1.1 ATC 5 (Class A) but become ambitious at high pressure with 1.1 ATC 3 (Class C) required for both types of ducts.

Finally, in the USA the regulation depends on the jurisdictions as for building airtightness. In some states, voluntary energy programs have requirements for duct leakage. The US EPA/DOE Energy Star program and the IECC specify ≤ 4 CFM25 per 100 ft² of conditioned floor area or 40 CFM25 whichever is larger. This is at rough-in before the home is complete with drywall, grilles, etc. The allowed values are doubled to 8 CFM25 per 100 ft² and 80 CFM25 when the home is complete. In California, the building regulations require less than 6% of total system air flow. This leakage specification is also required for compliance with ASHRAE 62.2. Some states have adopted other duct leak limits, such as 6 (North Carolina) or 12 (Kentucky) CFM25 per 100 ft². For commercial buildings leakage requirements are based on "classes" disaggregated by the pressures in the duct system.

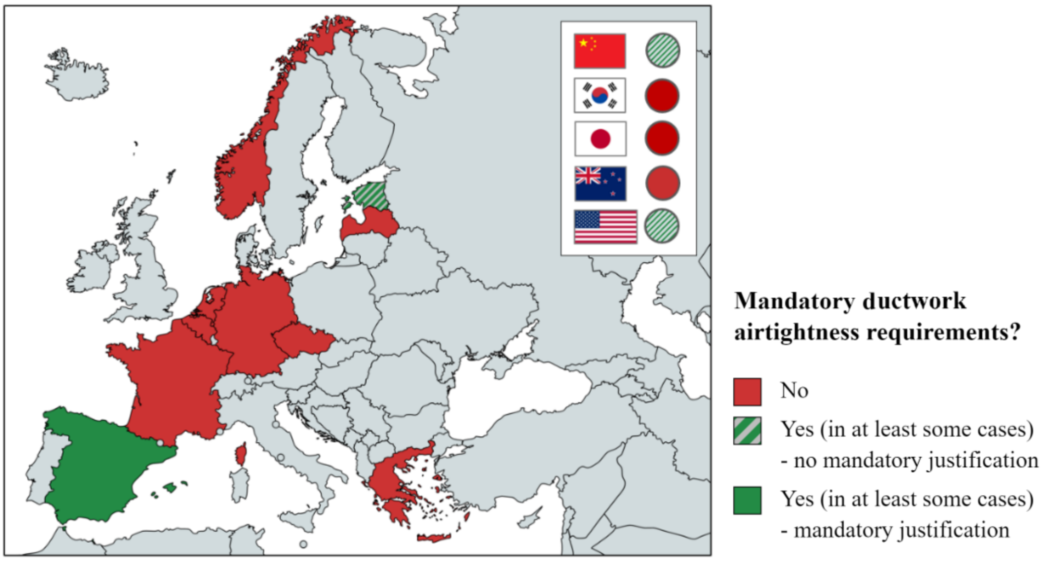

Figure 6: Ductwork airtightness requirements and justification in the 15 countries

Table 10: National mandatory requirements regarding ductwork airtightness currently in force in the 15 countries

Mandatory requirements?					
NO	YES				
	Country	Mandatory for:	Values		Mandatory justification?
			Indic.	Max. values	
	EE	All buildings?		ATC 4 (Class B) for ductwork, ATC 3 (Class C) for components	NO (only in case of contracted agreement)
	ES	New and retrofitted buildings		ATC 4 (Class B)	YES (by test since 2007 -UNE-EN 12599) but in practice: not always tested
	CN	All buildings	Q (m³/(m².h))	See Table 11 below	NO
	US	Some cases / States	CFM25 (CFM)	ENERGY STAR & IECC: Max (8 /100 ft²; 80) California & ASHRAE 62.2: 6% of total system airflow North Carolina: 6 /100 ft² Kentucky: 12 /100 ft²; …	NO

Table 11: Ductwork airtightness requirements in China with equivalence in terms of airtightness classes (ATC and old names)

Design pressure	Permitted air leakage rate $m^3/(m^2{\cdot}h)$			
	Rect. metal duct		Round metal duct	
	Requirement	Equiv. ATC Class	Requirement	Equiv. ATC Class
≤ 500 Pa	$\leq 0.1056P^{0.65}$	1,1 ATC 5 (A)	$\leq 0.0528P^{0.65}$	1,6 ATC 4 (B)
500 -1500 Pa	$\leq 0.0352P^{0.65}$	1,1 ATC 4 (B)	$\leq 0.0176P^{0.65}$	1,6 ATC 3 (C)
≥ 1500 Pa	$\leq 0.0117P^{0.65}$	1,1 ATC 3 (C)	$\leq 0.0117P^{0.65}$	1,1 ATC 3 (C)

Other incentives for ductwork airtightness

Other incentives than mandatory requirements to promote ductwork airtightness have been reported for some countries:

- Quality framework:
  - BE: due to the implementation of a quality framework for residential ventilation in Flanders in 2016, there is an indirect incentive for ductwork airtightness since ventilation flows are required to be measured.
- Recommendations in (non-mandatory) standards or other documents:
  - DE: DIN 1946-2:1994 requires that exhaust air ducts operated at positive pressure relative to the environment be ATC 4 (Class B) or better so that exfiltration of pollutants can be reliably prevented.
- Labels which include airtightness requirements:
  - CZ: there are optional building certification such as LEED, BREEM, etc.
  - FR: "Effinergie+" label requires a visual inspection of all the components of the ventilation system and a class ATC 5 (class A) for ductwork airtightness that must be justified by measurement.
- Subsidies (voluntary schemes):
  - US: For existing homes, there are many programs that require or provide incentives for improving duct leakage, such as The US DOE Weatherisation program and multiple voluntary utility programs. Some energy programs give rebates for duct sealing efforts.
  - DE: The guideline for federal funding for efficient buildings – non-residential buildings (BEG NWG) requires pneumatic balancing and proof of the airtightness of the air duct system. Additionally, for a promotion of energy and resource efficiency in the economy (EEW), a guideline was published in the Federal Gazette for Economy and Climate Protection on April 19, 2023, with in particular possible fundings for industrial and commercial facilities in case of investment to increase the energy efficiency for heat supply, cooling and ventilation.
- Regulation on the Specific Fan Power (SFP):
  - DE: because of the regulations on the SFP for air conditioning systems with > 12 kW of cooling capacity and for air handling units ≥ 4,000 m^3/h (SFP 4 or better), either a tight air duct system must be installed or the energy losses by duct leakage must be compensated for by other energy-saving measures on the air handling unit.

3.4. Ductwork airtightness in the energy performance calculation

The building airtightness was included in EP calculations for all countries but Japan, with various levels of accuracy and complexity. On the contrary, ductwork airtightness is rarely included in EP calculations, as illustrated in Figure 7 and detailed in Table 12.

In Belgium, it is included for residential buildings only, where a good ductwork airtightness can be valorised through a reduction in the factor m. This factor m is valorising the execution quality of the ventilation system, and can also be improved by taking into account the adjustment of valves and the degree of self-regulation of the natural inlets and outlets.

In Germany, it is possible to include the ductwork airtightness in EP calculations, but this is done only for "nominal operation", which is the exception rather than the rule as it implies additional costs. Such calculations are carried out only when anomalies are detected in energy consumption during the building-use phase, or for the return-on-investment calculations.

In France, the ductwork airtightness influences the total air change rate of the internal volume as it is taken into account in the calculation of the ventilation flow rate, and thus has an impact on the heating and/or cooling needs. A disadvantageous airtightness level of ATC 6 (2.5 Class A) is taken as a default value, and better performance must be justified. In case of conditioned air, heat and cold losses through ductwork air leakage are also taken into account. The additional fan energy use to compensate for air leakage is however not directly taken into account. The nominal fan power is supposed to be corrected by the design office when needed to account ductwork leakage but in practice it is usually not done.

Finally, in the USA, the regulation depends again on the jurisdictions. For the States that have adopted the IECC energy codes, one way of compliance is to use 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. The reference home has an assumed duct energy efficiency of 80% and the rated home uses the ASHRAE Standard 152 calculation method, with a steady state thermal model which includes leakage and conduction losses based on standard heat exchanger pipe heat transfer and simplified calculation methods for space temperatures surrounding ducts. In California, a multizone air flow and thermal model is used to calculate the impacts of duct leakage as a reference that other compliance software must match. Duct efficiency is calculated using procedures based on ASHRAE Standard 152. California uses a default duct leakage based on vintage, of 15% prior to 2013 and 5% since 2013 due to the introduction of minimum duct performance requirements that year.

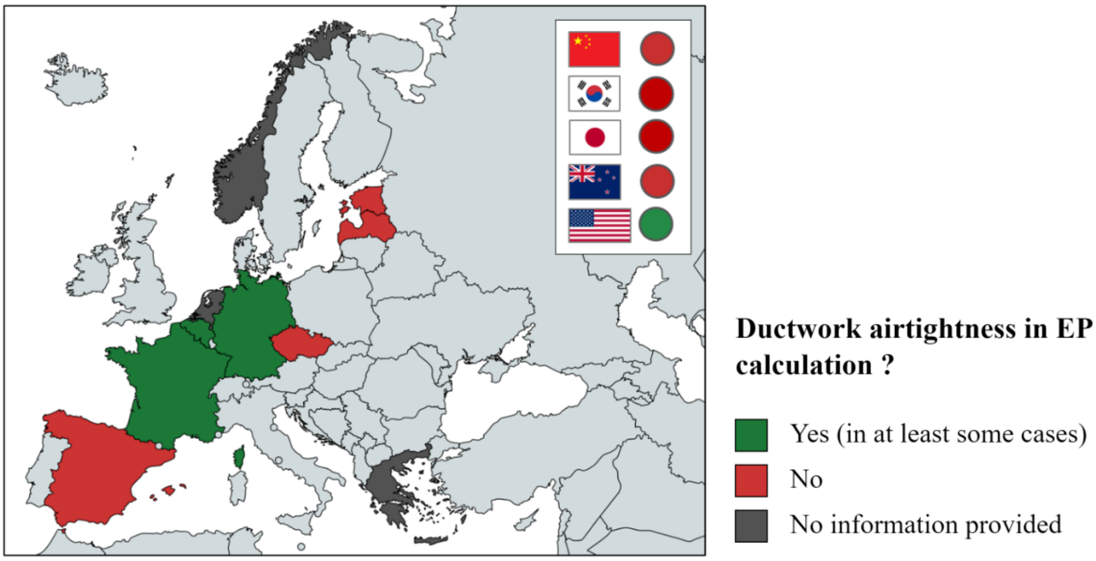

Figure 7: Inclusion of ductwork airtightness in the Energy Performance calculations for the 15 countries

Table 12: Ductwork airtightness in the Energy Performance calculations

Country	Details	Default values		
		Used?	Values	Comments
BE	non-residential: NO residential: can be valorised through a reduction in the factor m (valorising the execution quality of the vent. system)	-		
DE	For "nominal operation" only, which is the exception rather than the rule (additional costs): carried out when anomalies are detected in energy consumption or for the return-on-investment calculation	No information provided		
FR	The ductwork airtightness influences the total air change rate of the internal volume (included in the calculation of the ventilation flow rate)	YES	2.5 Class A	Any other class used in the EP calculation has to be justified
USA	RESNET (one of the IECC compliance path): steady state thermal model which includes leakage and conduction losses	NO?		
	California: multizone air flow and thermal model	YES	15% prior to 2013; 5% since 2013	

3.5. Ductwork airtightness test protocol

Only three countries have national qualification for ductwork airtightness testers: France, the Netherlands (for utility buildings), and the USA (see Table 13). And this qualification is mandatory only in France, in case the results are used for the EP calculation or to check compliance with labels' requirements.

Similarly, the same three countries are the only one with national guidelines for ductwork airtightness tests, as further detailed in Table 13. One can note that in the USA, several guidelines have been developed to differentiate testing in residential and non-residential buildings, and two levels of complexity for the residential ones.

The lack of qualification schemes for testers and national guidelines in most countries underlines once again that ductwork airtightness is generally less of a national concern than building airtightness.

3.6. Ductwork airtightness tests performed

As there are few countries with requirements on ductwork airtightness, and few national incentives to encourage good airtightness performances, there are also very few airtightness tests performed in new ventilation systems in most countries, as detailed in Table 14 and illustrated in Figure 8.

In most countries the percentage of new buildings which have a test on the ductwork airtightness is very low (or unknown), with the exception of:

- The USA: with probably more than 50% of residential buildings tested (no information provided for non-residential ones)
- Estonia: with almost 100% of public buildings being tested as it is necessary to perform a test only in the case of contracted agreement, which is almost always the case for state buildings, but usually not for detached houses (estimated to be 10-15% of all new buildings).
- Spain: the authors did not provide a precise percentage, but the number of tests is estimated to be low despite the theoretical mandatory justification of the ductwork airtightness by test.

The difference in the percentage of airtightness tests performed in buildings and ductworks is striking when comparing Figure 4 and Figure 8.

Concerning public database with the results of ductwork airtightness tests collected and publicly available, only two countries have implemented it: France with 100% of the test results collected, and Estonia, where in theory all test reports should be uploaded to the Estonian building registry[3].

[3] https://livekluster.ehr.ee/ui/ehr/v1

Table 13: Ductwork airtightness tests: national qualifications for testers and national guidelines

Country	National qualification for testers			National guidelines		
	Existing?	Mandatory?	Name	Existing?	Name (year)	Specificities
BE	NO	NO	-	NO	-	-
CN	NO	NO	-	N/A	-	-
CZ	NO	NO	(2 accredited laboratories to test products)	NO	-	-
DE	NO	NO	-	NO	-	Testing in accordance with DIN EN 12599
EE	NO	NO	-	NO	-	Finnish standard SFS 3542 sometimes used
ES	NO	NO	Usually: technicians who install the system also test it	NO	-	-
FR	YES	YES (for official justifi-cations)	Qualibat (133 testers)	YES	FD E 51-767 (Tests have to comply with EN 12237, EN 1507, EN 13403 and EN 12599)	- sampling rules for multi-family dwellings - rules to select a sample of houses among a group of houses, and a sample of ductworks for buildings than include more than 5 fans. - ductwork preparation requirements - reference pressure difference of the test depending of the type of building - corrections that shall be applied for particular situations
GR	N/A	N/A	-	N/A	-	-
JP	NO	NO	-	NO	-	-
KR	NO	NO		NO	-	-
LV	NO	NO	-	NO	-	-
NL	YES?	NO	LUKA for utility buildings (no official scheme)	YES	LUKA Quality Guide	Provides details on the test procedure for the airtightness of ducts
NO	NO	NO	-	NO	-	-
NZ	NO	NO		NO		
US	YES	NO	BPI (BPI 2017 ANSI/BPI-1200-S-2017) and RESNET	YES	For residential: - More commonly used for residential: ANSI/RESNET 380 - More advanced test methods in ASTM Standard (ASTM E1554) - In California (and ref. in ASHRAE 62.2): California Building Energy Efficiency Standards, Residential Appendix RA3.1 (CEC 2019) For non-residential: also fixed-pressure duct testing methods	

Table 14: Ductwork airtightness tests: percentage of buildings tested and public database

Country	Residential buildings	Non-residential buildings	Public database		
			Existing?	In charge:	% of tests
BE	< 1%	-	No	(not public: VEKA in Flanders)	limited
CN	Very few		NO	-	-
CZ	Very limited for special installations		NO	-	-
DE	Unknown		NO	-	-
EE	Single house: very few	Public: almost 100%	YES	Estonian building registry	In theory 100% (but less)
	10-15%				
ES	Rather low		NO	-	
FR	Few (1323 tests in 2020)		YES	Cerema	100%
GR	Close to 0%		NO	-	-
JP	Unknown		NO	-	-
KR	0%	Some tests	NO	-	-
LV	Very few		NO	-	-
NL	Negligible	Some tests	NO	-	-
NO	Unknown		NO	-	-
NZ	Unknown		NO	-	-
US	>50% (depends on the states)	-	NO	Old one from LBNL (150 000 entries)	

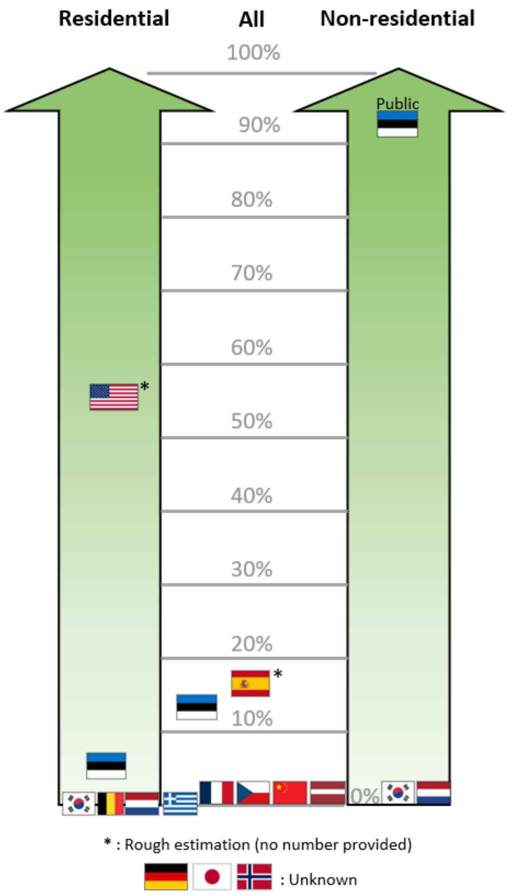

Figure 8: Percentage of new buildings (residential and non-residential) with a ductwork airtightness test performed according to the country

3.7. Guidelines to build airtight ductwork

In 6 out of the 15 countries, there are guidelines available to build airtight ductwork (see Table 15), developed as:

- Standards:
  - CN: the main guidelines are the standards GB 50738-2011 and JGJ 141-2017, compiled by the Ministry of Housing and Urban-Rural Development of the People's Republic of China. In order to build qualified ductwork, material selection, production, installation and inspection, etc., are stipulated.
  - FR: The DTU 68.3 is a national standard that provides rules for design and installation of ventilation systems in residential buildings. Its application it not mandatory regarding regulatory context, but it is very widely required by building owner for insurance purposes. Regarding ductwork airtightness, DTU 68.3 gives recommendations with technical drawings.
  - US: the California building standards include thorough instructions for duct and envelope sealing (California Energy Commission. 2019 Residential Compliance Manual for the 2019 Building Efficiency Standards, Title 24, Part 6).
- Documents from associations of manufacturers:
  - DE: Installation recommendations for square seamed air duct (HFL 4000: 2017) and round seamed air duct (spiral duct) (HFL 4001: 2017) have been published by the Air Duct Manufacturers Association (HFL). Moreover, at the professional association for building services engineering (FGK), a guide to the best practices for the construction of tight air ducts (Good Practice Guide Air Ducts) is currently being prepared in Working Group 10 (Air Ducts).
  - NL: A handbook has been published by LUKA, the Dutch trade association of ductwork manufacturers.
- Document from a public company:
  - EE: The only local guideline is compiled by RKAS, which is a public real estate development and management company, with reference to European standards.

5 other countries have no local guidelines to build airtight ductwork (BE, CZ, ES, JP and KR), and the authors from 4 additional countries did not report information on guidelines (GR, LV, NO and NZ) but mentioned that ductwork airtightness was not really a concern locally.

One can note that in Korea, the SPS-KARSE B 0016-0178:1999 standard describes the assembly method for the main sectors of the ductwork and emphasises the importance of ensuring a tight seal between ducts. However, this standard does not provide specific instructions on how to build airtight ductwork during the construction process. The guidelines and procedures for airtight construction of ducts are mainly developed privately by research institutions and construction companies.

Table 15: Details on the local guidelines to build airtight ductwork in the 15 countries

Country	Guidelines to build airtight ductwork		
	Existing?	Name	Details/Comments
BE	NO	-	-
CN	YES	Standard GB 50738-2011 and JGJ 141-2017	Stipulated: material selection, production, installation and inspection, etc.
CZ	NO	-	Every producer provides their products with installation description
DE	YES	HFL 4000 and HFL 4001	Installation recommendations by the manufacturers association (HFL); At the professional association for building services engineering (FGK), a “Good Practice Guide Air Duct” is currently being prepared
EE	YES	RKAS guideline	
ES	NO	-	-
FR	YES	DTU 68.3 (national standard)	Rules for design and installation of ventilation systems in buildings. Widely required by building owner for insurance purposes
GR	N/A	-	-
JP	NO	-	-
KR	NO	-	Mainly developed privately by research institutes and companies
LV	N/A	-	-
NL	YES	LUKA Handbook	Combination of internal policies and adherence to international standards
NO	N/A	-	-
NZ	N/A	-	-
US	YES	California: building standards include thorough instructions for duct and envelope sealing Many organisations provide training for testing and sealing ductwork: - US DOE Building America: BSC information on duct sealing for all climates - Energy Star duct sealing guidance for homeowners - SMACNA HVAC Duct Construction Standards - Metal and Flexible - ACCA Quality Installation Specification	

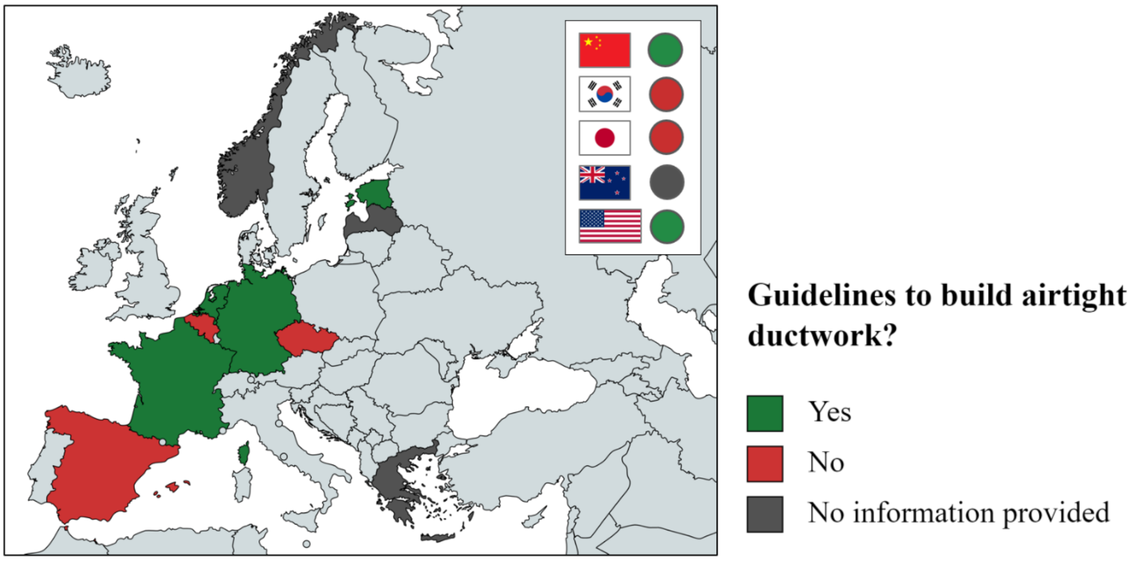

Figure 9: Existence of local guidelines to build airtight ductwork in the 15 countries

3.8. Conclusion

This overview on ductwork airtightness trends and regulations in 15 countries has shown that there is not yet a global concern and very significant interest on this issue, unlike for the envelope airtightness.

The main exception among the studied countries is the USA which has mandatory requirements in some States; ductwork airtightness sometimes included in the EP calculation, national qualifications and guidelines for testers; the highest percentage of tested buildings; and national guidelines to build airtight ductwork. This is probably explained by the early awareness, starting in the 1990s, because heating and cooling through air distribution is common in this country.

For the other countries, we have seen some national efforts to promote airtight ductwork, with for example national requirements in Estonia, Spain and China, but in most cases, it does not guarantee a good airtightness level nationally, as in general there are in practice only few tests performed.

A summary of the information provided in this section about ductwork airtightness in the 15 countries is presented in Table 16.

To conclude, despite a growing number of scientific studies proving the importance of ductwork airtightness, so far, less efforts are done nationally to address this issue. However, as building envelopes are getting tighter, the air renewal relies more and more on mechanical ventilation, which is also increasing the necessity of airtight ductwork to reduce energy losses and guarantee a proper IAQ. As a result, in a context of a global increasing need for energy savings, one can expect that more and more attention will be given on ductwork airtightness in the future.

Table 16: Summary of the ductwork airtightness status in the 15 countries

Country	Mandatory requirements?	Mandatory justifications?	(Sometimes) included in EP calculations ?	National qualification for testers?	Mandatory qualification?	National guidelines for tests?	Tests performed in new buildings		Public database?	Guidelines to build airtight?
							Residential	Non-residential		
BE	NO	NO	YES	NO	NO	NO	< 1%	-	NO	NO
CN	YES	NO	NO	NO	NO	N/A	Very few		NO	YES
CZ	NO	NO	NO	NO	NO	NO	Very limited for special installations		NO	NO
DE	NO	NO	YES	NO	NO	NO	Unknown		YES	YES
EE	NO	NO	NO	NO	NO	NO	Few (usually no test)	Public: almost 100%	NO	YES
ES	YES	YES	NO	NO	NO	NO	Rather low		NO	NO
FR	NO	NO	YES	YES	N/A	YES	Few (1323 tests in 2020)		YES	YES
GR	NO	NO	N/A	N/A	N/A	N/A	Close to 0%	-	NO	N/A
JP	NO	NO	NO	NO	NO	NO	Unknown		NO	NO
KR	NO	NO	NO	NO	NO	NO	0%	Some tests	NO	NO
LV	NO	NO	NO	NO	NO	NO	Very few		NO	N/A
NL	NO	NO	N/A	YES	NO	YES	Negligible	Some tests	NO	YES
NO	NO	NO	N/A	NO	NO	NO	Unknown		NO	N/A
NZ	NO	NO	NO	NO	NO	NO	Unknown		NO	N/A
US	YES	NO	YES	YES	NO	YES	>50% (depends on the states)	-	NO	YES

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ANNEX 5

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