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Abstract

Air infiltration through the building envelope has already been proven to have a significant energy impact in dwellings. Different studies have been carried out in Europe, but there is still a lack of knowledge in this field regarding mild climates. An experimental field study has been carried out in the Mediterranean climate area of Spain and the Canary Islands in order to assess the air permeability of the building envelope and its energy impact. A wide characterization and Blower Door tests have been performed in 225 cases in Alicante, Barcelona, Málaga, Sevilla and Las Palmas de Gran Canaria for this purpose. The obtained mean air permeability rate for the 225 studied cases was 6.56 m3/(h·m2). The influence of several variables on airtightness was statistically analysed, although only location, climate zone and window material were found to be significant. Air infiltration has an energy impact between 2.43 and 16.44 kWh/m2·year on the heating demand and between 0.54 and 3.06 kWh/m2·year on the cooling demand.

Keywords	Air infiltration; Airtightness; Blower door test; Residential buildings; Database
Taxonomy	Building Technology, Building Energy Analysis, Building Air Tightness, Construction Design
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Submission Files Included in this PDF

File Name [File Type]

COVER LETTER.docx [Cover Letter]

Response to reviewer 1.docx [Response to Reviewers]

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COVER LETTER

This work presents the results of the first extensive permeability experimental study carried out in the Mediterranean climate area of Spain and the Canary Islands. Its relevance is unquestionable, since there is a clear lack of knowledge in this concern in Mediterranean countries.

It has already been proved that air leakage causes a great impact in the energy performance of buildings. Regulations in most European countries establish maximum air change rates due to infiltrations for the construction of new dwellings and the refurbishment of the existing ones. However, in temperate climate countries (including Spain), air leakage is vaguely considered. As a consequence, problems of over-ventilation, uncontrolled air flows, poor indoor air quality and energy consumption are caused.

This paper contributes to characterize the envelope of the residential building stock in the Mediterranean area of Spain and the Canary Islands in terms of airtightness with real data. No extrapolation can be made from other areas or countries, given that construction systems and typologies vary from one region to another. A national database with representative samples is being accomplished. This is essential in order to identify common construction deficiencies and propose guidelines to avoid them.

All things considered, the authors strongly believe that the presented study constitutes a major contribution in the field, presenting the first permeability results in this areas of Spain. The study is a first step to fill the gap regarding this lack of knowledge, which will be complemented with future work.

The authors acknowledge that the submission declaration has been complied with and necessary permissions have been obtained.

Response to reviewer 1

Authors would like to thank you for your feedback regarding the paper. Improvements have been made based on the comments and suggestions received in the review.

The changes made are listed here:

- Sample: section 2.1 describes the sample chosen for the study. 225 is the number of dwellings tested, being some of them individual houses and, most of them, individual apartments in buildings. Two tests (Method A and Method B) were performed in each one.
- Year of construction: this parameter has not directly been addressed. However, all the cases have been divided into three categories according to the regulations which had to comply with. In other words, three periods can be distinguished: 1890-1979, 1980-2006, 2007-2015. Results for each period are shown in table 2. It can be seen that dwellings seem to be tighter the newer they are. Nevertheless, this relationship was found to be statistically not significant.
- Protocol: to ensure that the sealings and closure of different elements for Method B were consistent for all the cases, a protocol was created for the purposes of the study. In this protocol a specific section was included, detailing the required position of the openings (showed in Table 1) and example pictures. More information can be found in a previous paper, which describes the methodology (doi:10.3390/en11040704). A sentence has been added in the manuscript to clarify this issue.
- Calibration: a sentence has been added to point out that the equipment was calibrated, according to manufacturer's indications and guarantee of calibration.
- Grammar: the first sentence in the abstract has been grammatically corrected.

All things considered, we hope that this upgraded version complies with all the requirements and quality to be published.

Yours faithfully,

The authors

Response to reviewer 2

Authors would like to thank you for your feedback and comments regarding the paper.

Substantial changes have been made in order to improve it. The changes made are listed here:

1. Energy impact of infiltration: it is difficult to estimate the relative influence of air infiltration on the total energy consumption. The total energy consumption depends on many variables (location, orientation, shape of the building, relative position, materials and composition of the building envelope, retrofitting estate, shading patterns, etc.). Therefore, in order to estimate this value, specific simulation should be performed for each case study. Further research is expected to fill this gap. Nevertheless, estimation could be roughly performed for dwellings built after 2006, since regulations limited the energy demand. The energy impact of air infiltration can be divided by the maximum energy demand required, obtaining this way the percentage corresponding to air infiltration. It was obtained that infiltration can have an impact of 9-66% for heating and 2-11% for cooling. However, authors decided not to include this information given the inaccuracy of the calculation. On the one hand, the energy demand of regulations is a limit, but dwellings could have lower energy demands. On the other hand, regulations do not limit infiltration, therefore, it only considers an unreal value for airtightness for the energy demand estimation.
2. Page 6, line 1: it is clarified that the mentioned "Construction systems during the 20th century" refers specifically to the area under study.
3. Page 8, 2.1. Sample: the sampling method has been slightly elaborated. However, there is a reference to a previous paper (reference 14) with a more extended explanation.
4. Page 9, 2.1. Sample: the choice of the control variables has been elaborated. However, there is a reference to a previous paper (reference 14) with a more extended explanation.
5. Page 12: equations 3-7 have been obtained from EN 13829:2000. Thermal performance of buildings. Determination of air permeability of buildings. Fan pressurization method. (ISO 9972:1996, modified). Equations 1-2 have been empirically obtained from the power law equation.
6. Page 13: inter-zonal leakage estimation has been broadened to several studies that gathered different casuistries, not only the single case study referenced in the original manuscript. This way, it is estimated that leakage between different units can lead to a wide range of representativeness. The consideration of the whole leakage for the energy impact estimation covers the most unfavourable situation.
7. Page 14: it has been clarified that the energy impact of infiltrations estimation based on the comfort indoor temperature is theoretical. The real energy consumption depends on the particular temperature conditions of the dwellings, which is a so varying parameter and depending on the occupants, that would not be possible to calculate.
8. Page 16: *infilAPP* is a tool specifically developed for the study purposes by the research team. A reference to a previous paper covering the methodology of the study has been added.

All things considered, we hope that this upgraded version complies with all the requirements and quality to be published as a full paper.

Yours faithfully,

The authors

Energy impact of the air infiltration in residential buildings in the Mediterranean area of Spain and the Canary Islands

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Abstract

Air infiltration through the building envelope has already been proven to have a significant energy impact in dwellings. Different studies have been carried out in Europe, but there is still a lack of knowledge in this field regarding mild climates. An experimental field study has been carried out in the Mediterranean climate area of Spain and the Canary Islands in order to assess the air permeability of the building envelope and its energy impact. A wide characterization and Blower Door tests have been performed in 225 cases in Alicante, Barcelona, Málaga, Sevilla and Las Palmas de Gran Canaria for this purpose. The obtained mean air permeability rate for the 225 studied cases was 6.56 $m^3/(h \cdot m^2)$. The influence of several variables on airtightness was statistically analysed, although only location, climate zone and window material were found to be significant. Air infiltration has an energy impact between 2.43 and 16.44 $kWh/m^2 \cdot$year on the heating demand and between 0.54 and 3.06 $kWh/m^2 \cdot$year on the cooling demand.

Keywords

Air infiltration; Airtightness; Blower door test; Residential buildings; Database

1. Introduction

Residential buildings are responsible for one of the highest levels of energy consumption. It is the most common building use in the world with approximately 2 billion dwellings and around 214 million in the European Union alone. In Spain there are about 26 million homes, being 66.1% of them apartments in multi-family buildings [1].

The European Strategy for Sustainable Development, as well as the Paris Agreement reached after the United Nations Climate Change Conference [2] in 2015 (XXI UNFCCC) have promoted political awareness and established contemporary criteria of energy saving and efficiency and the reduction of emissions, especially from buildings. This has led to the need to define joint strategies aimed at achieving solutions to the high energy consumption related to building development.

However, the low replacement rate of existing and outdated dwellings by new ones under the new energy standards requires action with applicable models on existing buildings. These strategies are oriented towards the achievement of a low-energy housing stock or near Zero Energy Buildings (*nZEB*). These strategies seek to reduce energy losses through the envelope by improving heat transmission by conduction, which has been extensively solved through the use of more and better thermal insulation. In this sense, energy loss due to infiltration becomes a relevant issue to the overall energy impact of the building.

Previous studies have assessed the energy loss through ventilation processes, which is greater than 30% of the final energy used in dwellings [3]. The nZEB strategies consider the heat recovery from the extraction air, improving this way the energy efficiency. However, heat recovery is only possible in controlled ventilation processes. Thus, in order to achieve nZEB, it is important to limit infiltration to tolerable limits. The uncontrolled ventilation through leakage paths due to a deficient design and construction entails a challenge.

Air infiltrations through the building envelope produce a phenomenon of air mass exchange between the inside and the outside of the conditioned space, causing energy transfer with different hygrothermal conditions of the air. This transfer means not only the reduction of the conditions of comfort of the occupants but also extra energy consumption. Therefore, airtight envelopes must be designed in order to reduce the uncontrolled consumption of hygrothermal energy caused by infiltrations but also, they must be combined with efficient HVAC systems to provide a sufficient clean air flow in the optimum hygrothermal comfort conditions.

Numerous studies have been carried out so far in northern Europe, which estimate an energy impact of air infiltration on heating demand of around 10 kWh/m^2·year in regions with a moderately cold climate (2500 degrees-day) [4]. Other studies indicate that the lack of airtightness of the building envelope can increase the heating demand from 5 to 20 kWh/m^2·year in countries with temperate climates [5]. However, in Spain knowledge regarding this issue is still scarce. Some studies have been carried out in the south of the country [6,7] and in the Continental climate area of the country [8]. From the energy point of view, a study carried out by Meiss and Feijó [9] in 13 dwellings in the north of Spain obtained the first results to this respect. It was estimated an energy impact of infiltration between 10.5 and 27.4% of the energy demand in buildings built under the Technical Building Code (CTE) [10], between 21.9 and 27% in buildings regulated by the standard NBE CT-79 [11] and between 11.3 and 13% in buildings of previous construction but retrofitted by their occupants.

The vast existing housing stock in the eastern and southern coast of Spain has required the detailed evaluation of the energy impact of the air infiltration. In these regions, it is typical the absence of thermal insulation of the envelope, as well as constructions defects due to an accelerated urban expansion in recent decades.

The objective of this study is to collect and classify relevant information regarding the energy impact of air leakage through the thermal envelope of residential buildings located in the Mediterranean climate area of Spain in order to reduce its energy impact. The coastal regions around the Mediterranean Sea and the archipelago formed by the Canary Islands are evaluated. This study seeks not only to characterize the current housing stock, but also to establish construction systems that have an impact on air infiltration.

1.1. Climate Classification

Permeability tests were performed in 5 locations in Mediterranean climate areas of Spain and the Canary Islands: Alicante (ALC), Barcelona (BCN), Málaga (MAL), Sevilla (SEV) and Las Palmas de Gran Canaria (LPA) (Figure 1). In order to define the specific climatic conditions of each location, Köppen Climate Classification [12,13] was applied. This system defines distinct types of climate using average monthly values for precipitation and air temperature.

Type *B* climates are characterized for being dry climates, which Köppen distinguished between sub-type *BS* (steppe), and the sub-type *BW* (desert), in relation to the annual rainfall. These areas are also classified as hot climates (*h*), or cold climates (*k*) depending on whether the average annual temperature is below or above 18 °C. Climate type *BSh* can be found in Alicante and *BWh* climate in Las Palmas de Gran Canaria. On the other hand, climates type C are classified as temperate climates, where the average temperature in the coldest months is between 0 and 18 °C. Sub-type *Csa* climate refers to dry and hot summers (average temperature in the hottest month above 22 °C) whereas in *Csb* climates summers are temperate. Climate type *Csa* can be found in Sevilla, Málaga and Barcelona, covering most of the Iberian Peninsula and the Balearic archipelago, occupying approximately 40% of its surface.

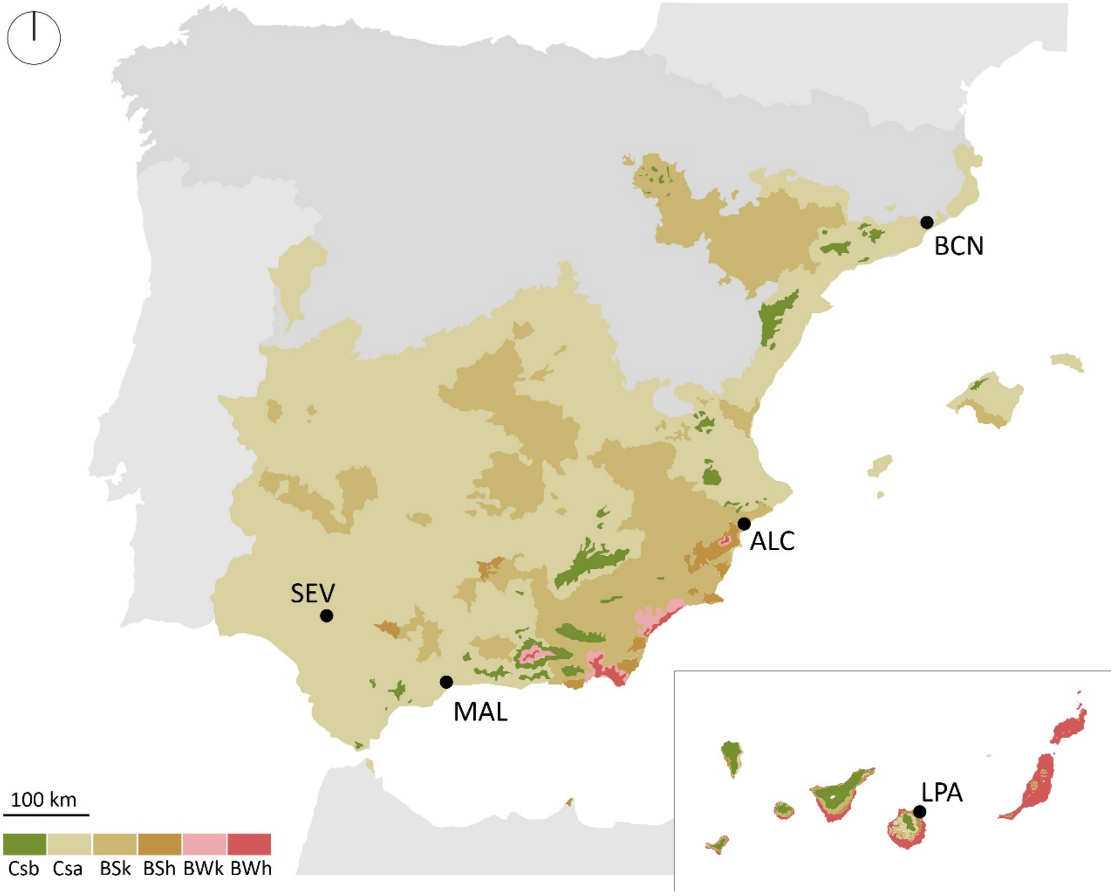


Figure 1: Köppen Climate Classification of the Spanish territory. Tests location.

1.2. The building envelope in the Mediterranean area of Spain and the Canary Islands

These areas are characterized by a low construction quality of the residential buildings. This is due to a large degree to the rapid building expansion suffered in the 70s and 80s derived from the great growth of tourism, which required a large number of dwellings in a short period of time. This fact resulted in deficit buildings that entail an important energetic impact.

Traditional building systems, usually before the 50s, are based on load-bearing walls of a single layer of variable thickness (always greater or equal to one foot), of ceramic bricks of different qualities coated with lime mortar to the exterior. With the generalization of concrete in the 60s, the facades have no longer a structural function and, therefore, they are lightened. Also remarkable is a significant proportion of self-built single-family housing ~~in this area~~.

In general terms, the construction systems during the 20th century in the Mediterranean area of Spain and the Canary Islands can be classified in three periods divided by the introduction of regulations regarding the energy performance of the buildings, namely, the NBE CT-79 [11] in 1979 and the Spanish Technical Building Code (CTE) [10] in 2006:

- Dwellings before 1979:
    - Façade: usually built with two layers of hollow brick, a small air chamber between them, and a finishing layer with cement mortar and painting. No thermal insulation is used. The interior finish is normally made of continuous plaster. In the specific case of the Canary Islands, the façade is made with a single layer of concrete hollow block with, without thermal insulation.
    - Roof: conventional trafficable flat roof, with terrazzo or ceramic tiles or gravel finish.
    - Windows: made of lacquered wood, aluminium or steel without thermal bridge break. In kitchens and bathrooms, it is common to place windows with orientable glass slats. Simple glass of 4 mm.
    - Shading: shutters, folding blinds, traditional exterior wooden rolling shutters or rolling shutters integrated into the enclosure.
- Dwellings complying with NBE CT-79:
    - Façade: double layer of double hollow brick, with 3-4 cm of thermal insulation in some occasions and air chamber. The most common façade finish is based on monolayer or plaster mortar. Ventilated facade systems begin to be introduced. The interior finish is normally made of continuous plaster. In the Canary Islands, the façades begin to be built with single-layer walls, without thermal insulation, generally executed with concrete double hollow block, externally coated with monolayer mortar or cement mortar and sand, finished with painting.
    - Roof: conventional or inverted (mostly after the 90s) trafficable flat roof, with terrazzo or ceramic tiles or gravel finish.

    - Windows: made of aluminium or PVC. In kitchens and bathrooms, windows with orientable glass slats are used at the beginning of this period. Simple glass with air chamber.
    - Shading: rolling shutters integrated into the enclosure. From the 90s, compact rolling shutters are introduced.
- Dwellings complying CTE:
    - Façade: a solution of two brick layers: a thicker one at the outside and another thinner one at the interior, with an intermediate air chamber. The insulation layer increases its thickness. The interior finish is usually a continuous plastering layer, often replacing it with lightweight plasterboard systems. In the case of the Canary Islands, the most common façade system is composed of a main layer of concrete hollow block, intermediate thermal insulation and an interior layer of concrete double hollow block. On the outside, the coating can be quite diverse: monolayer coatings, discontinuous coatings with natural stone or ceramic cladding, concrete panels, ventilated façades, external thermal insulation (ETI) systems, etc.
    - Roof: inverted trafficable flat roof, with terrazzo or ceramic tiles or gravel finish.
    - Windows: made of aluminium with thermal bridge break, recovering in some cases the wooden window. Double glass with air chamber.
    - Shading: compact rolling shutters and sliding shutters in some cases.

Therefore, regarding the airtightness of the building envelope in this area, it is possible to highlight the lightening of the façade, usually interrupted by the concrete slab, the introduction of the rolling shutters as a discontinuity of the envelope and the use of lightweight plasterboard systems in the last decades. It is also important to mention the presence of non-conditioned service spaces annexed to the kitchens and terraces, whose volume has in many cases been integrated into the conditioned space of the house through its closure with carpentry. Inadequate and careless execution of these systems has contributed to a poor energy performance of the dwellings.

1.3. Ventilation and conditioning systems

In the Mediterranean climate area of Spain and the Canary Islands, ~~V~~ventilation has traditionally been done in a natural way by manually opening the windows. Hence, air leakage has been the only continuous air inlet in dwellings. The installation of orientable glass slats in kitchens and bathrooms until the end of the 20th century in some locations also constitute a continuous ventilation source. It is often crossed ventilation through the exterior façade and light shafts, which also contributed to improve thermal comfort of the dwelling. Usually kitchens and bathrooms are ventilated through the unconditioned service spaces attached to this rooms. After the implementation of the NBE CT-79 natural air extraction is installed in bathrooms and kitchens by means of a vertical duct. After the introduction of CTE in 2006, controlled mechanical or hybrid ventilation is mandatory.

Regarding the conditioning systems, due to the climatic benevolence of this area, dwelling have usually no heating or refrigerating system. Only after 1970 individual air conditioning units were introduced in some cases. During the 70s and the 80s radiators (portable electric devices or standard ones) were used in winter. After the year 2000 HVAC systems have been frequently designed with a direct expansion split heat pump system, with outdoor unit on the deck and indoor unit in the bathroom, and ductwork along the corridor. In Barcelona, central heating systems with water radiator terminals were common solutions during the 20th century and its use has been extended again during in recent years. To a lesser extent, installations of hot water radiators with gas heater and boiler have been carried out in single-family homes, combined with a multi-split system for summer.

2. Methodology

2.1. Sample

The study has focused on the building typologies of the area of interest, ensuring the representativeness of the sample. A non-probabilistic quota sampling scheme has been considered in order to ensure the heterogeneity and proportionality of the selected cases. This method reproduces the population on a smaller scale on the basis of a considered sample size [14]. The residential stock in the Mediterranean area of Spain including the Canary Islands has been proportionally stratified into subgroups (strata) according to a series of control variables, namely, the period of construction, typology (single-family or multi-family housing) and the climate zone. The control variables have been chosen due to its impact on airtightness according to previous studies, being its distribution known [14].

A total of 225 cases built between 1890 and 2015 have been studied. The location of the cases according to typology and year of construction is shown in Figure 2. The distribution of the cases according to its main characteristics was assessed in order to verify the representativeness of the sample tested.

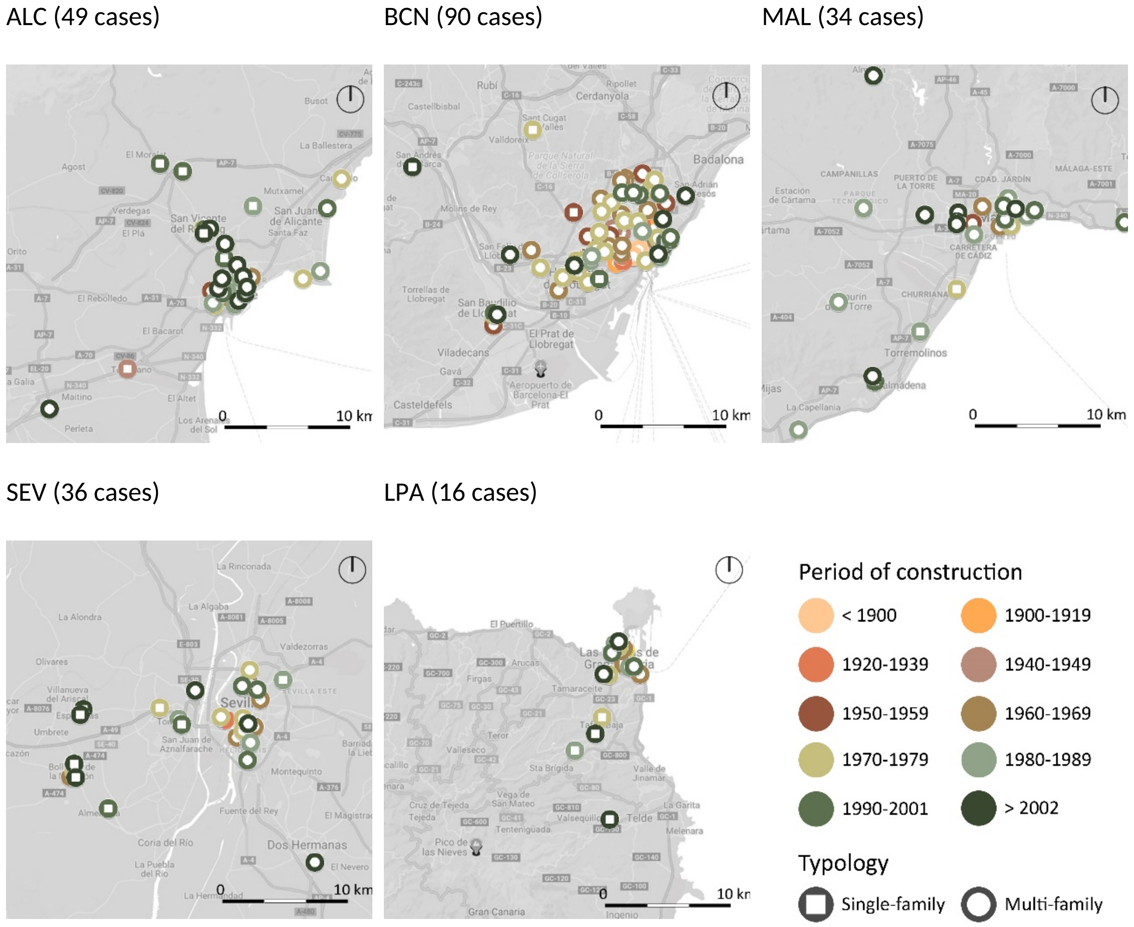


Figure 2: Location of the studied cases.

The year of construction has proven to be a significant factor regarding airtightness because it is related to regulations, deterioration of materials and joints [15] and development of construction systems. Regarding regulations (aforementioned in section 1.2) 53% of the sample was built before NBE CT-79 was implemented, 37% of the cases were built after it came into force and 10% after CTE. However, it was also taken into account if dwellings were in an original state (71%) or, by contrast, it had been retrofitted (29%).

Typology has also been considered, clearly reflecting the fact that multi-family housing prevails in this area. 76% of the cases were apartments within buildings and only 24% of the sample were single-family houses (isolated or detached). In the cases of apartments, the relative position of the dwelling was assessed: 72% of the apartments were located in an intermediate position with conditioned spaces in contact with the horizontal envelope, whereas 19% occupied the upper floor and only 9% the lower floor.

Construction systems were analysed from different points of view. Massive construction tradition can be proved in the sample with 99% of the cases. The envelope is usually built with a double massive layer (80% of the sample), intermediate insulation material (54%) or no insulation (44% of the cases) and air chamber (56%) or none (44% of the sample). The façade has in most of the cases (64%) an outer coating. The internal massive layer of the envelope and partition walls are mainly massive as well, although the most recent cases tend to introduce lightweight solutions (8% of the sample). Regarding windows, which constitute critical points of the envelope, the prevailing material is aluminium (71% of the sample) and most of the cases had rolling shutters (76%).

Finally, ventilation and conditioning systems have been assessed. Most of the housing stock in this area (90%) has natural ventilation by manually open the windows, given that regulations did not implemented controlled ventilation systems until the entry into force of CTE. Most of the cases had some sort of heating system (75%, 58% with water or electric radiators), whereas 45% had a refrigeration system, mostly based on individual units. The distribution of the cases according to its main characteristics is detailed in Annex I.

2.2. Testing method

The evaluation of the airtightness of the envelope has been carried out by means of the procedure described by the European Standard EN 13829 [16] which is a modified version of the International Standard ISO 9972:2006. The procedure, commonly called Blower Door Test, causes a stationary pressure differential inside the area to be tested with respect to the atmospheric conditions of the exterior. This standardized procedure establishes two possible evaluation methods:

- Method A is a test of the building in use. It evaluates the condition of the building envelope in its condition during the season in which the heating or cooling systems are used.
- Method B tests the building envelope. For that purpose, any intentional opening in the building envelope shall be closed or sealed (Table 1).

For the objectives proposed for this study, the analysis of Method B is considered more adequate, although tests are carried out by both methods in order to consolidate the results and perform possible complementary studies. A protocol was designed to ensure that the preparation of each dwelling was consistent for all the cases.

	Method A	Method B
Mechanical ventilation openings (air shafts, exhaust hood, etc.)	Closed and switched off	Sealed and switched off
HVAC ducts	Closed and switched off	Closed and switched off
Atmospheric open heaters	Closed and switched off	Sealed and switched off
Natural ventilation openings (adjustable)	Closed	Sealed
Natural ventilation openings (always open)	Opened	Sealed
Closing shaft chimney ducts	Closed	Sealed
Opened shaft chimney ducts	Opened	Sealed
Overflow sinks and sinks without hydraulic seal	Opened	Fulfilled/sealed
Hydraulic seal	Fulfilled	Fulfilled/sealed
Cupboards and closets	Closed	Closed
Outer doors and windows	Closed	Closed
Inner doors	O~~o~~pened	Opened

Table 1: Preparation of the building envelope for Methods A and B.

In addition, each case is tested under pressurization and depressurization conditions, minimizing the influence of wind and temperature action on the envelope. The final results of the infiltration and exfiltration flows are averaged to obtain a global value.

The correct calibration of the equipment was ensured to maintain accuracy specifications of 1% of reading, or 0.15 Pa.

2.3. Fundamentals

The infiltration curve is calculated according to the power law equation, based on the fundamental mechanics airflow [16] (equations 1 – 3).

$$n=\frac{\sum_r\left(Ln(|\overline{p}_r-\Delta p|)-\frac{\sum_r Ln(|\overline{p}_r-\Delta p|)}{r}\right)^2}{\sum_r Ln(|\overline{p}_r-\Delta p|)-\frac{\sum_r Ln(|\overline{p}_r-\Delta p|)}{r}\cdot Ln\left(c_d\cdot {P_r}^{n_d}\cdot\frac{\rho_o}{\rho_i}\cdot\sqrt{\frac{\rho_{20°C}}{\rho_o}}\right)-\frac{\sum_r Ln\left(c_d\cdot {P_r}^{n_d}\cdot\frac{\rho_o}{\rho_i}\cdot\sqrt{\frac{\rho_{20°C}}{\rho_o}}\right)}{r}} \qquad (1)$$

$$Cenv=e^{\left(\frac{\sum_r Ln\left(c_d\cdot {P_r}^{n_d}\cdot\frac{\rho_o}{\rho_i}\cdot\sqrt{\frac{\rho_{20°C}}{\rho_o}}\right)}{r}-\frac{n\cdot\sum_r Ln(|\overline{p}_r-\Delta p|)}{r}\right)} \qquad (2)$$

$$Cl=Cenv\cdot\left(\frac{\rho_o}{\rho_k}\right)^{1-n} \qquad (3)$$

where:

r is the number of samples taken in each case at different pressures [-].

$\overline{p}_r$ is the average pressure in each test sample [Pa].

Δp is the pressure differential in the test [Pa].

c_d is the reference flow rate for each diaphragm of the BlowerDoor [m^3/h].

P_r is the ventilation pressure in each sample [Pa].

n_d is the reference exponent for each diaphragm [-].

n is the air flow exponent [-].

ρ_o is the air density outside the building [kg/m^3].

ρ_i is the air density inside the tested dwelling [kg/m^3].

$\rho_{20°C}$ is the reference air density at 20°C [kg/m^3].

ρ_k is the calculation density for the interior temperature [kg/m^3].

$Cenv$ is the air Flow coefficient [m^3/(h·Pa^n)].

Cl is the air leakage coefficient [m^3/(h·Pa^n)].

The following parameters related to the infiltration phenomenon, which allow the comparison of results in different buildings, are evaluated (equations 4 – 7):

$$V_{50} = Cl \cdot 50^n \qquad (4)$$

$$q_{50} = \frac{V50}{Ae} \qquad (5)$$

$$w_{50} = \frac{V50}{Af} \qquad (6)$$

$$n_{50} = \frac{V50}{Vol} \qquad (7)$$

where:

V_{50} is the air leakage rate at 50 Pa [m^3/h].

q_{50} is the air permeability at 50 Pa [m^3/(h·m^2)].

w_{50} is the specific leakage rate at 50 Pa [m^3/(h·m^2)].

n_{50} is the air change rate at 50 Pa [h^{-1}].

Ae is the envelope area [m^2].

Af is the floor area [m^2].

Vol is the internal air volume [m^3].

It is important to note that in multi-family dwellings the non-guarded pressurization test does not allow to distinguish between the infiltration that occurs through the façade and the one produced in walls in contact with conditioned spaces (other dwellings) or unconditioned zones (common areas of the building). Inter-zonal leakages have been previously assessed by several studies with different methods in buildings with varying characteristics. It has been estimated that inter-zonal leakages can ~~represent~~ account for~~around 27~~ 2 to more than 60% of the total air leakage ~~[17]~~[17]. Therefore, the proportion of leakage between internal units in multi-family buildings can be within a wide range depending on building characteristics. In any case, the total infiltration rate was taken, which for energy impact purposes is the most unfavourable situation.

2.4. Energy impact assessment

The estimation of the energy impact of infiltration is a complex issue, given that it depends not only on the airtightness of the building envelope, but also on meteorological conditions that are sometimes difficult to predict. There is no common criterion about the appropriate model to evaluate the energy impact of infiltrations. Different calculation models have been developed so far with varying degrees of complexity and reliability. The more simplified models assume a uniform distribution of leakage paths and constant average leaks over time.

The energy impact of infiltrations has been assessed by means of a simplified model (equation 8), applying the concept of degree-day, which relates the average temperature outside the tested dwelling and the comfort indoor temperature (21°C for heating and 25°C for cooling). It is important to note that this estimation is theoretical and real energy consumption depends on the particular temperature conditions of the dwellings. This calculation procedure allows to evaluate the energy impact considering specific climate data of the locations where the tests have been performed, as a product of the air infiltration flow, the specific air capacity and the temperature difference between the inside and the outside of the dwelling [18].

$$Q_{inf} = C_p \cdot G_t \cdot V_{inf} \qquad (8)$$

where:

Q_{inf} is the annual energy loss [kWh/y] due to air infiltration for heating $Q_{inf\ -H}$ and cooling $Q_{inf\ -C}$. Annual energy losses are expressed per unit area.

C_p is the specific heat capacity of the air, which is 0.34 Wh/m^3·K.

G_t are the annual degree days [kKh/year], both for heating (G_{t-C}) with a base comfort temperature of 21 °C, and for cooling G_{t-R} with a base comfort temperature of 25 °C.

V_{inf} is the air leakage rate [m^3/h].

V_{inf} needs to be obtained from the values obtained from the test, which are expressed at a pressure difference of 50 Pa and do not reflect the actual filtration process to which the dwelling is subjected. Therefore, the results must be transformed into real filtration equivalent flows. The estimation of the actual filtration is complex, given that the wind and temperature conditions throughout the year are difficult to foresee and the test does not give precise information related to the distribution of infiltration leakages.

The Persily-Kronvall estimate [19], is a simple and widespread model in the scientific community. Its origin is uncertain, and it assumes a linear relationship between permeability at 50 Pa and the average annual infiltration (equation 9).

$$q_{inf} = \frac{q_{50}}{20} \qquad (9)$$

where:

q_{inf} is the air permeability [$m^3/(h \cdot m^2)$].

Subsequently, this linear relationship between airtightness and infiltration evolved [19] incorporating coefficients according to the characteristics of the location (equations 10 and 11).

$$q_{inf} = \frac{q_{50}}{\mathrm{N}} \qquad (10)$$

$$\mathrm{N} = \mathrm{C} \cdot \mathrm{cf}_1 \cdot \mathrm{cf}_2 \cdot \mathrm{cf}_3 \qquad (11)$$

where:

N is a constant.

C it is the climatic factor, calculated in the model from hourly climate data for more than 200 points in the US and Canada. Its value is in the range 15 - 30.

cf_1 is the height correction factor of the building, applicable to buildings in which the tested spaces are in 1 floor ($cf_1 = 1$) up to 3 floors ($cf_1 = 0.7$).

cf_2 is the site shielding correction factor, for well shielded cases ($cf_2 = 1.2$), ($cf_2 = 1$) or exposed dwellings ($cf_2 = 0.9$).

cf_3 is the leakiness correction factor, dependent on the value of the leakage exponent n. Buildings with small cracks, a typical situation of typical tighter buildings are given a correction factor $cf_3 = 1.4$, whereas leakier buildings with large holes have a correction factor $cf_3 = 0.7$.

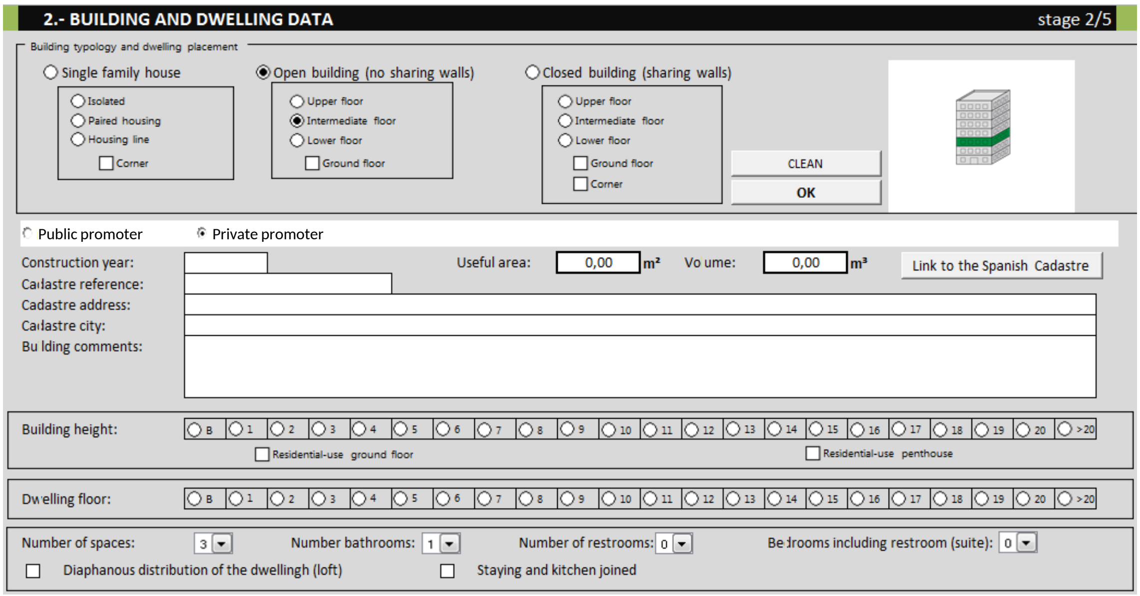
This extended simplified model has been adopted for the calculation of the average infiltration flow in the Mediterranean area of Spain and the Canary Islands, obtaining the value of the climatic factor C by assimilation to the US climates, comparatively according to the average temperature and wind speed. For the coefficients cf_1, cf_2 and cf_3 a value equal to 1 has been adopted in the three cases. The type of infiltration opening was obtained from the mean value of the flow exponent $n = 0.59$.

The air leakage rate V_{inf} needed for the calculation of the energy impact is calculated from the air permeability rate and the envelope area (equation 12):

$$V_{inf} = q_{inf} \cdot A_E \quad (12)$$

2.5. Airtightness database

The performance of the tests in each case was carried out by trained technicians, who have a tool (*infil-APP* [14]) to capture characterization information (Figure 3) and to import test data from the software provided by *Minneapolis Blower Door Model 3* (TECTITE 5.0).



○ Single family house
- ○ Isolated
- ○ Paired housing
- ○ Housing line
- ☐ Corner

● Open building (no sharing walls)
- ○ Upper floor
- ● Intermediate floor
- ○ Lower floor
- ☐ Ground floor

○ Closed building (sharing walls)
- ○ Upper floor
- ○ Intermediate floor
- ○ Lower floor
- ☐ Ground floor
- ☐ Corner

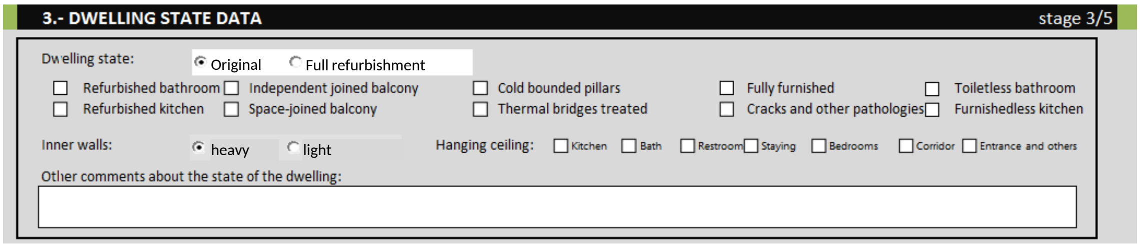
○ Public promoter ● Private promoter

Construction year:
Cadastre reference:
Cadastre address:
Cadastre city:
Building comments:
Useful area: 0,00 m²
Volume: 0,00 m³

Building height: ○ B ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ 10 ○ 11 ○ 12 ○ 13 ○ 14 ○ 15 ○ 16 ○ 17 ○ 18 ○ 19 ○ 20 ○ >20
☐ Residential-use ground floor ☐ Residential-use penthouse

Dwelling floor: ○ B ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ 10 ○ 11 ○ 12 ○ 13 ○ 14 ○ 15 ○ 16 ○ 17 ○ 18 ○ 19 ○ 20 ○ >20

Number of spaces: 3
Number bathrooms: 1
Number of restrooms: 0
Bedrooms including restroom (suite): 0
☐ Diaphanous distribution of the dwellingh (loft)
☐ Staying and kitchen joined



3.- DWELLING STATE DATA stage 3/5

Dwelling state: ● Original ○ Full refurbishment

☐ Refurbished bathroom ☐ Independent joined balcony ☐ Cold bounded pillars ☐ Fully furnished ☐ Toiletless bathroom
☐ Refurbished kitchen ☐ Space-joined balcony ☐ Thermal bridges treated ☐ Cracks and other pathologies ☐ Furnishedless kitchen

Inner walls: ● heavy ○ light

Hanging ceiling: ☐ Kitchen ☐ Bath ☐ Restroom ☐ Staying ☐ Bedrooms ☐ Corridor ☐ Entrance and others

Other comments about the state of the dwelling:

Figure 3: Screenshot of "infil-APP". Characterization of the dwelling.

This tool was specifically developed for the characterization of 140 parameters that can intervene in the phenomenon of filtration. These parameters are collected in a database that is used for the global evaluation of the results.

3. Results

3.1. Airtightness results

The distribution of the values obtained for the air change rate (n_{50}), the air permeability (q_{50}), the specific leakage rate (w_{50}) at 50 Pa and the air flow exponent (n) for the whole sample are shown in Figure 4.

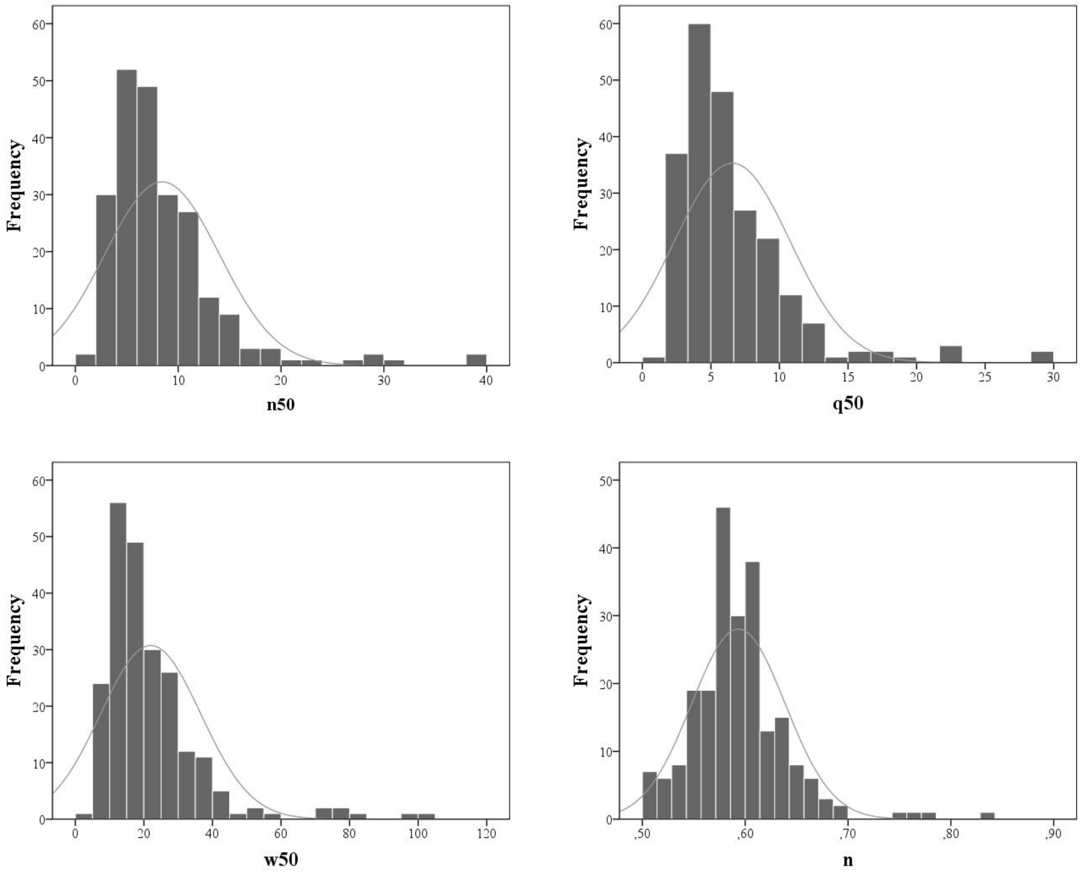


Figure 4: Distribution of test results for the whole sample

Mean values obtained for the assessed sample are shown in Table 2. The results obtained for q_{50} ranged from 1.90 to 39.42 $m^3/(h·m^2)$ with a mean value of 6.56 $m^3/(h·m^2)$, median 5.48 $m^3/(h·m^2)$ with a standard deviation of 4.24.

The flow exponent (n value) gives information regarding the resistance to the passage of air of the leakage paths, being close to 1 for laminar flows (airtight dwellings) and close to 0.5 for turbulent flows (leaky dwellings) [20]. The mean flow exponent n for the whole sample was 0.59.

The influence of different parameters on the air permeability rate at 50 Pa (q_{50}) has been assessed by means of Kruskal-Wallis test [21] in order to statistically verify the independence of the variables. Table 2 shows the values obtained for the test statistic *Chi-square* and the significance (*Sig*.), which can be considered significant for values below 0.05 (indicated by a *). Thus, a statistically significant relationship was found between the air permeability rate and the location of the dwellings, climate zone and window material (*Sig*. < 0.05).

Maximum q_{50} values were found in Barcelona and Sevilla (q_{50} = 7.53 and 6.81 $m^3/(h·m^2)$ respectively) and minimum values in Las Palmas de Gran Canaria (q_{50}= 4.60 $m^3/(h·m^2)$). Dwellings located in temperate climates with dry and hot summers (*Csa*) performed worse in terms of airtightness (q_{50} = 6.84 $m^3/(h·m^2)$) than those in dry hot desert climates (*BWh*), with q_{50} = 4.60 $m^3/(h·m^2)$. Although the sample size was irregular for different window materials, dwellings with aluminium windows (q_{50} = 5.90 $m^3/(h·m^2)$) performed better than those made of wood (q_{50} = 8.87 $m^3/(h·m^2)$).

Variable	**Category**	**cases**	**n_{50}** [h^{-1}]	**q_{50}** [$m^3/(h·m^2)$]	**w_{50}** [$m^3/(h·m^2)$]	**n** [-]	**Chi-square** (q_{50})	**Sig.** (q_{50})
TOTAL	-	225	8.43	6.56	21.97	0.59	-	-
Location	ALC	49	7.78	6.26	19.99	0.61	13.89	0.008*
	BCN	90	9.78	7.53	25.79	0.58		
	MAL	34	5.81	5.16	17.23	0.60		
	LPA	16	5.43	4.60	14.78	0.59		

	SEV	36	8.88	6.81	23.16	0.58		
Climate zone	BSh	49	7.78	6.26	19.99	0.61	7.83	0.020*
	BWh	16	5.43	4.60	14.78	0.59		
	Csa	160	8.93	6.84	23.30	0.59		
Regulations	None	118	8.99	6.96	23.83	0.59	2.17	0.338
	CT-79	84	8.11	6.35	20.64	0.60		
	CTE	23	6.78	5.25	17.27	0.60		
Typology	Multi-family	172	8.80	6.51	22.62	0.59	0.88	0.348
	Single-family	53	7.25	6.73	19.85	0.59		
Relative position	Lower	16	8.15	6.04	20.96	0.59	0.20	0.905
	Intermediate	123	9.14	6.75	23.62	0.59		
	Upper	33	7.84	5.82	19.72	0.59		
Developer	Private	188	8.56	6.77	22.42	0.59	0.93	0.335
	Public	37	7.76	5.49	19.70	0.60		
Retrofitting state	Original	159	8.51	6.52	22.09	0.59		
	Retrofitted	66	8.24	6.64	21.69	0.60		
Window material	Steel	4	8.85	6.75	22.92	0.59	18.03	0.000*
	Aluminium	158	7.67	5.90	19.64	0.60		
	Wood	46	11.19	8.87	30.49	0.58		
	PVC	16	7.53	6.18	19.24	0.59		
Rolling shutters	None	54	7.48	5.70	20.43	0.60	3.13	0.209
	Added	16	8.07	5.87	20.22	0.58		
	Integrated	155	8.80	6.93	22.69	0.59		
Massive layers	Single	46	7.46	5.98	20.93	0.59	0.85	0.357
	Double	179	8.68	6.71	20.93	0.59		
Insulation layer	None	120	8.97	6.84	23.79	0.59	1.12	0.249
	Interior	6	5.09	4.79	12.56	0.61		
	Intermediate	97	7.95	6.27	20.24	0.60		

	Exterior	2	9.74	8.84	24.76	0.55		
Air chamber	None	99	7.96	6.21	21.42	0.59	3.37	0.186
	Regular	118	8.81	6.77	22.39	0.59		
	Ventilated	8	8.81	7.62	22.71	0.58		
Partition walls	Lightweight	18	10.31	7.87	26.37	0.60	2.42	0.120
	Massive	207	8.27	6.44	21.59	.059		
Outer coating	No	81	8.45	6.65	21.98	0.59	0.00	0.961
	Yes	144	8.42	6.51	21.97	0.59		
Ventilation system	Natural	202	8.62	6.71	22.51	0.59	1.71	0.191
	Mechanical	23	6.78	5.25	17.27	0.60		
Heating system	No	56	9.18	6.68	24.19	0.58	0.25	0.616
	Yes	169	8.19	5.52	21.24	0.60		
Refrigerating system	No	121	8.50	6.76	22.63	0.59	1.02	0.312
	Yes	104	8.36	6.33	21.20	0.60		

Table 2: Mean values obtained depending on different variables and Kruskal-Wallis test results.

3.2. Energy impact

The energy impact estimation of the air infiltration obtained, both for the heating and cooling demand, is shown in Table 2 and Figure 5 for each of the locations studied. Furthermore, results are also expressed according to the period of construction, corresponding to implemented regulations. Figure 6 shows the tendency for each city where the study has been carried out.

	Ud.	**ALC**	**BCN**	**MAL**	**SEV**	**LPA**
N	-	22	22	23	20	19
q_{inf}	m³/(h·m²)	0.28	0.34	0.22	0.34	0.24
Q_{inf-H}	kWh/m²·year	10.02	16.44	8.61	14.21	2.43
Q_{inf-C}	kWh/m²·year	1.60	0.73	0.78	3.06	0.54
Q_{inf-H} **(no regulations)**	kWh/m²·year	10.42	16.43	10.55	14.63	3.55
Q_{inf-C} **(no regulations)**	kWh/m²·year	1.66	0.73	0.96	3.16	0.75

$Q_{inf\ -H}$ (CT-79)	kWh/m^2·year	10.08	16.90	8.03	15.92	1.89
$Q_{inf\ -C}$ (CT-79)	kWh/m^2·year	1.61	0.75	0.73	3.43	0.42
$Q_{inf\ -H}$ (CTE)	kWh/m^2·year	8.42	14.14	6.36	9.92	1.39
$Q_{inf\ -C}$ (CTE)	kWh/m^2·year	1.34	0.63	0.58	2.14	0.31

Table 3: Energy impact of infiltration results.

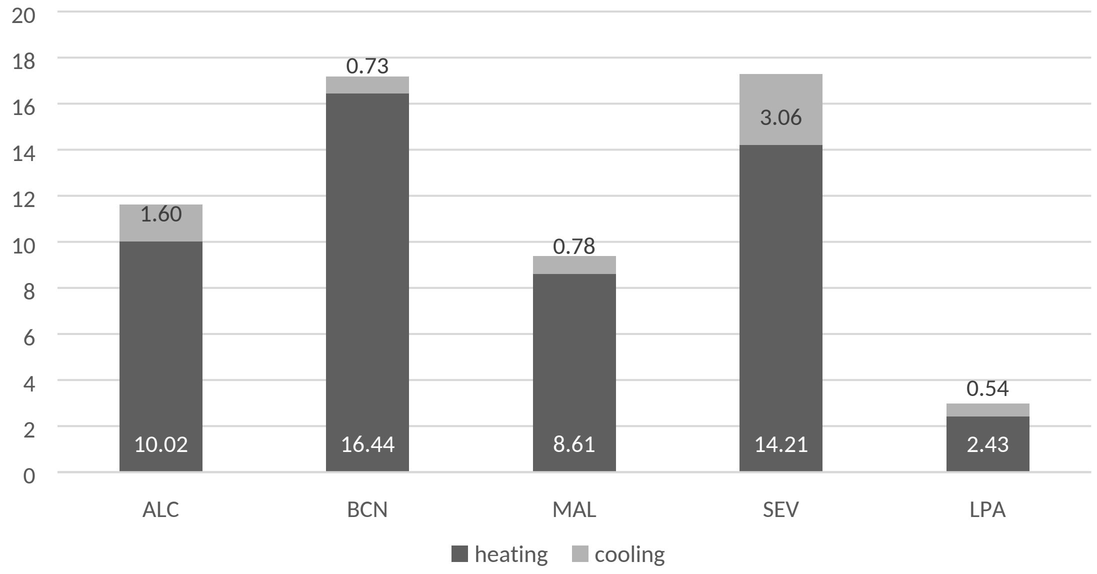


Figure 5: Annual energy losses (kWh/m^2·a) for heating and cooling due to infiltration.

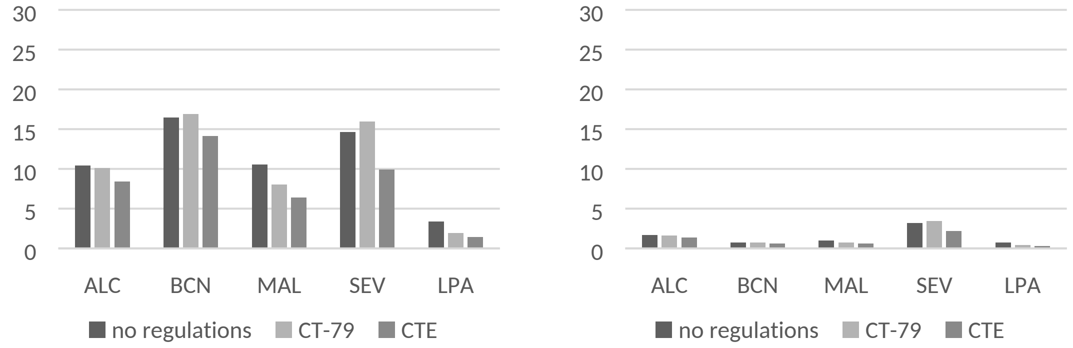


Figure 6: Annual energy losses (kWh/m^2·a) for heating (left) and cooling (right) due to infiltration, classified per regulations.

The energy impact has a greater impact on the heating demand, especially in Barcelona and Sevilla. Values up to 16.44 kWh/m^2·y have been obtained for the energy impact corresponding to the heating demand in the case of Barcelona, while in Las Palmas de Gran Canaria with hot climate, the value is reduced to 2.43 kWh/m^2·year. In the case of cooling demand, the energy impact of air infiltration is lower, with maximum values of 3.06 kWh/m^2·y in the case of Sevilla, whereas in Las Palmas de Gran Canaria this value is reduced to 0.54 kWh/m^2·year.

Regarding regulations, there is a general progressive improvement trend in all locations. It can be pointed out, though, that in Barcelona and Sevilla the oldest dwellings built during the first period performed better than the ones built after the entry into force of NBE CT-79.

4. Conclusions

The airtightness and the impact of the air infiltration through the building envelope in dwellings in Spanish cities with a Mediterranean climate and the Canary Islands has been assessed.

The mean air permeability rate at 50 Pa for the 225 studied cases was found to be 6.56 m^3/(h·m^2), whereas for the air change rate at 50 Pa the mean obtained value was 8.43 h^{-1}. These results are significantly higher than the average air change rate of 7.5 h^{-1} obtained for other case studies in different European countries [22] and the average air change rate 6.99 h^{-1} obtained in a previous study in the Continental area of Spain [8].

As for the flow exponent n, the obtained mean value was 0.59, associated to air loose construction solutions related to massive systems found in this area. Values close to 0.6 have been associated with leakage around the openings of the envelope [7].

Location, climate zone and window material were found to be statistically significant parameters that have an impact on airtightness. No statistically significant relationship was found between the air permeability rate and the other parameters analysed. General trends can be observed, although further analysis and a larger simple should be considered in order to deduce accurate conclusions.

In spite of the fact that the assessed area has a mild climate, the energy impact affects mainly the heating demand. Air infiltration has an energy impact between 2.43 and 16.44 kWh/m^2·year on the heating demand and between 0.54 and 3.06 kWh/m^2·year on the cooling demand. These results are in line with the values previously stated in other studies [5]. A general improvement trend can be observed regarding the implementation of regulations, although a fast expansion of the cities could have probably derived in poor quality construction in the cases of Barcelona and Sevilla during the period 1980 – 2006.

There is currently no limit in Spain regarding the airtightness of the building envelope in buildings (CTE only establishes requirements for windows). Consequently, compliance with the European Directive 2018/844 seems only possible by implementing limitations in this respect applicable both to the design of new buildings and to the renovation of the existing housing stock.

5. Acknowledgements

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Declarations of interest: none

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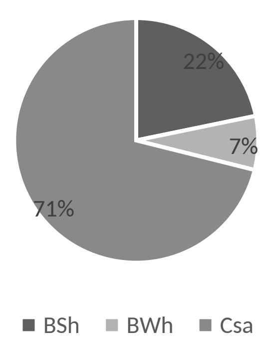
Annex I: characterization assessment of the sample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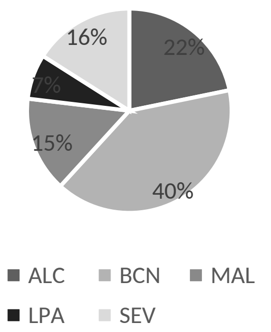
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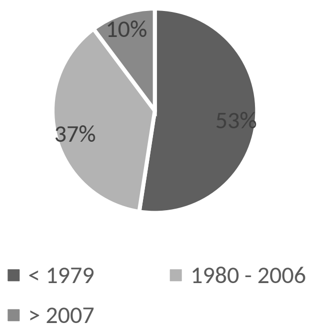
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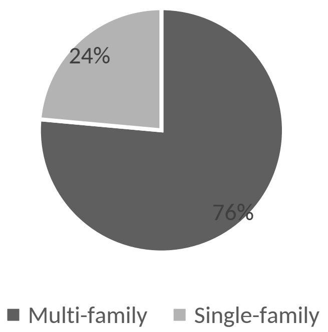
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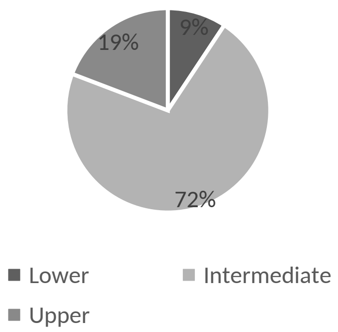
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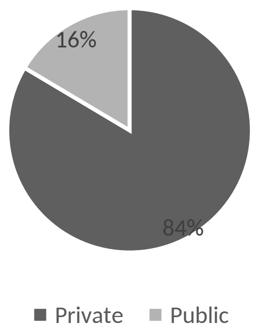
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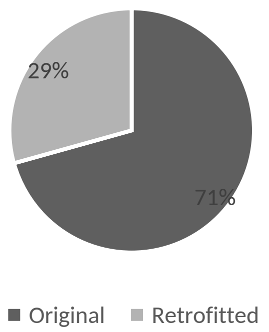
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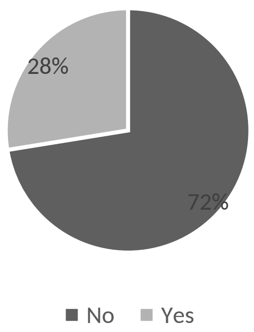
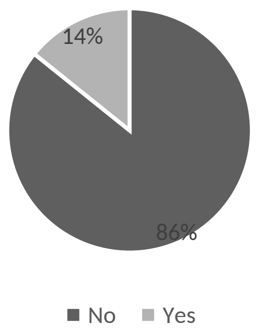
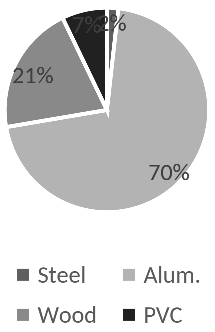
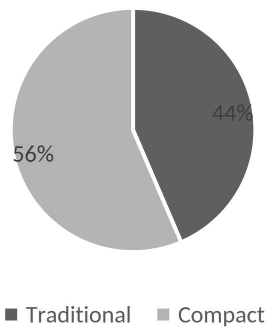
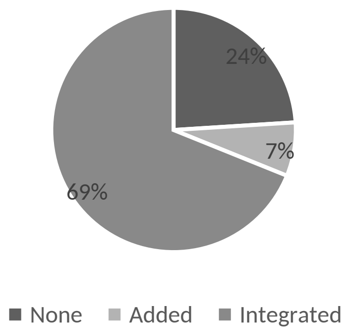

Attached closed balconies


Integrated balconies


Window material

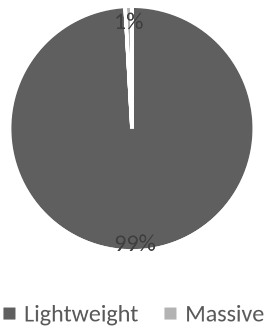

Type of rolling shutter

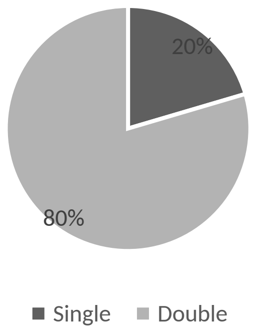

Position of rolling shutters

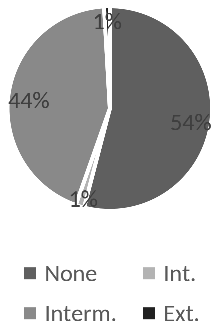
Construction system

Massive layers

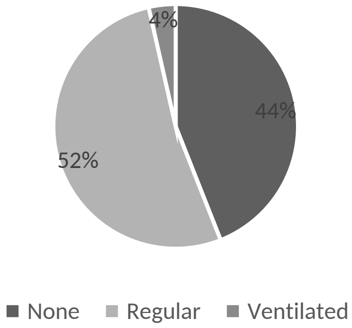
Insulation layer



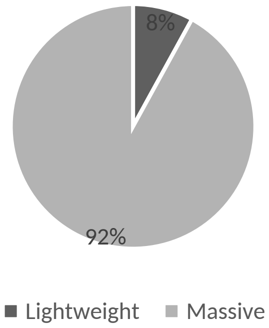




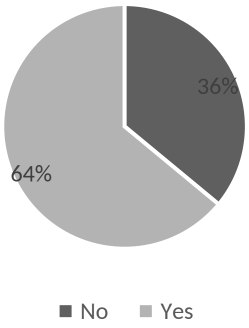
Air chamber



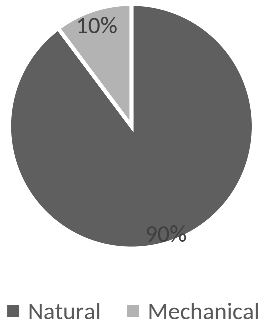
Partition walls



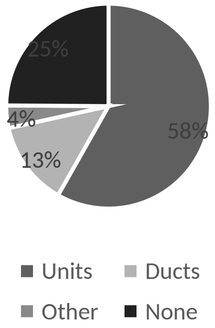
Outer coating



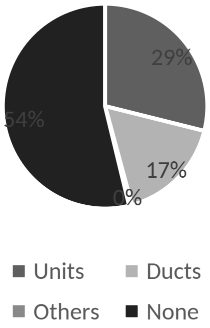
Ventilation system



Heating system



Refrigerating system



HIGHLIGHTS

- Pressurization tests were performed in 225 dwellings in hot and temperate areas of Spain.
- The mean air permeability rate at 50 Pa of the whole sample was 6.56 $m^3/(h \cdot m^2)$.
- Location, climate zone and window material have statistically an impact on airtightness.
- Air infiltration has an energy impact on the heating demand between 2.43 and 16.44 $kWh/m^2 \cdot year$.

Energy impact of the air infiltration in residential buildings in the Mediterranean area of Spain and the Canary Islands

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Abstract

Air infiltration through the building envelope has already been proven to have a significant energy impact in dwellings. Different studies have been carried out in Europe, but there is still a lack of knowledge in this field regarding mild climates. An experimental field study has been carried out in the Mediterranean climate area of Spain and the Canary Islands in order to assess the air permeability of the building envelope and its energy impact. A wide characterization and Blower Door tests have been performed in 225 cases in Alicante, Barcelona, Málaga, Sevilla and Las Palmas de Gran Canaria for this purpose. The obtained mean air permeability rate for the 225 studied cases was 6.56 $m^3/(h{\cdot}m^2)$. The influence of several variables on airtightness was statistically analysed, although only location, climate zone and window material were found to be significant. Air infiltration has an energy impact between 2.43 and 16.44 $kWh/m^2{\cdot}$year on the heating demand and between 0.54 and 3.06 $kWh/m^2{\cdot}$year on the cooling demand.

Keywords

Air infiltration; Airtightness; Blower door test; Residential buildings; Database

1. Introduction

Residential buildings are responsible for one of the highest levels of energy consumption. It is the most common building use in the world with approximately 2 billion dwellings and around 214 million in the European Union alone. In Spain there are about 26 million homes, being 66.1% of them apartments in multi-family buildings [1].

The European Strategy for Sustainable Development, as well as the Paris Agreement reached after the United Nations Climate Change Conference [2] in 2015 (XXI UNFCCC) have promoted political awareness and established contemporary criteria of energy saving and efficiency and the reduction of emissions, especially from buildings. This has led to the need to define joint strategies aimed at achieving solutions to the high energy consumption related to building development.

However, the low replacement rate of existing and outdated dwellings by new ones under the new energy standards requires action with applicable models on existing buildings. These strategies are oriented towards the achievement of a low-energy housing stock or near Zero Energy Buildings (*nZEB*). These strategies seek to reduce energy losses through the envelope by improving heat transmission by conduction, which has been extensively solved through the use of more and better thermal insulation. In this sense, energy loss due to infiltration becomes a relevant issue to the overall energy impact of the building.

Previous studies have assessed the energy loss through ventilation processes, which is greater than 30% of the final energy used in dwellings [3]. The nZEB strategies consider the heat recovery from the extraction air, improving this way the energy efficiency. However, heat recovery is only possible in controlled ventilation processes. Thus, in order to achieve nZEB, it is important to limit infiltration to tolerable limits. The uncontrolled ventilation through leakage paths due to a deficient design and construction entails a challenge.

Air infiltrations through the building envelope produce a phenomenon of air mass exchange between the inside and the outside of the conditioned space, causing energy transfer with different hygrothermal conditions of the air. This transfer means not only the reduction of the conditions of comfort of the occupants but also extra energy consumption. Therefore, airtight envelopes must be designed in order to reduce the uncontrolled consumption of hygrothermal energy caused by infiltrations but also, they must be combined with efficient HVAC systems to provide a sufficient clean air flow in the optimum hygrothermal comfort conditions.

Numerous studies have been carried out so far in northern Europe, which estimate an energy impact of air infiltration on heating demand of around 10 kWh/m^2·year in regions with a moderately cold climate (2500 degrees-day) [4]. Other studies indicate that the lack of airtightness of the building envelope can increase the heating demand from 5 to 20 kWh/m^2·year in countries with temperate climates [5]. However, in Spain knowledge regarding this issue is still scarce. Some studies have been carried out in the south of the country [6,7] and in the Continental climate area of the country [8]. From the energy point of view, a study carried out by Meiss and Feijó [9] in 13 dwellings in the north of Spain obtained the first results to this respect. It was estimated an energy impact of infiltration between 10.5 and 27.4% of the energy demand in buildings built under the Technical Building Code (CTE) [10], between 21.9 and 27% in buildings regulated by the standard NBE CT-79 [11] and between 11.3 and 13% in buildings of previous construction but retrofitted by their occupants.

The vast existing housing stock in the eastern and southern coast of Spain has required the detailed evaluation of the energy impact of the air infiltration. In these regions, it is typical the absence of thermal insulation of the envelope, as well as constructions defects due to an accelerated urban expansion in recent decades.

The objective of this study is to collect and classify relevant information regarding the energy impact of air leakage through the thermal envelope of residential buildings located in the Mediterranean climate area of Spain in order to reduce its energy impact. The coastal regions around the Mediterranean Sea and the archipelago formed by the Canary Islands are evaluated. This study seeks not only to characterize the current housing stock, but also to establish construction systems that have an impact on air infiltration.

1.1. Climate Classification

Permeability tests were performed in 5 locations in Mediterranean climate areas of Spain and the Canary Islands: Alicante (ALC), Barcelona (BCN), Málaga (MAL), Sevilla (SEV) and Las Palmas de Gran Canaria (LPA) (Figure 1). In order to define the specific climatic conditions of each location, Köppen Climate Classification [12,13] was applied. This system defines distinct types of climate using average monthly values for precipitation and air temperature.

Type *B* climates are characterized for being dry climates, which Köppen distinguished between sub-type *BS* (steppe), and the sub-type *BW* (desert), in relation to the annual rainfall. These areas are also classified as hot climates (*h*), or cold climates (*k*) depending on whether the average annual temperature is below or above 18 °C. Climate type *BSh* can be found in Alicante and *BWh* climate in Las Palmas de Gran Canaria. On the other hand, climates type C are classified as temperate climates, where the average temperature in the coldest months is between 0 and 18 °C. Sub-type *Csa* climate refers to dry and hot summers (average temperature in the hottest month above 22 °C) whereas in *Csb* climates summers are temperate. Climate type *Csa* can be found in Sevilla, Málaga and Barcelona, covering most of the Iberian Peninsula and the Balearic archipelago, occupying approximately 40% of its surface.

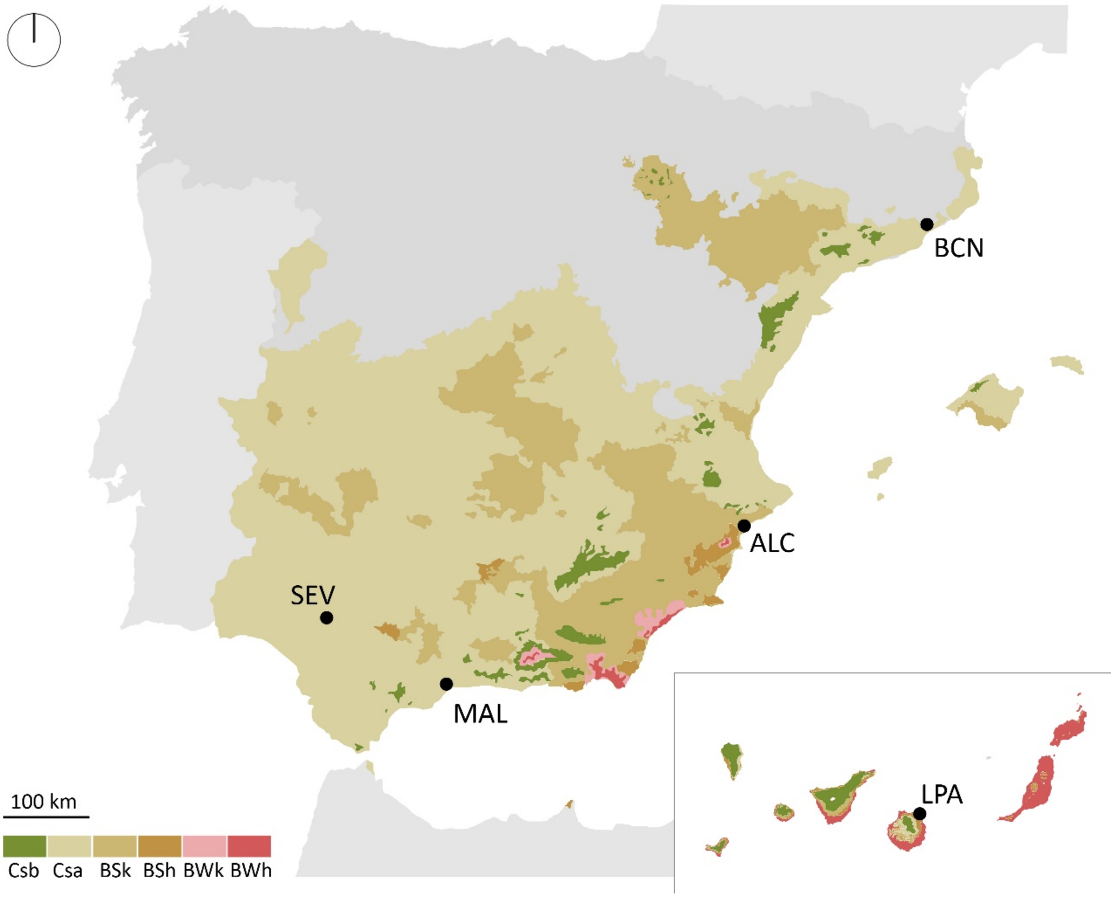


Figure 1: Köppen Climate Classification of the Spanish territory. Tests location.

1.2. The building envelope in the Mediterranean area of Spain and the Canary Islands

These areas are characterized by a low construction quality of the residential buildings. This is due to a large degree to the rapid building expansion suffered in the 70s and 80s derived from the great growth of tourism, which required a large number of dwellings in a short period of time. This fact resulted in deficit buildings that entail an important energetic impact.

Traditional building systems, usually before the 50s, are based on load-bearing walls of a single layer of variable thickness (always greater or equal to one foot), of ceramic bricks of different qualities coated with lime mortar to the exterior. With the generalization of concrete in the 60s, the facades have no longer a structural function and, therefore, they are lightened. Also remarkable is a significant proportion of self-built single-family housing.

In general terms, the construction systems during the 20th century in the Mediterranean area of Spain and the Canary Islands can be classified in three periods divided by the introduction of regulations regarding the energy performance of the buildings, namely, the NBE CT-79 [11] in 1979 and the Spanish Technical Building Code (CTE) [10] in 2006:

- Dwellings before 1979:
    - Façade: usually built with two layers of hollow brick, a small air chamber between them, and a finishing layer with cement mortar and painting. No thermal insulation is used. The interior finish is normally made of continuous plaster. In the specific case of the Canary Islands, the façade is made with a single layer of concrete hollow block with, without thermal insulation.
    - Roof: conventional trafficable flat roof, with terrazzo or ceramic tiles or gravel finish.
    - Windows: made of lacquered wood, aluminium or steel without thermal bridge break. In kitchens and bathrooms, it is common to place windows with orientable glass slats. Simple glass of 4 mm.
    - Shading: shutters, folding blinds, traditional exterior wooden rolling shutters or rolling shutters integrated into the enclosure.
- Dwellings complying with NBE CT-79:
    - Façade: double layer of double hollow brick, with 3-4 cm of thermal insulation in some occasions and air chamber. The most common façade finish is based on monolayer or plaster mortar. Ventilated facade systems begin to be introduced. The interior finish is normally made of continuous plaster. In the Canary Islands, the façades begin to be built with single-layer walls, without thermal insulation, generally executed with concrete double hollow block, externally coated with monolayer mortar or cement mortar and sand, finished with painting.
    - Roof: conventional or inverted (mostly after the 90s) trafficable flat roof, with terrazzo or ceramic tiles or gravel finish.

    - Windows: made of aluminium or PVC. In kitchens and bathrooms, windows with orientable glass slats are used at the beginning of this period. Simple glass with air chamber.
    - Shading: rolling shutters integrated into the enclosure. From the 90s, compact rolling shutters are introduced.
- Dwellings complying CTE:
    - Façade: a solution of two brick layers: a thicker one at the outside and another thinner one at the interior, with an intermediate air chamber. The insulation layer increases its thickness. The interior finish is usually a continuous plastering layer, often replacing it with lightweight plasterboard systems. In the case of the Canary Islands, the most common façade system is composed of a main layer of concrete hollow block, intermediate thermal insulation and an interior layer of concrete double hollow block. On the outside, the coating can be quite diverse: monolayer coatings, discontinuous coatings with natural stone or ceramic cladding, concrete panels, ventilated façades, external thermal insulation (ETI) systems, etc.
    - Roof: inverted trafficable flat roof, with terrazzo or ceramic tiles or gravel finish.
    - Windows: made of aluminium with thermal bridge break, recovering in some cases the wooden window. Double glass with air chamber.
    - Shading: compact rolling shutters and sliding shutters in some cases.

Therefore, regarding the airtightness of the building envelope in this area, it is possible to highlight the lightening of the façade, usually interrupted by the concrete slab, the introduction of the rolling shutters as a discontinuity of the envelope and the use of lightweight plasterboard systems in the last decades. It is also important to mention the presence of non-conditioned service spaces annexed to the kitchens and terraces, whose volume has in many cases been integrated into the conditioned space of the house through its closure with carpentry. Inadequate and careless execution of these systems has contributed to a poor energy performance of the dwellings.

1.3. Ventilation and conditioning systems

In the Mediterranean climate area of Spain and the Canary Islands, ventilation has traditionally been done in a natural way by manually opening the windows. Hence, air leakage has been the only continuous air inlet in dwellings. The installation of orientable glass slats in kitchens and bathrooms until the end of the 20th century in some locations also constitute a continuous ventilation source. It is often crossed ventilation through the exterior façade and light shafts, which also contributed to improve thermal comfort of the dwelling. Usually kitchens and bathrooms are ventilated through the unconditioned service spaces attached to this rooms. After the implementation of the NBE CT-79 natural air extraction is installed in bathrooms and kitchens by means of a vertical duct. After the introduction of CTE in 2006, controlled mechanical or hybrid ventilation is mandatory.

Regarding the conditioning systems, due to the climatic benevolence of this area, dwelling have usually no heating or refrigerating system. Only after 1970 individual air conditioning units were introduced in some cases. During the 70s and the 80s radiators (portable electric devices or standard ones) were used in winter. After the year 2000 HVAC systems have been frequently designed with a direct expansion split heat pump system, with outdoor unit on the deck and indoor unit in the bathroom, and ductwork along the corridor. In Barcelona, central heating systems with water radiator terminals were common solutions during the 20th century and its use has been extended again during in recent years. To a lesser extent, installations of hot water radiators with gas heater and boiler have been carried out in single-family homes, combined with a multi-split system for summer.

2. Methodology

2.1. Sample

The study has focused on the building typologies of the area of interest, ensuring the representativeness of the sample. A non-probabilistic quota sampling scheme has been considered in order to ensure the heterogeneity and proportionality of the selected cases. This method reproduces the population on a smaller scale on the basis of a considered sample size [14]. The residential stock in the Mediterranean area of Spain including the Canary Islands has been proportionally stratified into subgroups (strata) according to a series of control variables, namely, the period of construction, typology (single-family or multi-family housing) and the climate zone. The control variables have been chosen due to its impact on airtightness according to previous studies, being its distribution known [14].

A total of 225 cases built between 1890 and 2015 have been studied. The location of the cases according to typology and year of construction is shown in Figure 2. The distribution of the cases according to its main characteristics was assessed in order to verify the representativeness of the sample tested.

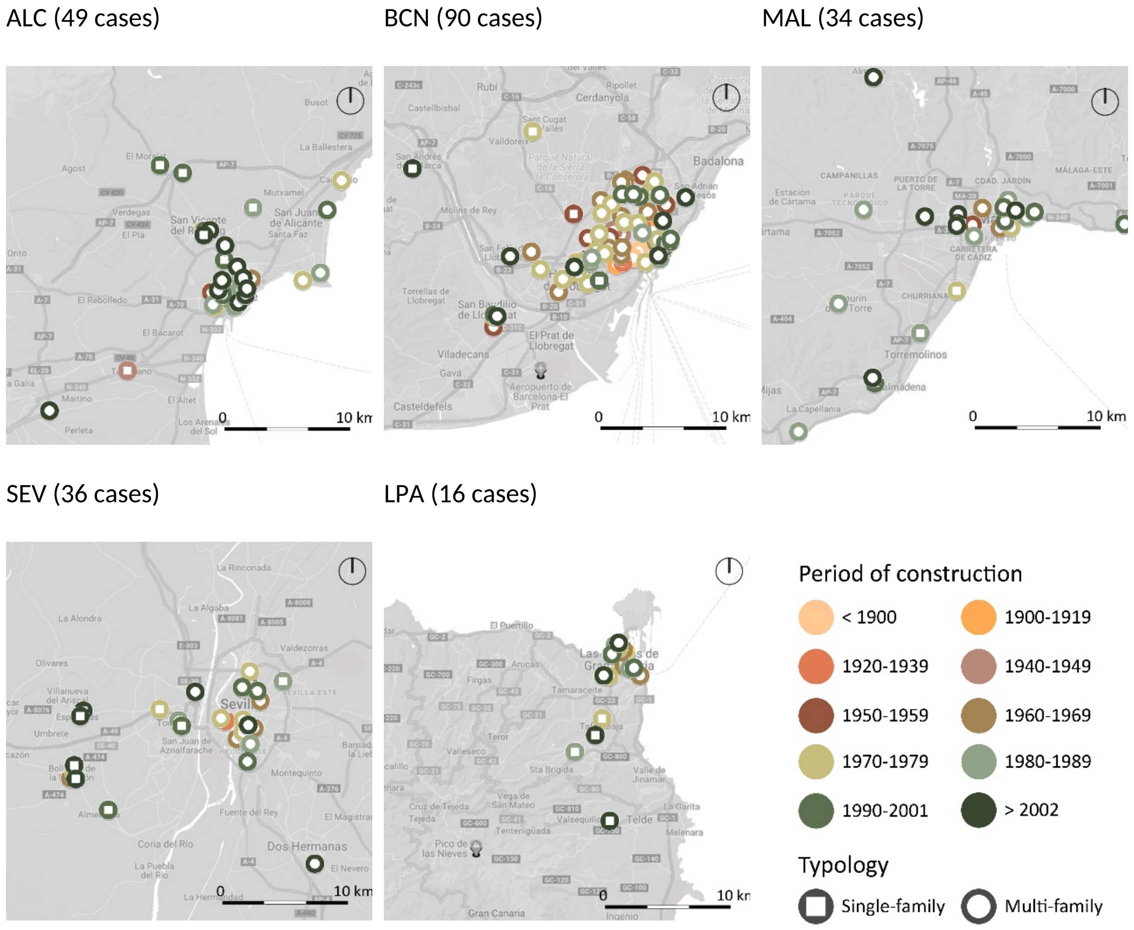


Figure 2: Location of the studied cases.

The year of construction has proven to be a significant factor regarding airtightness because it is related to regulations, deterioration of materials and joints [15] and development of construction systems. Regarding regulations (aforementioned in section 1.2) 53% of the sample was built before NBE CT-79 was implemented, 37% of the cases were built after it came into force and 10% after CTE. However, it was also taken into account if dwellings were in an original state (71%) or, by contrast, it had been retrofitted (29%).

Typology has also been considered, clearly reflecting the fact that multi-family housing prevails in this area. 76% of the cases were apartments within buildings and only 24% of the sample were single-family houses (isolated or detached). In the cases of apartments, the relative position of the dwelling was assessed: 72% of the apartments were located in an intermediate position with conditioned spaces in contact with the horizontal envelope, whereas 19% occupied the upper floor and only 9% the lower floor.

Construction systems were analysed from different points of view. Massive construction tradition can be proved in the sample with 99% of the cases. The envelope is usually built with a double massive layer (80% of the sample), intermediate insulation material (54%) or no insulation (44% of the cases) and air chamber (56%) or none (44% of the sample). The façade has in most of the cases (64%) an outer coating. The internal massive layer of the envelope and partition walls are mainly massive as well, although the most recent cases tend to introduce lightweight solutions (8% of the sample). Regarding windows, which constitute critical points of the envelope, the prevailing material is aluminium (71% of the sample) and most of the cases had rolling shutters (76%).

Finally, ventilation and conditioning systems have been assessed. Most of the housing stock in this area (90%) has natural ventilation by manually open the windows, given that regulations did not implemented controlled ventilation systems until the entry into force of CTE. Most of the cases had some sort of heating system (75%, 58% with water or electric radiators), whereas 45% had a refrigeration system, mostly based on individual units. The distribution of the cases according to its main characteristics is detailed in Annex I.

2.2. Testing method

The evaluation of the airtightness of the envelope has been carried out by means of the procedure described by the European Standard EN 13829 [16] which is a modified version of the International Standard ISO 9972:2006. The procedure, commonly called Blower Door Test, causes a stationary pressure differential inside the area to be tested with respect to the atmospheric conditions of the exterior. This standardized procedure establishes two possible evaluation methods:

- Method A is a test of the building in use. It evaluates the condition of the building envelope in its condition during the season in which the heating or cooling systems are used.
- Method B tests the building envelope. For that purpose, any intentional opening in the building envelope shall be closed or sealed (Table 1).

For the objectives proposed for this study, the analysis of Method B is considered more adequate, although tests are carried out by both methods in order to consolidate the results and perform possible complementary studies. A protocol was designed to ensure that the preparation of each dwelling was consistent for all the cases.

	Method A	Method B
Mechanical ventilation openings (air shafts, exhaust hood, etc.)	Closed and switched off	Sealed and switched off
HVAC ducts	Closed and switched off	Closed and switched off
Atmospheric open heaters	Closed and switched off	Sealed and switched off
Natural ventilation openings (adjustable)	Closed	Sealed
Natural ventilation openings (always open)	Opened	Sealed
Closing shaft chimney ducts	Closed	Sealed
Opened shaft chimney ducts	Opened	Sealed
Overflow sinks and sinks without hydraulic seal	Opened	Fulfilled/sealed
Hydraulic seal	Fulfilled	Fulfilled/sealed
Cupboards and closets	Closed	Closed
Outer doors and windows	Closed	Closed
Inner doors	Opened	Opened

Table 1: Preparation of the building envelope for Methods A and B.

In addition, each case is tested under pressurization and depressurization conditions, minimizing the influence of wind and temperature action on the envelope. The final results of the infiltration and exfiltration flows are averaged to obtain a global value.

The correct calibration of the equipment was ensured to maintain accuracy specifications of 1% of reading, or 0.15 Pa.

2.3. Fundamentals

The infiltration curve is calculated according to the power law equation, based on the fundamental mechanics airflow [16] (equations 1 – 3).

$$n = \frac{\sum_r \left(Ln(|\overline{p}_r - \Delta p|) - \frac{\sum_r Ln(|\overline{p}_r - \Delta p|)}{r} \right)^2}{\sum_r Ln(|\overline{p}_r - \Delta p|) - \frac{\sum_r Ln(|\overline{p}_r - \Delta p|)}{r} \cdot Ln\left(c_d \cdot P_r{}^{n_d} \cdot \frac{\rho_o}{\rho_i} \cdot \sqrt{\frac{\rho_{20^\circ C}}{\rho_o}} \right) - \frac{\sum_r Ln\left(c_d \cdot P_r{}^{n_d} \cdot \frac{\rho_o}{\rho_i} \cdot \sqrt{\frac{\rho_{20^\circ C}}{\rho_o}} \right)}{r}} \tag{1}$$

$$Cenv = e^{\left(\frac{\sum_r Ln\left(c_d \cdot P_r{}^{n_d} \cdot \frac{\rho_o}{\rho_i} \cdot \sqrt{\frac{\rho_{20^\circ C}}{\rho_o}} \right)}{r} - \frac{n \cdot \sum_r Ln(|\overline{p}_r - \Delta p|)}{r} \right)} \tag{2}$$

$$Cl = Cenv \cdot \left(\frac{\rho_o}{\rho_k} \right)^{1-n} \tag{3}$$

where:

r is the number of samples taken in each case at different pressures [-].

$\overline{p}_r$ is the average pressure in each test sample [Pa].

Δp is the pressure differential in the test [Pa].

c_d is the reference flow rate for each diaphragm of the BlowerDoor [m^3/h].

P_r is the ventilation pressure in each sample [Pa].

n_d is the reference exponent for each diaphragm [-].

n is the air flow exponent [-].

ρ_o is the air density outside the building [kg/m^3].

ρ_i is the air density inside the tested dwelling [kg/m^3].

$\rho_{20^\circ C}$ is the reference air density at 20°C [kg/m^3].

ρ_k is the calculation density for the interior temperature [kg/m^3].

$Cenv$ is the air Flow coefficient [m^3/(h·Pa^n)].

Cl is the air leakage coefficient [m^3/(h·Pa^n)].

The following parameters related to the infiltration phenomenon, which allow the comparison of results in different buildings, are evaluated (equations 4 – 7):

$$V_{50} = Cl \cdot 50^n \qquad (4)$$

$$q_{50} = \frac{V50}{Ae} \qquad (5)$$

$$w_{50} = \frac{V50}{Af} \qquad (6)$$

$$n_{50} = \frac{V50}{Vol} \qquad (7)$$

where:

V_{50} is the air leakage rate at 50 Pa [m^3/h].

q_{50} is the air permeability at 50 Pa [m^3/(h·m^2)].

w_{50} is the specific leakage rate at 50 Pa [m^3/(h·m^2)].

n_{50} is the air change rate at 50 Pa [h^{-1}].

Ae is the envelope area [m^2].

Af is the floor area [m^2].

Vol is the internal air volume [m^3].

It is important to note that in multi-family dwellings the non-guarded pressurization test does not allow to distinguish between the infiltration that occurs through the façade and the one produced in walls in contact with conditioned spaces (other dwellings) or unconditioned zones (common areas of the building). Inter-zonal leakages have been previously assessed by several studies with different methods in buildings with varying characteristics. It has been estimated that inter-zonal leakages can account for 2 to more than 60% of the total air leakage [17]. Therefore, the proportion of leakage between internal units in multi-family buildings can be within a wide range depending on building characteristics. In any case, the total infiltration rate was taken, which for energy impact purposes is the most unfavourable situation.

2.4. Energy impact assessment

The estimation of the energy impact of infiltration is a complex issue, given that it depends not only on the airtightness of the building envelope, but also on meteorological conditions that are sometimes difficult to predict. There is no common criterion about the appropriate model to evaluate the energy impact of infiltrations. Different calculation models have been developed so far with varying degrees of complexity and reliability. The more simplified models assume a uniform distribution of leakage paths and constant average leaks over time.

The energy impact of infiltrations has been assessed by means of a simplified model (equation 8), applying the concept of degree-day, which relates the average temperature outside the tested dwelling and the comfort indoor temperature $(21°\mathrm{C}\text{ for heating and }25°\mathrm{C}\text{ for cooling})$. It is important to note that this estimation is theoretical and real energy consumption depends on the particular temperature conditions of the dwellings. This calculation procedure allows to evaluate the energy impact considering specific climate data of the locations where the tests have been performed, as a product of the air infiltration flow, the specific air capacity and the temperature difference between the inside and the outside of the dwelling [18].

$$Q_{inf} = C_p \cdot G_t \cdot V_{inf} \qquad (8)$$

where:

Q_{inf} is the annual energy loss [kWh/y] due to air infiltration for heating $Q_{inf\ -H}$ and cooling $Q_{inf\ -C}$. Annual energy losses are expressed per unit area.

C_p is the specific heat capacity of the air, which is 0.34 Wh/m^3·K.

G_t are the annual degree days [kKh/year], both for heating $(G_{t\,-C})$ with a base comfort temperature of 21 °C, and for cooling $G_{t\,-R}$ with a base comfort temperature of 25 °C.

V_{inf} is the air leakage rate [m^3/h].

V_{inf} needs to be obtained from the values obtained from the test, which are expressed at a pressure difference of 50 Pa and do not reflect the actual filtration process to which the dwelling is subjected. Therefore, the results must be transformed into real filtration equivalent flows. The estimation of the actual filtration is complex, given that the wind and temperature conditions throughout the year are difficult to foresee and the test does not give precise information related to the distribution of infiltration leakages.

The Persily-Kronvall estimate [19], is a simple and widespread model in the scientific community. Its origin is uncertain, and it assumes a linear relationship between permeability at 50 Pa and the average annual infiltration (equation 9).

$$q_{inf} = \frac{q_{50}}{20} \qquad (9)$$

where:

q_{inf} is the air permeability [m^3/(h·m^2)].

Subsequently, this linear relationship between airtightness and infiltration evolved [19] incorporating coefficients according to the characteristics of the location (equations 10 and 11).

$$q_{inf} = \frac{q_{50}}{\mathrm{N}} \qquad (10)$$

$$\mathrm{N} = \mathrm{C} \cdot \mathrm{cf}_1 \cdot \mathrm{cf}_2 \cdot \mathrm{cf}_3 \qquad (11)$$

where:

N is a constant.

C it is the climatic factor, calculated in the model from hourly climate data for more than 200 points in the US and Canada. Its value is in the range 15 - 30.

cf_1 is the height correction factor of the building, applicable to buildings in which the tested spaces are in 1 floor ($cf_1 = 1$) up to 3 floors ($cf_1 = 0.7$).

cf_2 is the site shielding correction factor, for well shielded cases ($cf_2 = 1.2$), ($cf_2 = 1$) or exposed dwellings ($cf_2 = 0.9$).

cf_3 is the leakiness correction factor, dependent on the value of the leakage exponent n. Buildings with small cracks, a typical situation of typical tighter buildings are given a correction factor $cf_3 = 1.4$, whereas leakier buildings with large holes have a correction factor $cf_3 = 0.7$.

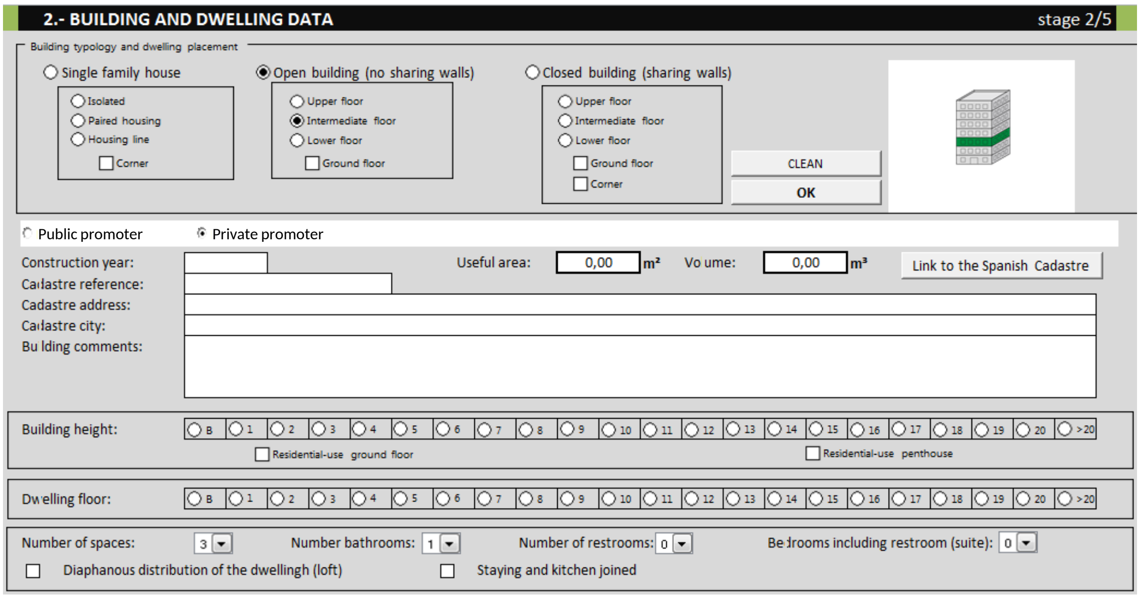
This extended simplified model has been adopted for the calculation of the average infiltration flow in the Mediterranean area of Spain and the Canary Islands, obtaining the value of the climatic factor C by assimilation to the US climates, comparatively according to the average temperature and wind speed. For the coefficients cf_1, cf_2 and cf_3 a value equal to 1 has been adopted in the three cases. The type of infiltration opening was obtained from the mean value of the flow exponent $n = 0.59$.

The air leakage rate V_{inf} needed for the calculation of the energy impact is calculated from the air permeability rate and the envelope area (equation 12):

$$V_{inf} = q_{inf} \cdot A_E \quad (12)$$

2.5. Airtightness database

The performance of the tests in each case was carried out by trained technicians, who have a tool (*infil-APP* [14]) to capture characterization information (Figure 3) and to import test data from the software provided by *Minneapolis Blower Door Model 3* (TECTITE 5.0).



2.- BUILDING AND DWELLING DATA stage 2/5

Building typology and dwelling placement

○ Single family house
  ○ Isolated
  ○ Paired housing
  ○ Housing line
  ☐ Corner

● Open building (no sharing walls)
  ○ Upper floor
  ● Intermediate floor
  ○ Lower floor
  ☐ Ground floor

○ Closed building (sharing walls)
  ○ Upper floor
  ○ Intermediate floor
  ○ Lower floor
  ☐ Ground floor
  ☐ Corner

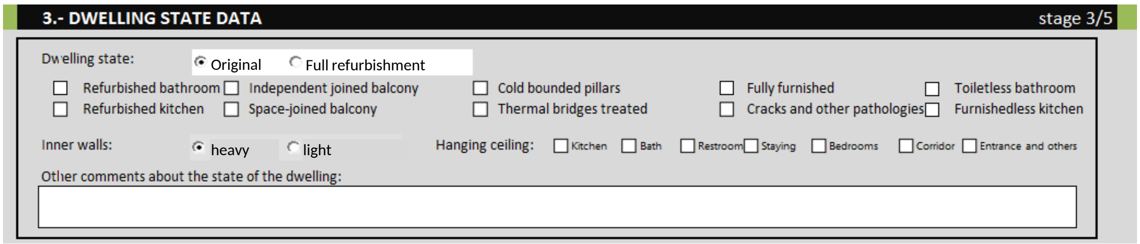
○ Public promoter ● Private promoter

Construction year:
Cadastre reference:
Cadastre address:
Cadastre city:
Building comments:
Useful area: 0,00 m²
Volume: 0,00 m³

Building height: ○ B ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ 10 ○ 11 ○ 12 ○ 13 ○ 14 ○ 15 ○ 16 ○ 17 ○ 18 ○ 19 ○ 20 ○ >20
☐ Residential-use ground floor ☐ Residential-use penthouse

Dwelling floor: ○ B ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ 10 ○ 11 ○ 12 ○ 13 ○ 14 ○ 15 ○ 16 ○ 17 ○ 18 ○ 19 ○ 20 ○ >20

Number of spaces: 3 Number bathrooms: 1 Number of restrooms: 0 Bedrooms including restroom (suite): 0
☐ Diaphanous distribution of the dwellingh (loft) ☐ Staying and kitchen joined



3.- DWELLING STATE DATA stage 3/5

Dwelling state: ● Original ○ Full refurbishment

☐ Refurbished bathroom ☐ Independent joined balcony ☐ Cold bounded pillars ☐ Fully furnished ☐ Toiletless bathroom

☐ Refurbished kitchen ☐ Space-joined balcony ☐ Thermal bridges treated ☐ Cracks and other pathologies ☐ Furnishedless kitchen

Inner walls: ● heavy ○ light

Hanging ceiling: ☐ Kitchen ☐ Bath ☐ Restroom ☐ Staying ☐ Bedrooms ☐ Corridor ☐ Entrance and others

Other comments about the state of the dwelling:

Figure 3: Screenshot of "infil-APP". Characterization of the dwelling.

This tool was specifically developed for the characterization of 140 parameters that can intervene in the phenomenon of filtration. These parameters are collected in a database that is used for the global evaluation of the results.

3. Results

3.1. Airtightness results

The distribution of the values obtained for the air change rate (n_{50}), the air permeability (q_{50}), the specific leakage rate (w_{50}) at 50 Pa and the air flow exponent (n) for the whole sample are shown in Figure 4.

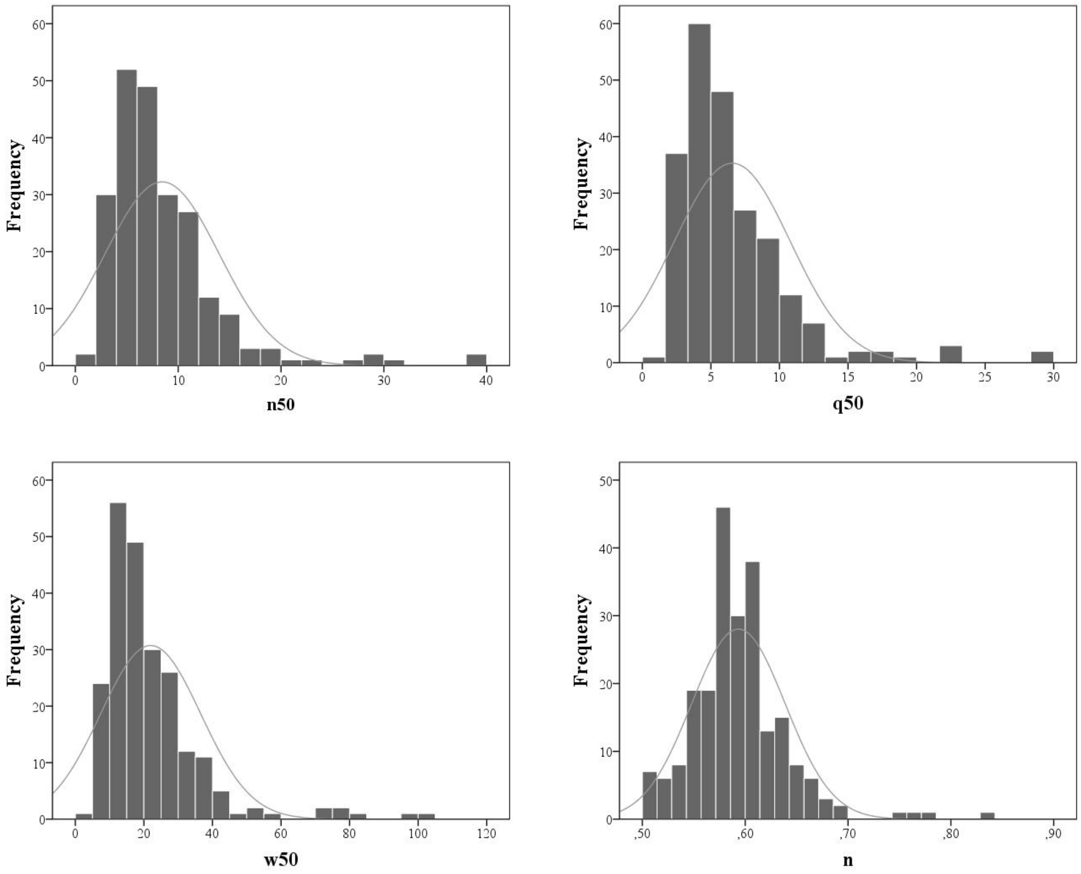


Figure 4: Distribution of test results for the whole sample

Mean values obtained for the assessed sample are shown in Table 2. The results obtained for q_{50} ranged from 1.90 to 39.42 $m^3/(h \cdot m^2)$ with a mean value of 6.56 $m^3/(h \cdot m^2)$, median 5.48 $m^3/(h \cdot m^2)$ with a standard deviation of 4.24.

The flow exponent (n value) gives information regarding the resistance to the passage of air of the leakage paths, being close to 1 for laminar flows (airtight dwellings) and close to 0.5 for turbulent flows (leaky dwellings) [20]. The mean flow exponent n for the whole sample was 0.59.

The influence of different parameters on the air permeability rate at 50 Pa (q_{50}) has been assessed by means of Kruskal-Wallis test [21] in order to statistically verify the independence of the variables. Table 2 shows the values obtained for the test statistic *Chi-square* and the significance (*Sig.*), which can be considered significant for values below 0.05 (indicated by a *). Thus, a statistically significant relationship was found between the air permeability rate and the location of the dwellings, climate zone and window material (*Sig*. < 0.05).

Maximum q_{50} values were found in Barcelona and Sevilla (q_{50} = 7.53 and 6.81 $m^3/(h \cdot m^2)$ respectively) and minimum values in Las Palmas de Gran Canaria (q_{50}= 4.60 $m^3/(h \cdot m^2)$). Dwellings located in temperate climates with dry and hot summers (*Csa*) performed worse in terms of airtightness (q_{50} = 6.84 $m^3/(h \cdot m^2)$) than those in dry hot desert climates (*BWh*), with q_{50} = 4.60 $m^3/(h \cdot m^2)$. Although the sample size was irregular for different window materials, dwellings with aluminium windows (q_{50} = 5.90 $m^3/(h \cdot m^2)$) performed better than those made of wood (q_{50} = 8.87 $m^3/(h \cdot m^2)$).

Variable	**Category**	**cases**	**n_{50}** [h^{-1}]	**q_{50}** [$m^3/(h \cdot m^2)$]	**w_{50}** [$m^3/(h \cdot m^2)$]	**n** [-]	**Chi-square** (q_{50})	**Sig.** (q_{50})
TOTAL	-	225	8.43	6.56	21.97	0.59	-	-
Location	ALC	49	7.78	6.26	19.99	0.61	13.89	0.008*
	BCN	90	9.78	7.53	25.79	0.58		
	MAL	34	5.81	5.16	17.23	0.60		
	LPA	16	5.43	4.60	14.78	0.59		

	SEV	36	8.88	6.81	23.16	0.58		
Climate zone	BSh	49	7.78	6.26	19.99	0.61	7.83	0.020*
	BWh	16	5.43	4.60	14.78	0.59		
	Csa	160	8.93	6.84	23.30	0.59		
Regulations	None	118	8.99	6.96	23.83	0.59	2.17	0.338
	CT-79	84	8.11	6.35	20.64	0.60		
	CTE	23	6.78	5.25	17.27	0.60		
Typology	Multi-family	172	8.80	6.51	22.62	0.59	0.88	0.348
	Single-family	53	7.25	6.73	19.85	0.59		
Relative position	Lower	16	8.15	6.04	20.96	0.59	0.20	0.905
	Intermediate	123	9.14	6.75	23.62	0.59		
	Upper	33	7.84	5.82	19.72	0.59		
Developer	Private	188	8.56	6.77	22.42	0.59	0.93	0.335
	Public	37	7.76	5.49	19.70	0.60		
Retrofitting state	Original	159	8.51	6.52	22.09	0.59		
	Retrofitted	66	8.24	6.64	21.69	0.60		
Window material	Steel	4	8.85	6.75	22.92	0.59	18.03	0.000*
	Aluminium	158	7.67	5.90	19.64	0.60		
	Wood	46	11.19	8.87	30.49	0.58		
	PVC	16	7.53	6.18	19.24	0.59		
Rolling shutters	None	54	7.48	5.70	20.43	0.60	3.13	0.209
	Added	16	8.07	5.87	20.22	0.58		
	Integrated	155	8.80	6.93	22.69	0.59		
Massive layers	Single	46	7.46	5.98	20.93	0.59	0.85	0.357
	Double	179	8.68	6.71	20.93	0.59		
Insulation layer	None	120	8.97	6.84	23.79	0.59	1.12	0.249
	Interior	6	5.09	4.79	12.56	0.61		
	Intermediate	97	7.95	6.27	20.24	0.60		

	Exterior	2	9.74	8.84	24.76	0.55		
Air chamber	None	99	7.96	6.21	21.42	0.59	3.37	0.186
	Regular	118	8.81	6.77	22.39	0.59		
	Ventilated	8	8.81	7.62	22.71	0.58		
Partition walls	Lightweight	18	10.31	7.87	26.37	0.60	2.42	0.120
	Massive	207	8.27	6.44	21.59	.059		
Outer coating	No	81	8.45	6.65	21.98	0.59	0.00	0.961
	Yes	144	8.42	6.51	21.97	0.59		
Ventilation system	Natural	202	8.62	6.71	22.51	0.59	1.71	0.191
	Mechanical	23	6.78	5.25	17.27	0.60		
Heating system	No	56	9.18	6.68	24.19	0.58	0.25	0.616
	Yes	169	8.19	5.52	21.24	0.60		
Refrigerating system	No	121	8.50	6.76	22.63	0.59	1.02	0.312
	Yes	104	8.36	6.33	21.20	0.60		

Table 2: Mean values obtained depending on different variables and Kruskal-Wallis test results.

3.2. Energy impact

The energy impact estimation of the air infiltration obtained, both for the heating and cooling demand, is shown in Table 2 and Figure 5 for each of the locations studied. Furthermore, results are also expressed according to the period of construction, corresponding to implemented regulations. Figure 6 shows the tendency for each city where the study has been carried out.

	Ud.	**ALC**	**BCN**	**MAL**	**SEV**	**LPA**
N	-	22	22	23	20	19
q_{inf}	$m^3/(h \cdot m^2)$	0.28	0.34	0.22	0.34	0.24
$Q_{inf\,-H}$	$kWh/m^2 \cdot year$	10.02	16.44	8.61	14.21	2.43
$Q_{inf\,-C}$	$kWh/m^2 \cdot year$	1.60	0.73	0.78	3.06	0.54
$Q_{inf\,-H}$ **(no regulations)**	$kWh/m^2 \cdot year$	10.42	16.43	10.55	14.63	3.55
$Q_{inf\,-C}$ **(no regulations)**	$kWh/m^2 \cdot year$	1.66	0.73	0.96	3.16	0.75

$Q_{inf\ -H}$ (CT-79)	kWh/m^2·year	10.08	16.90	8.03	15.92	1.89
$Q_{inf\ -C}$ (CT-79)	kWh/m^2·year	1.61	0.75	0.73	3.43	0.42
$Q_{inf\ -H}$ (CTE)	kWh/m^2·year	8.42	14.14	6.36	9.92	1.39
$Q_{inf\ -C}$ (CTE)	kWh/m^2·year	1.34	0.63	0.58	2.14	0.31

Table 3: Energy impact of infiltration results.

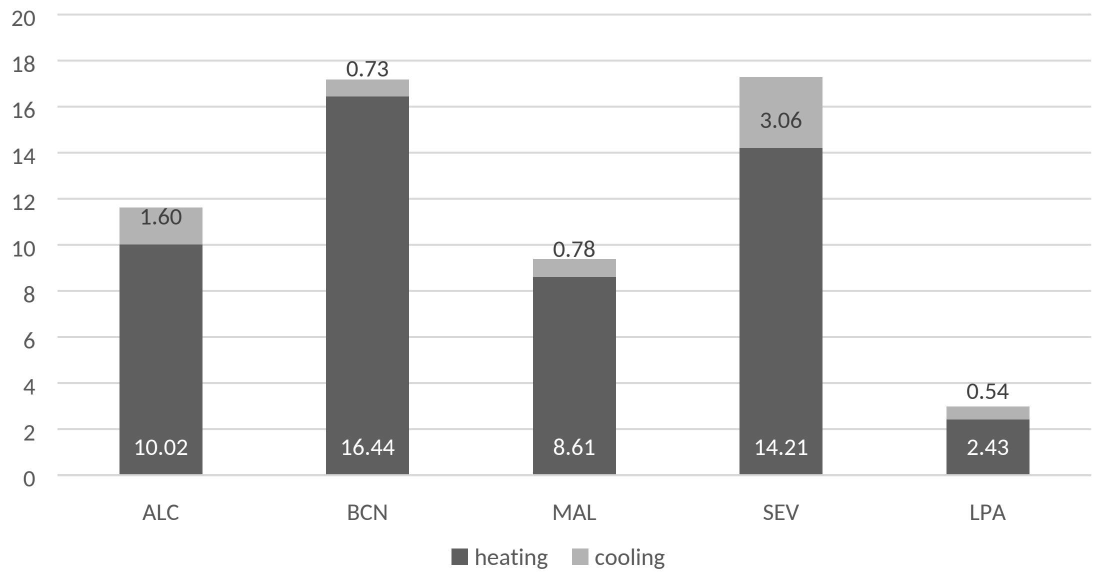


Figure 5: Annual energy losses (kWh/m^2·a) for heating and cooling due to infiltration.

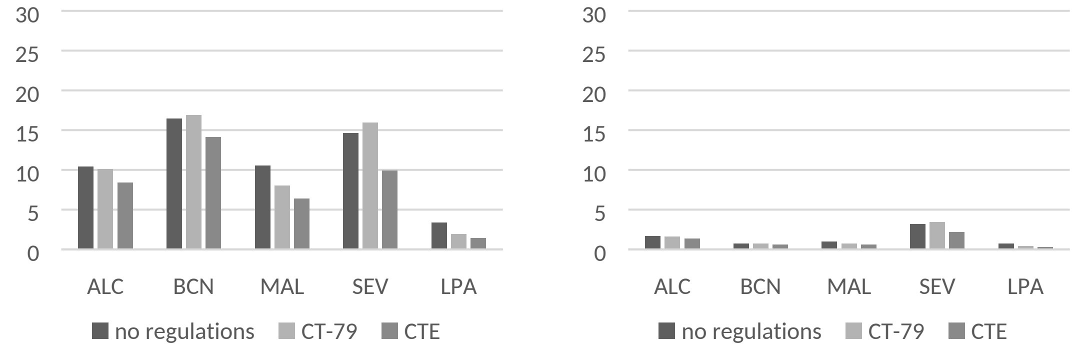


Figure 6: Annual energy losses (kWh/m^2·a) for heating (left) and cooling (right) due to infiltration, classified per regulations.

The energy impact has a greater impact on the heating demand, especially in Barcelona and Sevilla. Values up to 16.44 kWh/m^2·y have been obtained for the energy impact corresponding to the heating demand in the case of Barcelona, while in Las Palmas de Gran Canaria with hot climate, the value is reduced to 2.43 kWh/m^2·year. In the case of cooling demand, the energy impact of air infiltration is lower, with maximum values of 3.06 kWh/m^2·y in the case of Sevilla, whereas in Las Palmas de Gran Canaria this value is reduced to 0.54 kWh/m^2·year.

Regarding regulations, there is a general progressive improvement trend in all locations. It can be pointed out, though, that in Barcelona and Sevilla the oldest dwellings built during the first period performed better than the ones built after the entry into force of NBE CT-79.

4. Conclusions

The airtightness and the impact of the air infiltration through the building envelope in dwellings in Spanish cities with a Mediterranean climate and the Canary Islands has been assessed.

The mean air permeability rate at 50 Pa for the 225 studied cases was found to be 6.56 m^3/(h·m^2), whereas for the air change rate at 50 Pa the mean obtained value was 8.43 h^{-1}. These results are significantly higher than the average air change rate of 7.5 h^{-1} obtained for other case studies in different European countries [22] and the average air change rate 6.99 h^{-1} obtained in a previous study in the Continental area of Spain [8].

As for the flow exponent n, the obtained mean value was 0.59, associated to air loose construction solutions related to massive systems found in this area. Values close to 0.6 have been associated with leakage around the openings of the envelope [7].

Location, climate zone and window material were found to be statistically significant parameters that have an impact on airtightness. No statistically significant relationship was found between the air permeability rate and the other parameters analysed. General trends can be observed, although further analysis and a larger simple should be considered in order to deduce accurate conclusions.

In spite of the fact that the assessed area has a mild climate, the energy impact affects mainly the heating demand. Air infiltration has an energy impact between 2.43 and 16.44 kWh/m^2·year on the heating demand and between 0.54 and 3.06 kWh/m^2·year on the cooling demand. These results are in line with the values previously stated in other studies [5]. A general improvement trend can be observed regarding the implementation of regulations, although a fast expansion of the cities could have probably derived in poor quality construction in the cases of Barcelona and Sevilla during the period 1980 – 2006.

There is currently no limit in Spain regarding the airtightness of the building envelope in buildings (CTE only establishes requirements for windows). Consequently, compliance with the European Directive 2018/844 seems only possible by implementing limitations in this respect applicable both to the design of new buildings and to the renovation of the existing housing stock.

5. Acknowledgements

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Declarations of interest: none

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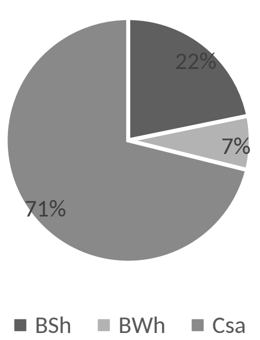
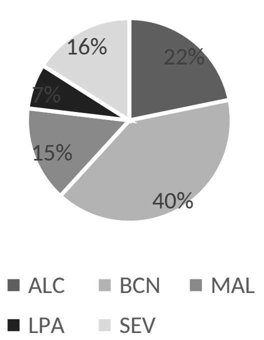
Annex I: characterization assessment of the sample

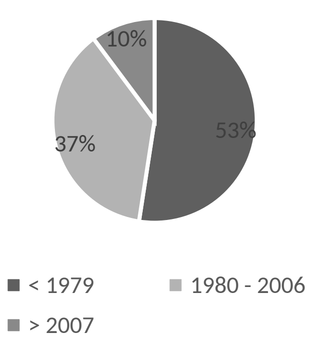
Climate zone



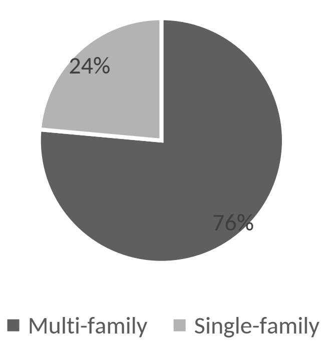
Location



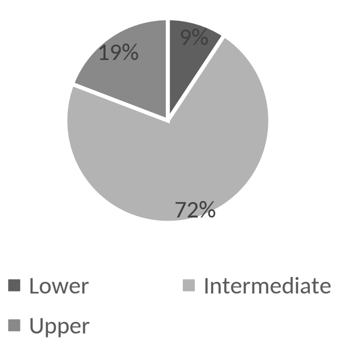
Period of construction



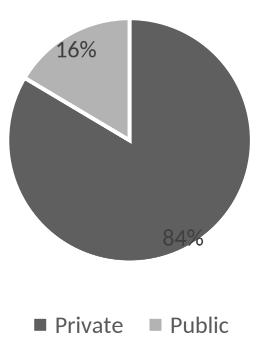
Building typology



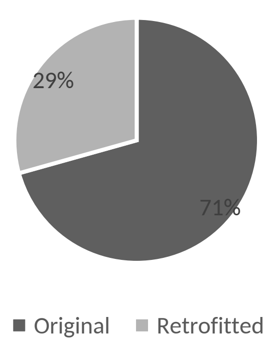
Relative position



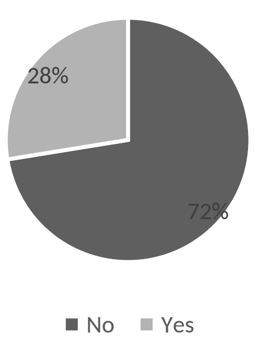
Developer



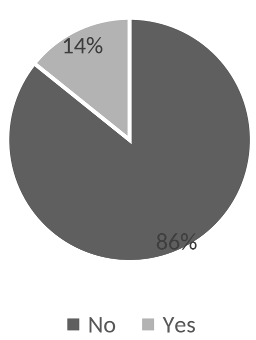
Retrofitting state



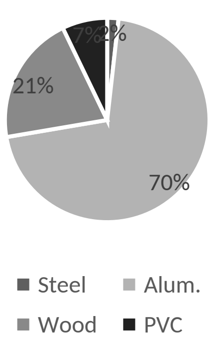
Attached closed balconies



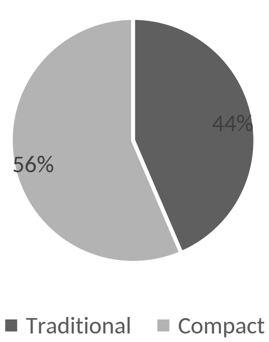
Integrated balconies



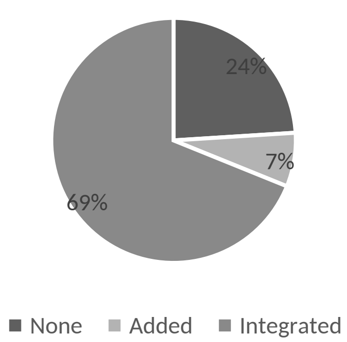
Window material



Type of rolling shutter



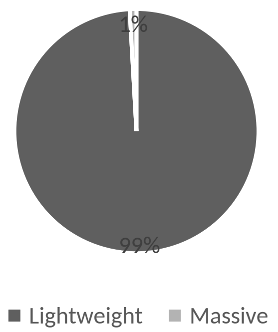
Position of rolling shutters

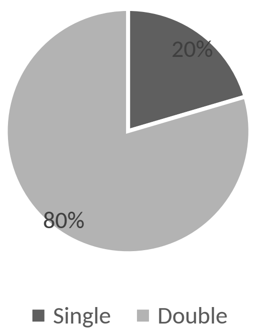


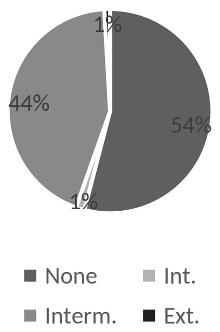
Construction system

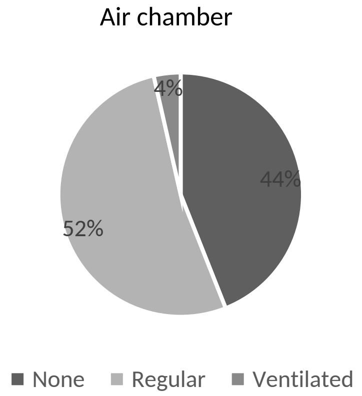
Massive layers

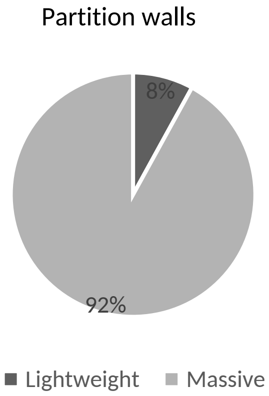
Insulation layer

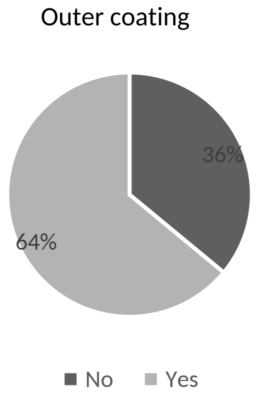

1%
99%
Lightweight
Massive

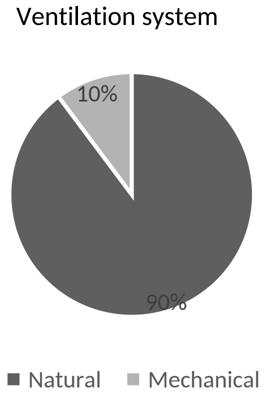

20%
80%
Single
Double

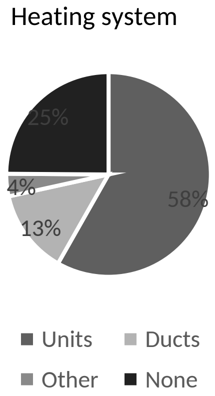

1%
44%
54%
1%
None
Int.
Interm.
Ext.

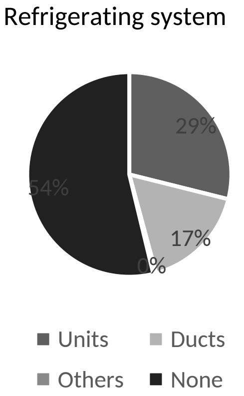

Air chamber
4%
44%
52%
None
Regular
Ventilated


Partition walls
8%
92%
Lightweight
Massive


Outer coating
36%
64%
No
Yes


Ventilation system
10%
90%
Natural
Mechanical


Heating system
25%
4%
58%
13%
Units
Ducts
Other
None


Refrigerating system
29%
54%
17%
0%
Units
Ducts
Others
None

AUTHORS DECLARATION

We wish to confirm that there are no known conflicts of interest associated with this publication.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

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Valladolid, 12th December 2018

Irene Poza Casado