# Air infiltrations and energy demand for residential low energy buildings in warm climates

Silvia Guillén-Lambea[1, 2,*], Beatriz Rodríguez-Soria[1], José M. Marín[2]

[1] University Center of Defense, Ctra. Huesca, s/n, 50090, Zaragoza, Spain.

[2] Aragón Institute of Engineering Research (I3A), Thermal Engineering and Energy Systems Group, University of Zaragoza, EdificioTorres Quevedo, C/Maria de Luna 3, 50018 Zaragoza, Spain.

## Abstract

European building legislation is establishing increasingly stricter requirements to reduce the energy demand of buildings as a measure to decrease energy use and associated carbon emissions. In order to comply with the new standards, the most impactful parameters are subject to important revisions.

Airtightness is revealed as an impacting parameter on air conditioning energy demand for nearly Zero Energy Buildings (nZEB). Currently the Passivhaus standard, taken as a constructive reference for nZEB in Europe, establishes 0.6 ACH as the maximum infiltration at 50 Pa for all new buildings irrespective of the climate zone. Nevertheless, the influence of infiltrations on the energy demand is lower in warm climates.

This study estimates the potential heating and cooling energy demand for different levels of infiltration rates in southern Europe. For this purpose, a dwelling equipped with a mechanical ventilation system with a heat exchanger has been simulated in TRNSYS. The calculations have been performed in different cities with different levels of infiltrations.

This research provides the information required to set airtightness parameters in residential buildings in southern Europe to satisfy the new requirements for nZEB.

## Keywords

Air Infiltrations; Mediterranean climate; Residential dwellings; Building energy demand; nZEB

## 1. Introduction

The building sector accounts for more than 40% of the total energy consumption, with estimated saving energy potential of 28% which represents a massive 11% of total European Union final energy use [1].

Reduction of energy consumption in the building sector constitutes an important part of the measures needed to reduce greenhouse gas emissions and comply with the Kyoto Protocol and with the 20-20-20 European commitment [2]. The EU Green Paper for Energy Efficiency [3] estimates that by 2020, 41 MTOE (million tons of oil equivalent) can be saved by improving heating and cooling demands in buildings.

The term Zero Energy Building (ZEB) is now extensively used internationally in building design. The main drawback for the implementation of this concept in international standards since 2010 has been the lack of a clear and consistent definition and a common method to calculate energy consumption. Some countries have already adopted a common definition for nZEB building but the standardization of the calculation procedure seems to be a rather complicated task [4].The prefix n preceding this term has different meanings- nearly in Europe and net in the USA- but the target is the same. The Energy Performance of Building Directive (EPDB) defines this concept as follows [5]:

According to article 2.2. "'*nearly zero-energy building' means a building that has a very high energy performance, as determined in accordance with Annex I. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby;" Article 9.1. regulates that "Member States shall ensure that by 31 December 2020, all new buildings are nearly zero-energy buildings (1a) and after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero energy buildings."*

While the EPBD sets the framework definition of NZEBs, its detailed application in practice (e.g. what is a 'very high energy performance' and what would be the recommended significant contribution of 'energy from renewable sources') is the responsibility of the Member States when they transpose Article 9 of the Directive into their national systems [6]:

"*the Member State's detailed application in practice of the definition of nearly zero-energy buildings, reflecting their national, regional or local conditions, and including a numerical indicator of primary energy use expressed in kWh/m2 per year. Primary energy factors used for the determination of the primary energy use may be based on national or regional yearly average values and may take into account relevant European standards;"*

At the European level the problem is that, given the great diversity of building and climatic cultures, the EPDB does not establish any line of action to implement the nZEB. Neither does it define accepted values for their energy consumption and nor does it set out a procedure to calculate the energy balance. So, although the methodology was defined by a regulation in 2012, quantitative values for the factors that determine the energy efficiency of buildings do not yet exist [7]. This situation has provoked considerable discrepancies in the reference values adopted by every country for energy consumption [8]. In order to increase the number of buildings with low energy consumption, the national plans must translate the concept of nZEB to their standards and implement useful and practical measures.

The Buildings Performance Institute Europe (BPIE) published on 2011 a guide [9]to actually implement these targets. At the time, more than half of the European countries had not yet included the nZEB definition in their legal standards. The existing definitions had great differences. In particular, it should be pointed out that:

- Most of the definitions set limitations on the primary energy consumption, but there are big differences in the ways of calculating and representing this (e.g., by built surface area or by net surface area).

- The preexisting definitions do not specify any fraction of energy coming from renewable sources in the total consumption. The EPDB is not clear in this respect as it states only that the share of renewable energy must be relevant. The EU Commission has adopted the Passivhaus standard as example of nZEB.

In 2016, the BPIE published a report on the situation of all the EU members plus Norway as regards the definition of nZEB buildings [10]. At that date, 15 countries (besides Brussels and Flanders) had included a nZEB definition in their legislation and three countries had defined the requirements to be fulfilled by a nZEB building, but these were yet to be included in their national standards. The remaining countries were still in the previous debate and development stage. In most countries, the nZEB definition takes as its main indicator the maximum primary energy consumption; in some countries (such as the UK and Norway) the main indicator is the $CO_2$ emissions, while in others (Austria, Romania and Spain) the $CO_2$ emissions are a complementary criterion to the primary energy limitation.

Xiaodong et al. have reviewed the current situation in Europe, China and the USA [11]. Their paper provides an overview of building energy consumption situations and the recent proposals for ZEBs to address increasing building energy demands. They discuss the influence of global climate change on the evolution of building energy use in the future, stating that climate change significantly impacts building energy performance, particularly in space heating and cooling, and concluding that improvements in the building envelope and ventilation can play an important role in reducing air-conditioning energy consumption.

There are many publications in Europe illustrating a number of nZEB concepts and examples. Examples of very low energy buildings with clearly defined requirements in the European Member States are: German Passive House [12] (Passivhaus standard), the French Effinergie [13], the Swiss Minergie [14] and the Italian CasaClima [15].The Passivhaus is generally the best-known type of very low energy since it is the oldest concept having been devised in Germany in the 1990s. It is generally recognized that the requirement for calling a building passive is that it lives up to the standards developed by the German Passive House Institute. The Passivhaus standard is increasingly being considered across Europe as a leader in terms of introducing regulatory changes to adapt buildings to nZEB. Fundamentally, it consists of a total primary energy consumption limit of 120 $kWh/m^2y$ and an energy demand for heating and cooling of 15 $kWh/m^2y$ each [16]. The limit for airtightness is 0.6 ACH (air changes per hour) for a pressure drop of 50 Pa.

The energy demand of air conditioning is mainly produced by the heat transfer losses through the building envelope, the heat losses due to forced ventilation and the losses of air infiltration determined by the airtightness of the building enclosure.

Maximum infiltration-level requirements have been included in the building codes of many European countries (e.g. in Belgium, Denmark, France, Germany, Sweden and the United Kingdom). The trend in countries in central and northern Europe shows that their aim is to achieve the values required by the Passivhaus standard: $n_{50}$< 0.6 ACH. However, countries located in warmer climates

(Mediterranean countries) do not have the same concern and, in consequence, the airtightness requirements for dwellings are not regulated in building codes.

Several publications relating to residential buildings contain measured results for existing dwellings in several countries, for example Finland [17], the UK [18], the north of China [19], and Spain [20,21]. A recent research study [20] concludes that infiltration represents between 10.5 and 27.4% of winter energy demand in buildings built under the current Spanish building code for buildings located in north central Spain. Also, as a representative of the Mediterranean/southern European type of climate, Sfakianaki et al. [22] show results from experimental studies conducted to measure the infiltration in 40 single-family buildings in Greece. The buildings were rated according to their measured air tightness from 1.8 ACH (Air Changes per Hour at 50Pa) to 13.1 ACH.

However, the influence of airtightness in dwellings located in mild climates has not been sufficiently investigated. Sherman et al. [23] state that in buildings with designed ventilation systems, especially those with heat recovery, airtightness may be a determining factor in the performance of the system, because the infiltrated air cannot be heated by the heat exchanger and thus reduces the efficiency of the heat recovery system.

This research demonstrates that the maximum value for infiltration set by Passivhaus for all climatic zones may be too restrictive for residential buildings located in the warm climates found in southern Europe. The aim of this work is to find the maximum value of $n_{50}$ which would be acceptable for Mediterranean countries in residential nZEB. For this purpose, simulations have been performed in TRNSYS [24] for several levels of infiltration in the selected dwelling in numerous European cities, in order to ascertain the influence of airtightness on the heating and cooling demands. The parameters to convert $n_{50}$ to the real infiltration level ($n_{average}$ to be used by the model) for nZEB have been proposed.

## 2. Theory review for airtightness

Building airtightness, which represents the resistance of the building envelope to inward or outward air leakage, is a crucial aspect of energy performance in buildings. No building is 100% airtight and all buildings allow some level of air flow through the building envelope. The term air permeability is also used and means the opposite of airtightness.

Infiltration is the uncontrolled leakage of air inward into a space through walls, crack openings around doors and windows or through the building materials used in the structure. It is difficult to estimate the heat gain or loss through infiltration as there are numerous factors involved. Infiltration is natural ventilation that is driven by the indoor-outdoor temperature and pressure difference and the outdoor wind speed through envelope leaks. Wind will increase infiltration and tall buildings have a stack effect that draws air into the bottom of the building and forces it out at the top. The effect is minor during warm weather but significant in winter, which is verified by the simulation results demonstrated in Section 5.

### *2.1. Blower door test.*

The method for measuring the infiltrations of buildings through fan pressurization is described in the European Standard EN 13829 [25]. The test should be carried out at a pressure difference across the building envelope at 50Pa. This pressure is high enough to be independent of weather influences.

The method is based on the mechanical pressurization or depressurization of a dwelling, using a blower door mounted in the front door with all ventilation sealed.

The basic technique involves measuring the steady-state flow through the fan necessary to maintain a steady pressure across the building envelope. The measurement method is not complicated but the interpretation of the results requires a degree of knowledge.

Most countries express their airtightness requirements as $n_{50}$, however, 50Pa is not the real pressure difference throughout the building envelope. Real pressures would be in the 1-4 Pa range for houses [26], but it is very difficult to obtain a precise measurement of air flow at such low pressures.

The pressurization test is a required test for the Passivhaus standard, since it is important to maintain a certain level of building airtightness to optimize the energy efficiency of a building. The test result to meet this standard is $n_{50} \leq 0.6$ ACH. This value is quite demanding compared with the current European legislation requirements. For example, in Germany the requirement is 1.5 ACH for dwellings.

***2.2. Correlation factor N***

Several studies have addressed the correlation between the airtightness of a building envelope at 50Pa and an annual infiltration rate for residential buildings. The correlation factor N relates the Blower door data to the average air change rate following the simple Equation 1:

$$n_{average}=n_{50}/N \qquad (1)$$

The N factor varies from 10 to 30. Kronvall and Persily [27] obtained the widely used "rule of thumb" for an annual infiltration rate of N=20 from test results measured in houses in Sweden and the USA (New Jersey). It is interesting to remark that the value is taken from houses located in cold areas.

Persily [28] used the data to correlate the infiltration against the leakage for more than 40 houses and achieved the following result (Equation 2):

$$n_{average}=n_{50}/18-0.08 \qquad (2)$$

Sherman [29,30] developed the Lawrence Berkeley Laboratory (LBL) infiltration model obtaining a new expression to convert n50 to 'natural' air-leakage. The value of N ranges between 17 and 23 for most of the US, depending on the climate zone (Figure 1). The procedure gives a more accurate conversion factor N (the ''LBL Factor'') based on correction coefficients for the regional climate, the number of stories, and the amount of shelter from the wind. It is important to remark than those values come from existing dwellings which do not follow the new requirements for low energy demand. The n-factor values are shown in Table 1, these values ranging from 9.8 for a 3-storey building with no shielding in a cold climate zone to 29.4 for a well-shielded, 1-storey building in a warm climate zone.

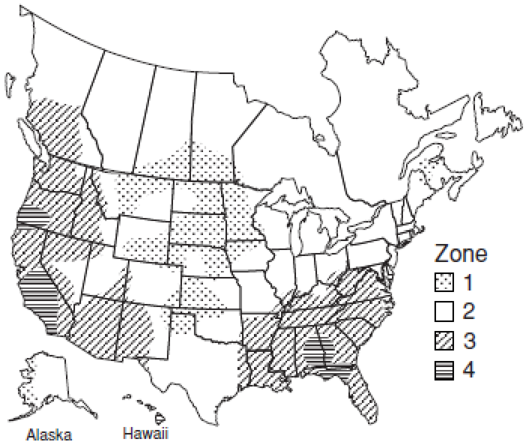


**Figure 1. USA Climate zone for LBL infiltration model** [29,30]

**Table 1. N-factor table** [29,30]

| Climate zone | House stories | 1 | 1.5 | 2 | 3 |
|---|---|---|---|---|---|
| 1 | Well-shielded | 18.6 | 16.7 | 14.9 | 13.0 |
| | Normal | 15.5 | 14.0 | 12.4 | 10.9 |
| | Exposed | 14.0 | 12.6 | 11.2 | 9.8 |
| 2 | Well-shielded | 22.2 | 20.0 | 17.8 | 15.5 |
| | Normal | 18.5 | 16.7 | 14.8 | 13.0 |
| | Exposed | 16.7 | 15.0 | 13.3 | 11.7 |
| 3 | Well-shielded | 25.8 | 23.2 | 20.6 | 18.1 |
| | Normal | 21.5 | 19.4 | 17.2 | 15.1 |
| | Exposed | 19.4 | 17.4 | 15.5 | 13.5 |
| 4 | Well-shielded | 29.4 | 26.5 | 23.5 | 20.6 |
| | Normal | 24.5 | 22.1 | 19.6 | 17.2 |
| | Exposed | 22.1 | 19.8 | 17.6 | 15.4 |

More recently, a study analyzed more than 70,000 air leakage measurements in houses across the United States and found that N= 16 gives the best fit for the data available in the US [31]. Jokisalo et al. [17] concluded that the corrected approximations of annual infiltration rates for a typical one- and two-storey house with a balanced ventilation system in sheltered wind conditions in Finnish climate zones were $n_{50}$/39 and $n_{50}$/ 24, respectively.

The ISO 13789 [32] estimates the annual infiltration rate as $n_{50}$/N, where N=20, and many standards for energy balance refer to this steady-state calculation method.

For example, the German standard DIN 18599 [33] applies 1/N = 0.07, in France there is also a constant coefficient for energy balance calculations of 1/N= 0.06, based on EN 12831[34].

### *2.3. Power law*

The air infiltration measurements fit a power law which has the form shown in Equation 3. The subscript f is related to the fan induced pressure or flow:

$$Q_f = \kappa \cdot \Delta P^n{}_f \tag{3}$$

Where

$Q_f$ is the air flow rate ($m^3/s$) passing through the building envelope,

κ is the leakage coefficient that is related to the size of the opening ($m^3/sPa^n$),

$\Delta P_f$ is the pressure difference (Pa),

and n is the flow exponent characterizing the flow regime (-).

The pressure exponent is between 0.5 and 1.0. An exponent of 0.5 denotes fully turbulent flow and an exponent of 1.0 represents laminar flow. The flow exponent is in the vicinity of 0.65 [35]. The exponent provides an indication of the relative size of the dominant leaks. If the leakage paths are dominated by short leaks (e.g. orifices) the expected value for the exponent is closer to 0.5; though if the leakage is dominated by long-path leaks the exponent value should be closer to 1. A flow exponent closer to 1 indicates a very airtight building whereas an n closer to 0.5 indicates a very leaky building. The n values for northern Europe in existing homes are usually higher than for warmer climates. An analysis of 170 Finnish detached houses [17] shows that the average flow exponent was 0.73; over 90% of the flow exponents in this study being in the range 0.73±0.1. Orme et al, found the average exponent to be approximatively 0.65 from a large dataset [36].

The EN 15242:2007 standard [37] recommends using the conventional value for the exponent of 0.667. The norm indicates that for leaky buildings, the exponent is lower than 0.667, and higher for airtight constructions.

The building leakage at different pressure drops through the envelope can be calculated using eq.3, assuming that the leakage coefficient remains constant, giving Equation 4.

$$\frac{Q_{\Delta P1}}{\Delta P1^n} = \frac{Q_{\Delta P2}}{\Delta P2^n} \tag{4}$$

The exponent value is critical for extrapolating measurements from one pressure regime to another. There is very little information available regarding infiltration measurements of buildings in the Mediterranean region, and even less regarding buildings with heat recovery ventilation systems.

### *2.4. Sherman Grimsrud and LBL infiltration models.*

The Sherman Grimsrud model developed by Sherman in 1980 [38] and the LBL (Lawrence Berkeley Laboratory) infiltration model developed by Sherman in 1986 [39] propose that air infiltration is a function of a building's leakiness and the pressure difference across the building. Such pressure differences are caused by two separate driving forces: the wind effect and the stack effect. The stack effect is caused by the temperature difference between indoor and outdoor air. The LBL model is incorporated into the ASHRAE Standard 119 [40].

The Sherman model, like the LBL model, is based upon knowledge of the overall building leakage as might be obtained by the blower door test. The models use the ELA (effective leakage area) at 4 Pa.

The volumetric flow rate of infiltration air ($m^3/s$) is calculated by the following expression:

$$Q_f = ELA \cdot s \tag{5}$$

The ELA of a building is equal to the area of a perfect nozzle (discharge coefficient of unity) which, at a fan induced pressure, would pass the same amount of air as the building envelope. The ELA ($m^2$) characterizes the leakage of the envelope and can be obtained from the blower door test and is defined as follows:

$$ELA = Q_f \cdot \frac{\sqrt{\rho/2\Delta p_r}}{C_D} \tag{6}$$

Where ρ ($kg/m^3$) is the density of air.

Assuming that Equation (3) and Equation (6) characterize the flow at some reference pressure difference $\Delta p_r$ and the discharge coefficient $C_D$=1, the ELA can be calculated from the blower door data:

$$ELA = \kappa \cdot \Delta P_r^{n-1/2} \sqrt{\frac{\rho}{2}} \tag{7}$$

Which leads to:

$$Q_f = ELA \cdot \left(\frac{\Delta P_f}{\Delta P_r}\right)^n \cdot \sqrt{\frac{2P_r}{\rho}} \tag{8}$$

50 Pa is used as the reference pressure in Europe, while 10 Pa is used as the reference pressure in Canada and the Netherlands. ELA is computed at 4 Pa in the ASHRAE standards.

s is the specific infiltration (m/s) as a function of the temperature difference, wind speed and dwelling parameters.

The LBL model defines the specific infiltration as

$$s = \sqrt{f_s^2 \cdot |\Delta T| + f_w^2 \cdot V^2} \tag{9}$$

Where

ΔT (ºC) is the indoor-outdoor temperature difference

V (m/s) is the wind speed at the local weather station

$f_s$ is the stack factor (m/s $K^{1/2}$)) calculated from eq.10

$$f_s = \left(\frac{1+R/2}{3}\right) \cdot \left(1 - \frac{X^2}{(2-R)^2}\right)^{3/2} \cdot \left(\frac{g \cdot H}{T_0}\right) \tag{10}$$

where R and X are measurements of leakage distribution, H is the height of the building and $T_0$ the outside temperature.

$f_w$ (-) is the wind factor given as follows:

$$f_w = C \cdot (1-R)^{1/3} \cdot A \cdot \left(\frac{H}{10m}\right)^B \tag{11}$$

C is an empirical shielding parameter whose values are given in Table 2. The second term corrects the wind speed. A and B are terrain parameters whose values are indicated in Table 3.

**Table 2. Local shielding classes** [30]

| Shelter class | Shielding parameter C | Description |
|---|---|---|
| 1 | 0.34 | No obstructions |
| 2 | 0.30 | Light local shielding, few obstructions |
| 3 | 0.25 | Moderate local shielding, some obstructions |
| 4 | 0.19 | Heavy shielding, typical suburban shielding |
| 5 | 0.11 | Very heavy shielding, typical downtown shielding |

**Table 3. Terrain parameters values** [30]

| A | B | Terrain Description |
|---|---|---|
| 1.30 | 0.10 | Ocean or other body of water |
| 1.00 | 0.15 | Flat terrain with some isolated obstacles |
| 0.85 | 0.20 | Rural areas |
| 0.67 | 0.25 | Urban, industrial or forest areas |
| 0.47 | 0.35 | Center of a large city |

For the Sherman and Grimsrud model these factors ($f_s$ and $f_w$) are replaced by the coefficients $C_s$ and $C_w$. The model is semi empirical, requiring that the user enter a stack coefficient $C_s$ ($(l/s)^2/(cm^2K)$) and a wind coefficient ($C_w$) ($(l/s)^2/(cm^4\ (m/s)^2)$). These coefficients are functions of a factor that it calls the shelter class together with the height of the building (in stories).

$$s = \sqrt{C_s \cdot \Delta T + C_w \cdot V^2} \tag{12}$$

**Table 4. Stack coefficient Cs** [38]

| House stories | 1 | 2 | 3 |
|---|---|---|---|
| $C_s$ | 0.000145 | 0.00029 | 0.000435 |

**Table 5. Wind coefficient Cw** [38]

| $C_w$ | House stories | | |
|---|---|---|---|
| Shelter class | 1 | 2 | 3 |
| 1 | 0.000319 | 0.000420 | 0.000494 |
| 2 | 0.000246 | 0.000325 | 0.000382 |
| 3 | 0.000174 | 0.000231 | 0.000271 |
| 4 | 0.000104 | 0.000137 | 0.000161 |
| 5 | 0.000032 | 0.000042 | 0.000049 |

### *2.5. Infiltrations according to the Passivhaus standard*

The infiltration air change rate as a result of leaks is determined by the PH standard on the basis of a simple approximation equation found also in the EN ISO 13790 until 2008 [41]. (Eq. 13).

$$n_{average} = \frac{V_{50}}{V} \cdot n_{50} \cdot e \quad (13)$$

In balanced ventilation systems with heat recovery, the rate of air leakage depends on the fan pressurization test result ($n_{50}$) and the wind screening coefficient (e) according to EN 832 [42]. The values are listed in Table 6. Also, a correction factor is applied, the relation between $V_{50}$ (air volume during blower door test) and V (theoretical air volume contained in the house).

**Table 6. Wind protection coefficient according to EN 832.**

| Wind protection coefficient | | |
|---|---|---|
| Coefficient e for screening class | Several sides exposed | One side exposed |
| No screening | 0.10 | 0.03 |
| Moderate screening | 0.07 | 0.02 |
| High screening | 0.04 | 0.01 |

The default value for infiltration for PHPP (Passivhaus Projecting Package, which is the standard tool developed by PH to calculate the energy demand for low energy buildings) is 0.042 ACH, which corresponds to $n_{50}$=0.6 and a value for the wind coefficient corresponding to moderate screening of 0.07. This value is considered constant throughout the year in the PHPP for energy calculations. The worst value admitted accepted by Passivhaus corresponds to no screening and then $n_{average}$ will be 0.06.

## 3. Computational model

In order to simulate the energy demand for heating and cooling of the selected residential housing a computational model has been developed using TRNSYS [43] software. The building model in TRNSYS incorporates all the requirements set by the Passivhaus standard as an example of a nZEB dwelling, including the heat recovery ventilation system. Simulations have been run for different cities with varied climate conditions. The infiltration rates change in order to check the impact on heating and cooling demand for a year for Mediterranean and northern European cities.

### *3.1. Dwelling description and model parameters*

The dwelling is taken from a real project and it is representative of a family of 4 persons. The apartment has a kitchen, a living room, three bedrooms and two bathrooms. It has a net area of 81.15m$^2$ and the ceiling height is 2.5m. The apartment is located on the third floor of a building of 3 floors. As regards the orientation, the dwelling has windows on the north facade in the living room and in one bedroom, and on the south facade in the kitchen, bathroom and two bedrooms. Only the hall, corridor and toilet have no exterior windows. The layout has been previously been considered by the authors [44,45] and the TRNSYS model has been calibrated and validated in a previous research [46].

Moreover, the selected dwelling fulfills the requirements defined by the Spanish Institute for Energy Diversification and Saving (IDAE) [47] concerning the percentage of the windows and external wall areas versus the net area of the dwelling. This guarantees a representative percentage of heat gains (internal gains and solar gains) and heat losses (external walls, windows and ventilation losses). The total area of the windows and door in the dwelling is 21.20 $m^2$, including the entrance main door. The percentage of openings related to the net area of the dwelling is 26.07% and it is detailed in Table 7.

**Table 7. Dwelling enclosure areas.**

| Building enclosure | Area ($m^2$) |
|---|---|
| External walls | North: 24.10<br>South: 29.00<br>East: 20.00 |
| External wall to neighbor | West: 24.90 |
| Floor to neighbor | 81.15 |
| Flat roof | 81.15 |
| Windows | North: 8.40<br>South: 10.80 |
| Main door (internal) | West: 2.00 |

The input parameters considered to define the dwelling in TRNSYS which remain constant in all simulations meet the Passivhauss requirements. The recommended envelope transmittance limit values for central and northern European countries are different from those for Mediterranean countries. For Central and Northern Europe: 0.15 $W/m^2K$ for exterior walls, floors and roofs and 0.8 $W/m^2K$ for windows and doors. For Mediterranean countries: 0.34 $W/m^2K$ for exterior walls, 0.26 $W/m^2K$ for floors and roofs and 1.4 $W/m^2K$ for windows and doors.

Russell et al. made a complete review of residential ventilation technologies [26]. The mechanical air ventilation system including heat recovery is decisive for reducing the air ventilation losses and consequently is an obligatory requirement for the Passivhaus standard. Average ventilation volumetric flow recommended by Passivhaus standard is 30 $m^3/h$ per person in the household. For the model the whole air flow ventilation is 120 $m^3/h$ (4 persons) and is considered to be constant all through the year. The supply air ventilation flow is 40% for living room, and 20% for each of the three sleeping rooms. For exhaust air flow the 40% is leaving the kitchen and 20% is leaving each of the two bathrooms.

*Mardiana et al. made a review of residential ventilation technologies* [48] *and presents and discusses physical and performance parameters of heat recovery unit and the significances of these parameters on operation and efficiency of the system* [49]. The efficiency of the heat exchanger, following the Passivhaus recommendations, has to be greater than 75%. The heat exchanger efficiency in the model is 85%, representative efficiency of what currently exists in the market, where it is not uncommon to find exchangers with an efficiency of up to 95% for Passivhaus constructions. The by-pass mode operates if the outside temperature is higher than the inside temperature during the winter season and lower during the summer season.

The set temperature values are different depending on the countries´ regulations [46]. The simulations were performed with a room temperature set at 20°C for heating and 26°C for cooling, following the Passivhaus recommendations and those of the European Standard EN 15251:2007 [50].

The calculations have been done with the strategy of free cooling. The south Mediterranean cities have high solar radiation, and free cooling is needed to maintain cooling demand at reasonable levels. Values obtained for cooling demand will be much lower when implementing free cooling strategies. The regulations in some Mediterranean countries such as Spain require this strategy for energy calculation [51] consisting of opening windows during summer months from 01:00a.m to 08:00a.m. This strategy is not specifically for houses with mechanical ventilation systems where opening windows is only justified for its impact on the cooling demand. For the simulations, a mid-way strategy has been applied. Windows will be open in summer months for 3 hours during the night and for 3 hours during the early morning. The free cooling has been applied to all the simulated cities in order to compare the results.

The model includes sensible loads due to occupation. During nights four people are in the house (2 in the double room and one each in the sleeping rooms), during days an occupational calendar is applied by considering also four people in the house: 2 people in the kitchen and 2 people in the living room. The heat generated according to different degrees of activity follows the values detailed in the ISO 7730: 2005 [52].

For internal sources, a load of 2.5 W/m$^2$ for lighting and equipment and a computer with monitor in the living room with a load of 230W, have been considered. The nominal sensible loads are multiplied by a coefficient depending on the time of day, related to the occupancy.

### *3.2. Climate data and city selection*

Several locations across Europe were selected to test the sensitivity of the infiltrations on the heating and cooling demand depending on the climate. As there is no clear guide as to whether a city has a central European or a Mediterranean climate, the climatic stratification of the environment of Europe according to Metzger et al.[53] has been used. The locations have been chosen in accordance with a high-resolution climatic stratification of Europe within 13 environmental zones. The cities selected are shown in Table 8, three of them located in northern Europe for the purposes of comparison.

**Table 8. Selected cities.**

| COUNTRY | CITY | CLIMATIC ZONE |
|---|---|---|
| SPAIN | Almería | MDS |
| | Valencia | MDS |
| | Barcelona | MDS |
| | Bilbao | LS |
| | Madrid | MDS |
| FRANCE | Nice | MDN |
| | Paris | ATC |
| ITALY | Milan | MDM |

| | | |
|---|---|---|
| | Rome | MDN |
| | Palermo | MDS |
| GERMANY | Berlin | CONT |
| UK | London | ATC |

MDS: Mediterranean South

MDM: Mediterranean Mountains

MDN: Mediterranean North

ATC: Atlantic Central

CONT: Continental

LS: Lusitanian

The southern and northern cities are indicated in Figure 2.

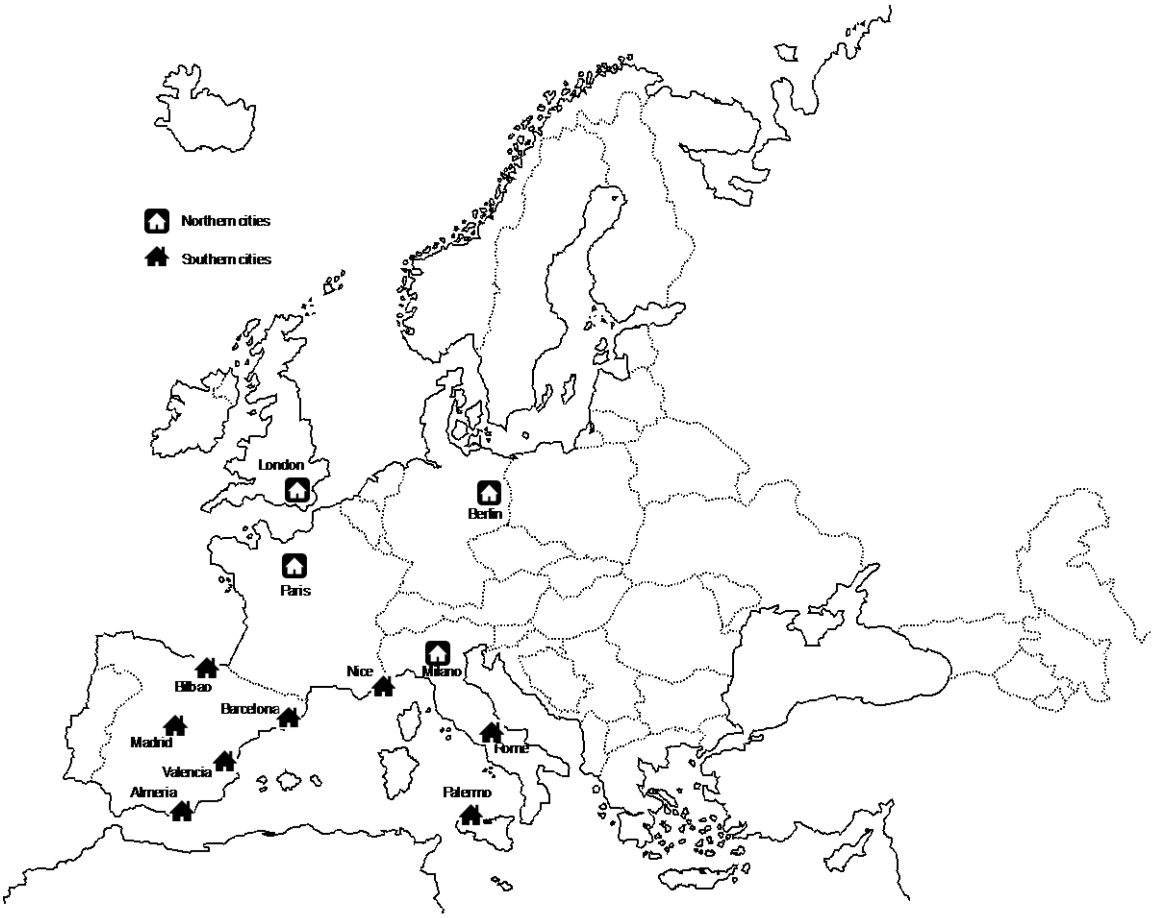


**Figure 2. City locations.**

The climate data files are taken from the Meteonorm meteorological database [54]. The Typical Meteorological Year (TMY 2) weather data format is compatible with TRNSYS using a Type15-6 and contains hourly weather data for yearly building energy analysis.

## 4. Methodology

To investigate the impact of different degrees of infiltration in terms of energy demand for heating and cooling, the degree of infiltration included in the model simulations throughout a year should be under natural driving pressures and real temperatures. Unfortunately, the infiltration rate at 50 Pa is not the quantity of interest, and the maximum set value of 0.6 ACH cannot be directly incorporated in the model. Several difficulties are involved in converting the most common normalized airtightness metric, $n_{50}$, to the real average infiltration rate in real conditions, $n_{average}$.

The average pressure across a leak in a building envelope is closer to 1Pa, 2.5Pa or 4Pa [35] than to 50Pa. Therefore, the average infiltration rate ($n_{average}$) should be changed to $n_{50}$ (at 50Pa) in order to check directly the impact on energy demands of the value imposed by the Passivhaus standard.

Simulations were performed in two steps. For the first step, an average remained constant every hour throughout the year (as for the PHPP tool). The reverse conversion to $n_{50}$ could be done applying the Correlation factor N, where the difficulty is the lack of information regarding the value of N (Eq. 1) for houses with heat recovery ventilation. The reverse conversion can also be carried out by applying the Power Law (Eq. 3), where the difficulty is to define the value for the flow exponent (n). The incertitude of this conversion is fairly high.

Taking in account the values recommended by Sherman, the simulated dwelling which is carefully chosen to be located on the last floor, the correction factor N will vary depending on the climate zone (for $n_{50}$=0.6 ACH). In the case of a well-shielded apartment, N is 20.6 for the warmest US climate area (similar to Mediterranean cities, climate zone 4) and 15.5 for the cities located in Northern Europe (climate zone 2). In the case of exposed apartments, N is 15.4 and 11.7 respectively.

The results certainly give conclusions related to the impact on energy demand in the cities selected depending on the level of infiltrations. The heating and cooling demand for warmer locations can be compared with the coldest ones under the same conditions. The conversion values according to the recommended correlation factor N and the Power law with different flow exponent values are shown in Table9.

Table 9 shows very significant discrepancies in the conversion of the $n_{average}$ to $n_{50}$. This is due to the fact that the correlations are mostly based on existing dwellings which are not representative of new constructions which are more focused on reducing energy consumption. There is a lack of information regarding the correlation factor for houses with heat recovery ventilation. The correlation factors found in the bibliography come from existing dwellings, mainly located in the United States, Canada and Northern Europe, which are ventilated primarily through leaks in the building envelope rather than by mechanical ventilation systems.

As a first step, simulations were performed varying the $n_{average}$ in steps of 0.04ACH, from 0 to 0.24ACH (shorter intervals give too insignificant variations in energy demand). A value for $n_{50}$ greater than 2 ACH could be proposed in terms of energy demand, but for $n_{50}$ greater than 3 the ventilation system cannot be run with energy efficiency [23].

**Table 9. $n_{average}$ and the corresponding $n_{50}$ value**

| | $n_{average}$ (value to the simulation model) | 0.04 | 0.08 | 0.12 | 0.16 | 0.2 | 0.24 |
|---|---|---|---|---|---|---|---|
| $n_{50}$ Applying correlation | Kronvall and Persily and ISO 13789 (N=20) | 0.80 | 1.60 | 2.40 | 3.20 | 4.00 | 4.80 |
| | Persily (Eq.2) | 0.80 | 1.52 | 2.24 | 2.96 | 3.68 | 4.40 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| factor N | Sherman LBL (zone 4- well-shielded*) N=20.6 | 0.82 | 1.65 | 2.47 | 3.30 | 4.12 | 4.94 |
| | Sherman LBL (zone 2- well-shielded*) N=15.5 | 0.62 | 1.24 | 1.86 | 2.48 | 3.10 | 3.72 |
| | Sherman LBL (zone 4- exposed*) N=15.4 | 0.62 | 1.23 | 1.85 | 2.46 | 3.08 | 3.70 |
| | Sherman LBL (zone 2- exposed*) N=11.7 | 0.47 | 0.94 | 1.40 | 1.87 | 2.34 | 2.81 |
| | Chan et al. (N=16) | 0.64 | 1.28 | 1.92 | 2.56 | 3.20 | 3.84 |
| | Germany DIN V 18599 (1/N=0.07) | 0.57 | 1.14 | 1.71 | 2.29 | 2.86 | 3.43 |
| | France EN 12831 (1/N=0.06) | 0.67 | 1.33 | 2.00 | 2.67 | 3.33 | 4.00 |
| $n_{50}$ Applying Power law for dP=2.5Pa | Orme et al. n=0.65 | 0.28 | 0.56 | 0.84 | 1.12 | 1.40 | 1.68 |
| | Jokisalo et al. n=0.71 | 0.34 | 0.67 | 1.01 | 1.34 | 1.68 | 2.01 |
| | EN 15242 n=0.667 | 0.30 | 0.59 | 0.89 | 1.18 | 1.48 | 1.77 |
| $n_{50}$ Applying Power law for dP=4Pa | Orme et al. n=0.65 | 0.21 | 0.41 | 0.62 | 0.83 | 1.03 | 1.24 |
| | Jokisalo et al. n=0.71 | 0.24 | 0.48 | 0.72 | 0.96 | 1.20 | 1.44 |
| | EN 15242 n=0.667 | 0.22 | 0.43 | 0.65 | 0.86 | 1.08 | 1.29 |

* Tree stories

In a second step, an infiltration model was added to the simulation project as described in Section 2.4, where the infiltration air flow is calculated on an hourly basis and depends on the climatic conditions (wind speed and outside temperature). The infiltrations are simulated in the TRNSYS project using the Type932 Sherman Grimsrud infiltration model from the TESS library (Thermal Engineering System Specialists) [55]. The values used were Cs= 0.000435, which is the recommended value for three storeys, and $C_w$= 0.000494 and $C_w$= 0.000049, which are the recommended values for three storey shelter class 1 and 5. The value of $ELA_4$ is 25.4 $cm^2$ ($n_{50}$=0.6).

### *4.1. Single zone model or multi-zone model*

The models presented are single zone models, developed to be applied for single family houses. Multi-zone models are applied to high-rise buildings to calculate air flow and contaminant transport between zones. The measurement of air leakage on a building- wide scale requires similar basic equipment to that used for component testing (fans, flow measurement devices, etc.), only on a much larger scale.

For mid-to-high rise construction, additional fans may be required to provide even pressure distribution throughout the full height of the space. This is not the case for the dwelling under study, were the air leakage measurement should come from an independent blower door test as recommended by the Passivhaus standard.

The inconvenience of applying the single model to the dwelling is that the model does not distinguish the air leakage location (from outside or from the neighbors or common areas). For the dwelling under study, it is not possible to estimate separately the leakage to the outside and the leakage to other adjacent units. However, in a summary report, Gulay et al. [56] tabulated the percentage distribution of the whole building leakage by component: 42% windows, 26% doors, 14% vertical shafts, and 6% building envelopes.

Taking into account that building envelope leakage is not very significant and that only the main entry door is located at the common areas of the building, the air leakage coming from those areas will not be so important. Consequently, the hypothesis of the most unfavorable situation for the energy demand will be assumed: the infiltration air entering the house is at the outside temperature.

## 5. Results and discussion

Figure 3 shows the heating energy demand for each city depending on the $n_{average}$ (constant for every hour throughout the year). The graph also represents the values obtained applying the Sherman Grimsrud infiltration model ($n_{avSG}$ values represented by a triangle). The $n_{avSG}$ represented for each city is the mean value obtained during the winter months (from October to May).

Simulations have been performed for two cases:

Squares: Sherman Grimsrud infiltration model for wind coefficient Cw= 0.000494 for no wind obstructions, class 1.

Triangles: Sherman Grimsrud infiltration model for wind coefficient Cw= 0.000049 for local shielding, class 5: shelter produced by buildings or other structures that are immediately adjacent.

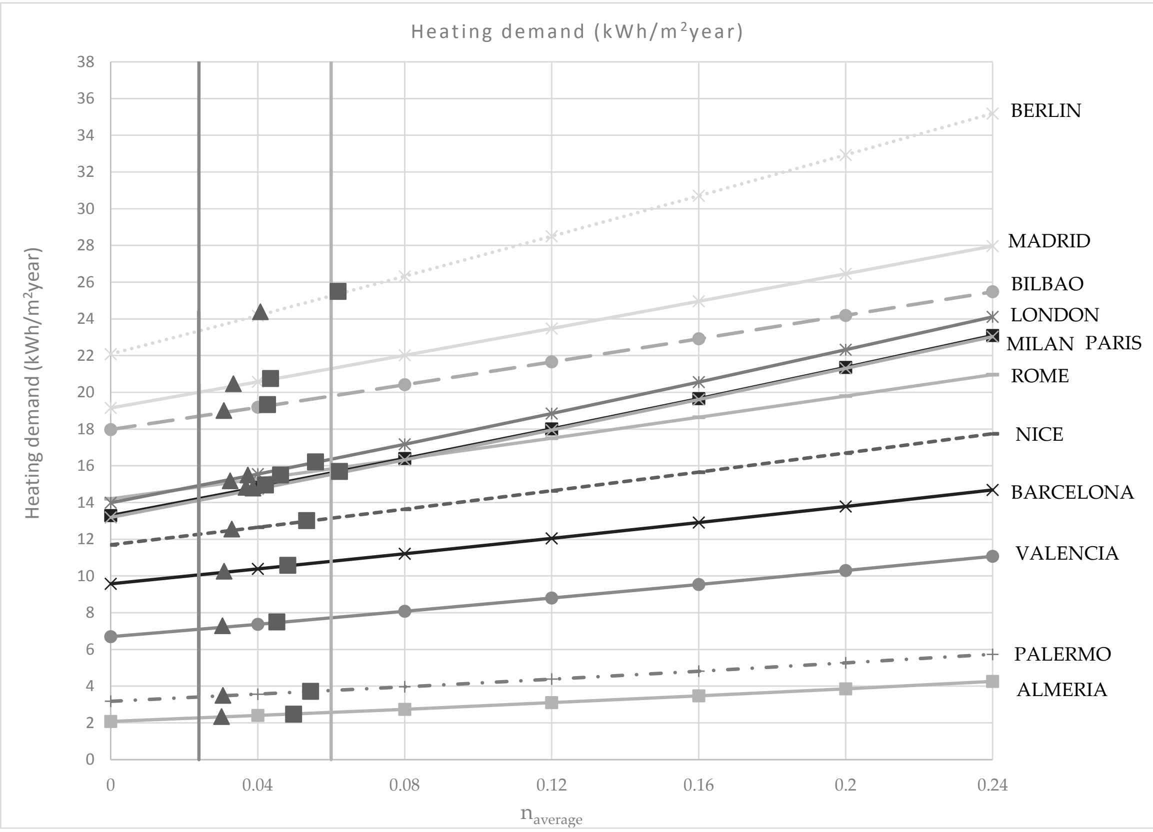


**Figure 3. $n_{average}$ and heating energy demand depending on the air infiltration**

The vertical lines represent the $n_{average}$ value for the Passivhaus standard. For e= 0.1 (no screening), the $n_{average}$ is 0.06 while for e= 0.04 (high screening) the $n_{average}$ is 0.024. The $n_{average}$ values converted by Passivhaus are more demanding than the result obtained by applying the Sherman Grimsrud model in the cases of windy locations and less demanding for protected dwellings (third floor) for all the cities except for Milan and Berlin.

One northern city (Berlin) and two southern cities (Bilbao and Madrid) do not fulfill the heating demands set by the Passivhaus standard for this dwelling even for zero infiltrations. It is evident that additional specific strategies and design modifications could be implemented to reach the required level (15 $kWh/m^2$ y), as for example increasing the heat exchanger efficiency, optimizing the window size and location or controlling the air ventilation rate as a function of the dwelling occupancy.

The increase in the heating energy demand for each increase in the air infiltration grows slightly at every step. For example, for Berlin increasing the $n_{average}$ from 0.04 to 0.08 ACH increases the heating demand by 2.09 $kWh/m^2y$ and for the last step a variation of the $n_{average}$ from 0.2 to 0.24 ACH increases the heating demand by 2.26 $kWh/m^2y$. The increase in heating demand depends on the climate and, as expected, the greatest impact is seen in Berlin, the coldest city. Meanwhile, for cities located in southern Europe, such as Almeria and Palermo, the heating demand increases by only 0.34 and 0.40 $kWh/m^2y$ respectively, when increasing the $n_{average}$ from 0.04 to 0.08 ACH.

The infiltration values $n_{avSG}$ obtained (average for winter months) are from 0.042 ACH (lowest value for Milan) to 0.062 ACH (highest value for Berlin and Paris) for class 1, and from 0.030 ACH (lowest value for Almeria and Valencia) to 0.041 ACH (highest value for Berlin) for class 5.

The cooling demand depending on the $n_{average}$ for each city is shown in Figure 4. As expected, the cooling demand is slightly affected by infiltrations. The graph also represents the values obtained applying the Sherman Grimsrud infiltration model ($n_{avSG}$ values represented by a triangle). The $n_{avSG}$ represented for each city is the mean value obtained during the summer months (from June to September).

Simulations have been performed for two cases:

Squares: Sherman Grimsrud infiltration model for wind coefficient Cw= 0.000494 for no wind obstructions, class 1.

Triangles: Sherman Grimsrud infiltration model for wind coefficient Cw= 0.000049 for local shielding, class 5: shelter produced by buildings or other structures that are immediately adjacent.

The vertical lines represent the $n_{average}$ value for the Passivhaus standard, as in Figure 4. The $n_{average}$ values considered by Passivhaus are more demanding in all the cities for class 1 and in warm cities for class 5 (third floor).

Four Mediterranean cities, Almeria, Valencia, Barcelona and Palermo, have a higher cooling demand than heating demand. The results show that strategies such as opening windows are necessary and highly recommended for Mediterranean cities, which have some difficulties in meeting the Passivhaus requirements for cooling demands. Two cities, Almeria and Palermo, do not fulfill the cooling demands of the Passivhaus standard for this dwelling. Additional specific strategies and design modifications could be implemented to reach the required level (15 $kWh/m^2$ y), such as high performance shading devices or an optimal orientation as well as extending the time for opening windows.

Increasing the air flow due to infiltrations reduces the cooling demand in all the cities, in contrast to the heating demand.

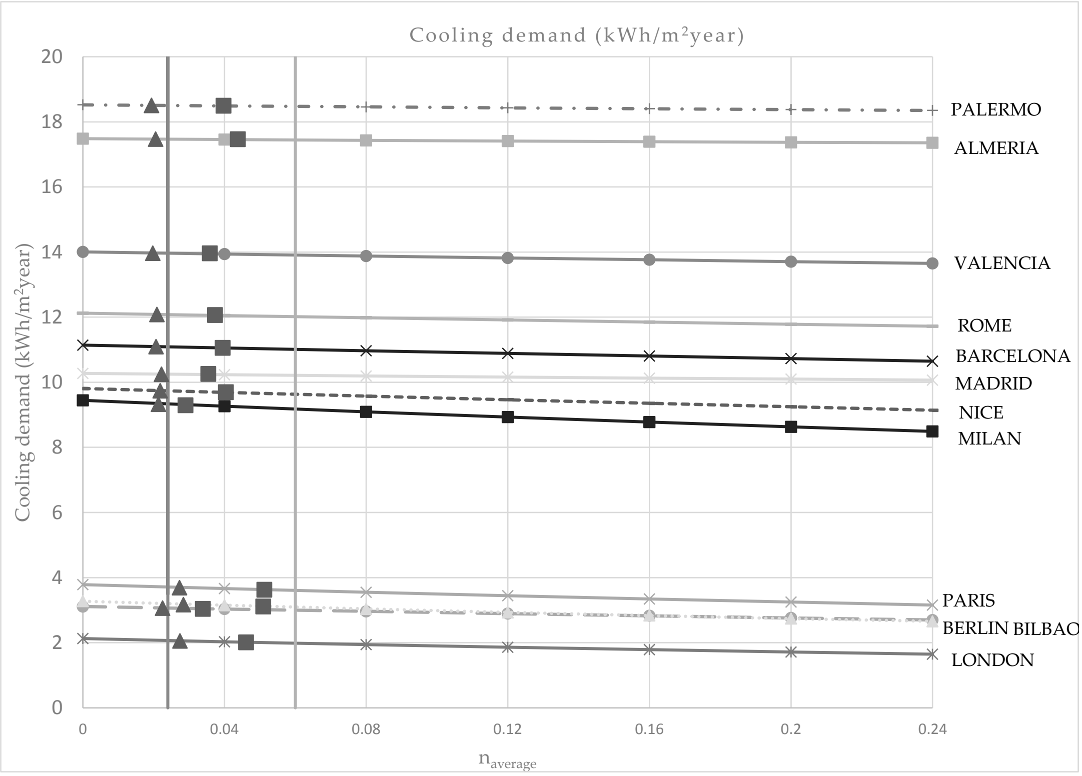


**Figure 4.** $n_{average}$ and cooling energy demand depending on the air infiltration

The values obtained applying the Sherman Grimsrud infiltration model, the $n_{avSG}$ values, which are the mean values obtained during the summer months (from June to September), range from 0.029 ACH (lowest value for Milan) to 0.051 ACH (highest value for Berlin and Paris) for class 1, and from 0.019 ACH (lowest value for Palermo) to 0.028 ACH (highest value for Berlin) for class 5.

Figure 5 represents the increase in the total air conditioning energy demand (heating plus cooling) throughout the year.

These results indicate that for southern Europe the impact of the infiltration level on energy demand is much lower than for northern Europe. For example, for 0.08 ACH, the energy demand is increased by 3% for Almeria and by 19% for London. For central Mediterranean cities (Madrid, Barcelona, Rome and Nice) the impact, although not as significant as in the north, remains lower: for example, 8% for Rome versus 17% for Munich. The coldest cities, London, Berlin and Paris have increases of 19%, 17% and 16 %, respectively, in the total energy demand for 0.08 ACH.

The $n_{avSG}$ values are represented by a triangle (class 5) and by a square (class 1) for each city. The value is the mean infiltration rate applied with the Sherman Grimsrud model throughout the year.

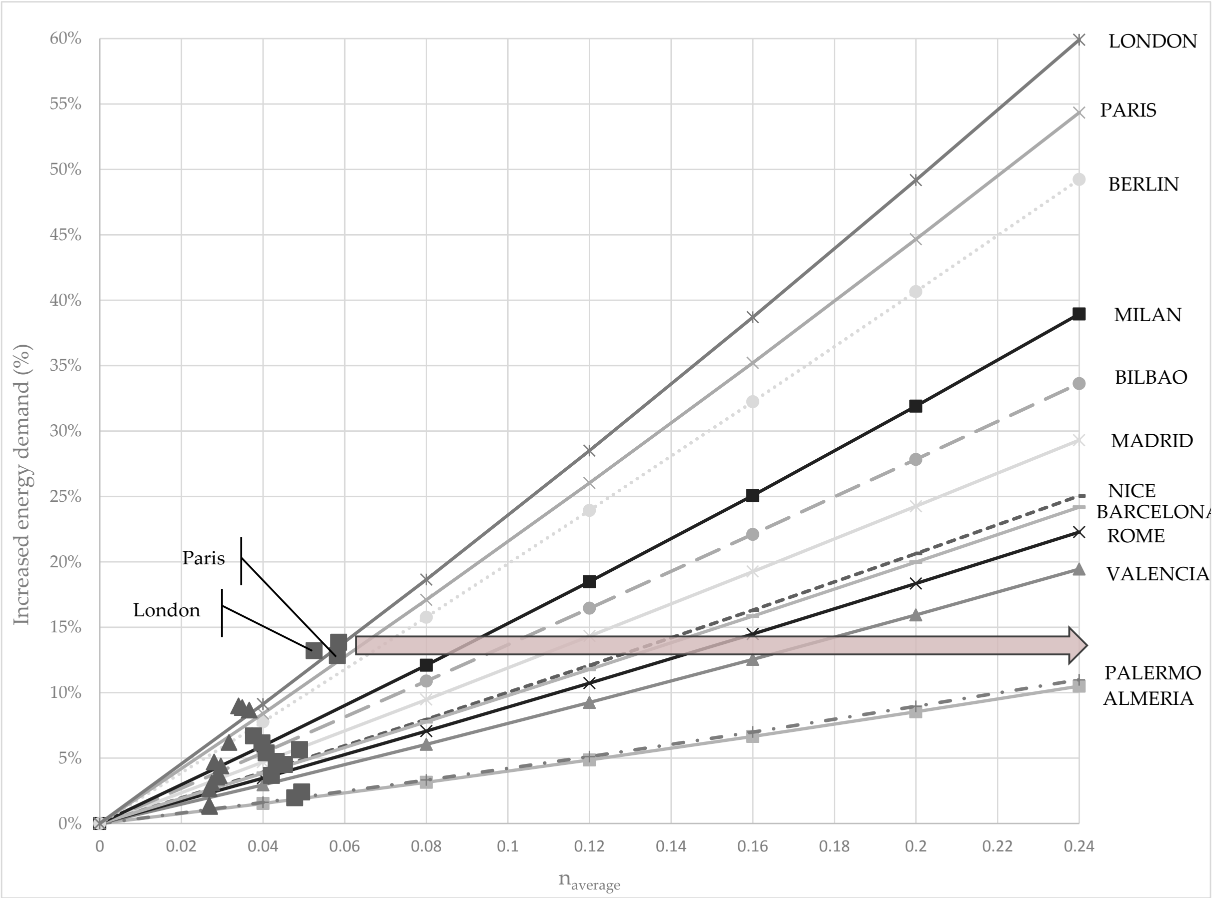


**Figure 5. Increased energy demand (%) depending on the air infiltration $n_{average}$.**

The total energy demand increased by around 13% for the coldest cities (Paris, London and Berlin) for $n_{average}$ values equal to 0.06 (worst case) comparing with zero infiltrations. Maintaining this increase in the energy demand, the $n_{average}$ for Mediterranean cities could be relaxed. For Milan, Bilbao and Madrid the $n_{average}$ could be increased between 0.09 ACH and 0.12 ACH; for Nice, Barcelona, Rome and Valencia between 0.13 ACH and 0.17 ACH; and even more than 0.24 ACH for Palermo and Almeria.

In the case of Almeria, the infiltration from 0 to 0.24 ACH increases the total energy demand by only 2 kWh/m$^2$y, whereas the impact in Berlin is 12.5kWh/m$^2$y and in London 9.7kWh/m$^2$y.

The mean infiltration values ($n_{avSG}$) obtained applying the Sherman Grimsrud infiltration model throughout the year range from 0.038 ACH (lowest value for Milan) to 0.059 ACH (highest value for Paris) for class 1, and from 0.027 ACH (lowest value for Almeria, Valencia, Barcelona and Palermo) to 0.037 ACH (highest value for Berlin) for class 5.

For the Mediterranean cities the values obtained for $n_{avSG}$ are over the curve found when applying a constant $n_{average}$ throughout the year. This is due to the fact that the variations in the infiltration rate for each month are minor since the stack effect caused by the temperature difference between indoor and outdoor air is not as relevant as for colder cities. The total air conditioning demand obtained for colder cities is slightly greater because the infiltration during winter is higher than during summer.

Figure 6 shows both effects more clearly:

1) The same value obtained from the Blower door test (0.6 ACH for all the cities) gives the same ELA in the dwelling, but the infiltration rate depends on the climate conditions. The highest $n_{SGav}$ values are obtained for the coldest cities (more important stack effect).

2) Similar values of $n_{SGav}$ have a much greater impact on heating and cooling energy demand for colder cities. The outdoor temperature for colder cities during winter is much lower.

These effects suggest than infiltration requirements for cities located in warmer climates could be relaxed.

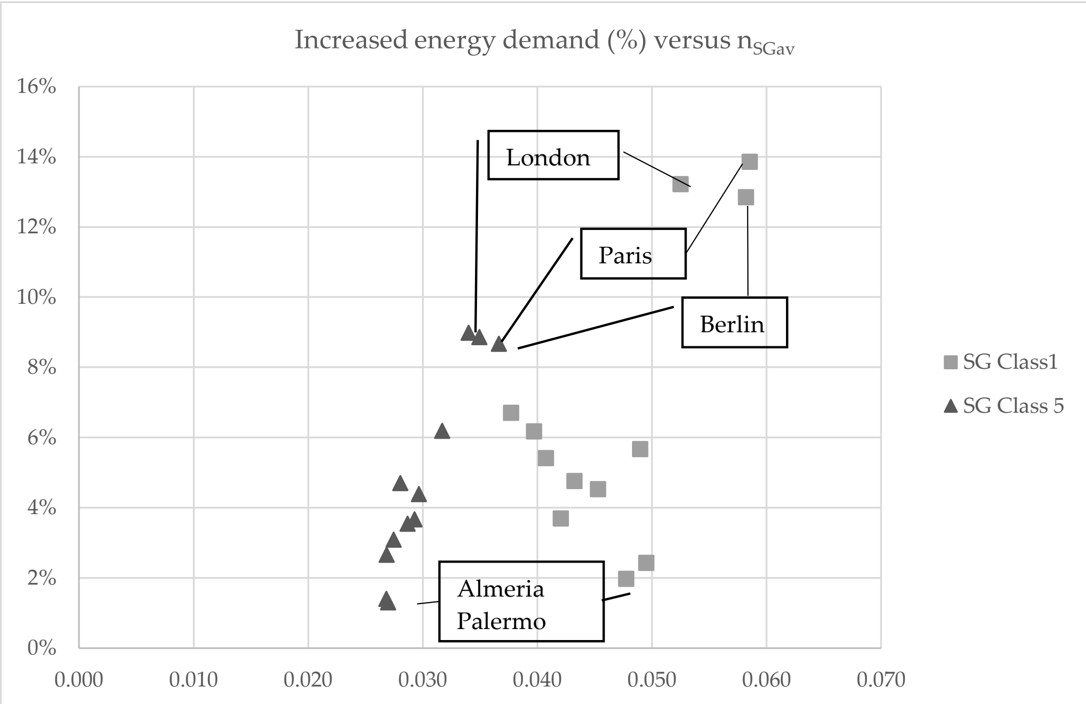


**Figure 6. Increased energy demand (%) depending on the air infiltration $n_{average}$.**

The variation of the air infiltration rate during different months of the year can be seen in Figure 7 for class 1 and in Figure 8 for class 5.

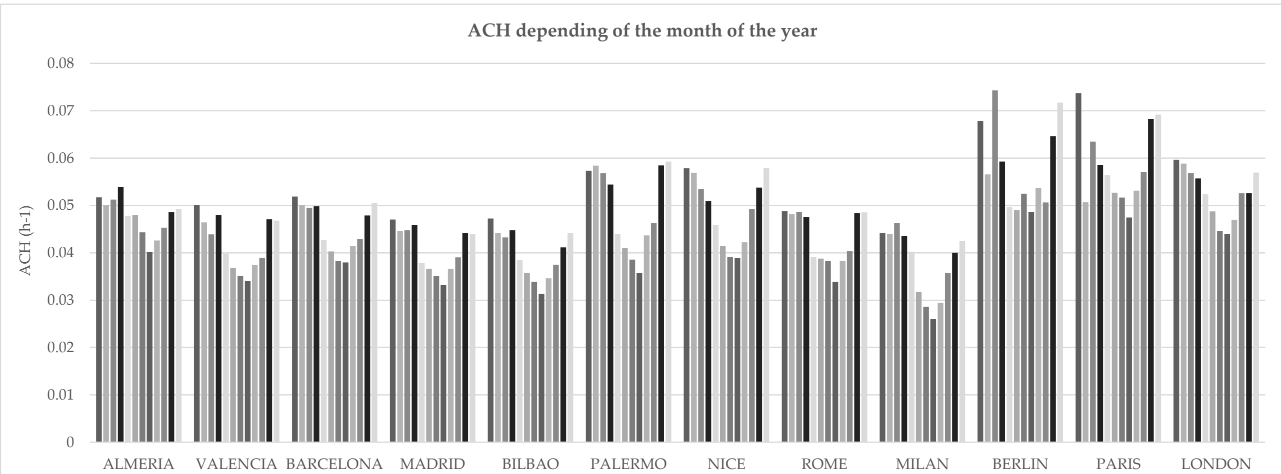


**Figure 7.** ACH depending of the month of the year. Sherman Grimsrud model Class 1.

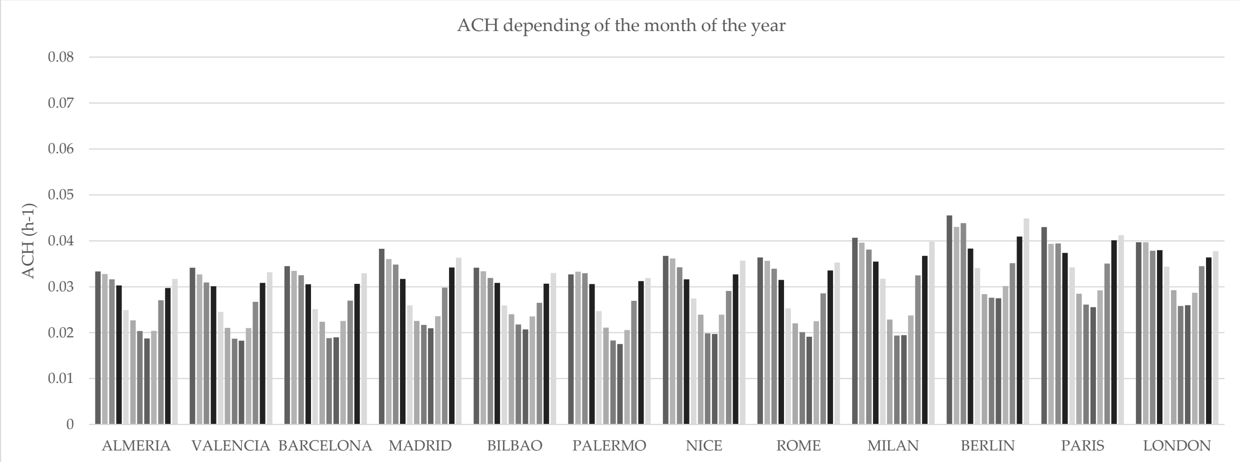


**Figure 8.** ACH depending of the month of the year. Sherman Grimsrud model Class 5.

The difference in the air infiltration rate between the months of August and January, due to the greater temperature difference between indoors and outdoors in winter, is significant in cities such as Paris where the difference is 0.026 ACH but minor in Almeria with a difference of 0.012 ACH for class 1.

For class 5, the differences all the year round are as significant as for class 1. The greatest difference is obtained for Milan, with 0.021 ACH, and the lowest for Bilbao with 0.013 ACH.

Looking at the ACH values during the winter months, the differences between southern and northern European cities are substantial. As an example, Berlin has 0.045 ACH and Almeria 0.032 ACH in December. The difference is due mainly to the fact that the temperature difference between indoors and outdoors is greater in Berlin than in Almeria.

The N correlation factor was calculated (Equation 1) with the $n_{avSG}$ obtained for nZEB dwellings located in areas without wind obstructions (class 1) and in city centres (well-shielded). The values are shown in Table 10.

For class 1, the correlation factor value is between 12 and 14 for all the Mediterranean cities and approximatively 10 for cities located in northern Europe.

For class 5, the correlation factor value is between 20 and 22 for all the Mediterranean cities and approximatively 17 for cities located in northern Europe.

**Table 10. N correlation factor obtained from Sherman Grimsrud model.**

| CITY | ACH average (year). Sherman Grimsrud model Wind coef. $C_w$= 0.000494 (Class 1) | Correlation factor N | ACH average (year). Sherman Grimsrud model Wind coef. $C_w$= 0.000049 (Class 5) | Correlation factor N |
|---|---|---|---|---|
| ALMERIA | 0.048 | 12.57 | 0.027 | 22.25 |
| VALENCIA | 0.042 | 14.27 | 0.027 | 22.35 |
| BARCELONA | 0.045 | 13.25 | 0.027 | 21.86 |
| MADRID | 0.041 | 14.73 | 0.030 | 20.23 |
| BILBAO | 0.040 | 15.11 | 0.028 | 21.40 |
| PALERMO | 0.049 | 12.12 | 0.027 | 22.37 |

| | | | | |
|---|---|---|---|---|
| NICE | 0.049 | 12.26 | 0.029 | 20.51 |
| ROME | 0.043 | 13.88 | 0.029 | 20.93 |
| MILAN | 0.038 | 15.92 | 0.032 | 18.95 |
| BERLIN | 0.058 | 10.31 | 0.037 | 16.39 |
| PARIS | 0.059 | 10.25 | 0.035 | 17.18 |
| LONDON | 0.052 | 11.43 | 0.034 | 17.65 |

## 6. Conclusions

The correlation factor N has been calculated for an airtight dwelling located in several cities in Europe. The real infiltration average values corresponding to $n_{50}$=0.6 ACH have been obtained from simulations performed with TRNSYS applying the Sherman Grimsrud model. The air infiltration impact on cooling and heating demand has been calculated.

The cooling is less affected by infiltrations compared with the energy losses occasioned during the heating season. Therefore, in cities where the nZEB cooling demand is higher than the heating demand, the infiltration value should not be so restrictive. The air flow rate achieved by mechanical ventilation systems is not enough to cool homes at night in hot climates.

For cities located in northern Europe the air conditioning energy demand increases by 13% when the value set for infiltration is 0.6 ACH (50Pa) while for cities located in the Mediterranean area this impact is 4 % to 7 %. Moreover, the impact is even lower for southern European cities such as Almeria and Palermo where the increases are lower than 3%.

The energy demand due to the infiltration air flow (for the same $n_{50}$ value) is higher in cities located in colder climates due to two effects: first, the greater temperature difference between outdoors and indoors increases the air flow due to infiltrations and, second, the outdoor air temperature is lower. These effects are not considered in the Passivhaus standard, which established identical limitations for $n_{50}$ irrespective of the climate area.

The infiltration air flow is higher during winter than during summer. This is another fact not taken into account by the Passivhaus standard which established a constant value for $n_{50}$ throughout the year.

The results of this research suggest that the current maximum value for infiltrations (0.6 ACH at 50 Pa) required by the Passivhaus standard is excessive for residential buildings located in warm climates found in the Mediterranean area. For cities located in the Mediterranean area the maximum $n_{50}$ value for nZEB could be relaxed to 1 ACH. Furthermore, for cities in the south of the Mediterranean the value could be increased even further to 2 ACH to achieve the same percentage increase in air conditioning demand posed by 0.6 ACH in cities in northern Europe. These values are low enough to ensure that the ventilation system will be energy efficient.

A recommended value for the correlation factor N to convert $n_{50}$ to $n_{average}$ for nZEB has been obtained from the Sherman Grimsrud model depending on the shielding of the dwelling. For local shielding its value is approximatively 12 for Mediterranean cities and 10 for cities located in northern

Europe  while for city centre dwellings its value is approximatively 22 for Mediterranean cities and 17 for cities located in northern Europe.

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*Highlights

# Air infiltrations and energy demand for residential low energy buildings in warm climates

Silvia Guillén-Lambea[1, 2,*], Beatriz Rodríguez-Soria[1], José M. Marín[2]

[1] *University Center of Defense, Ctra. Huesca, s/n, 50090, Zaragoza, Spain.*

[2] *Aragón Institute of Engineering Research (I3A), Thermal Engineering and Energy Systems Group, University of Zaragoza, Edificio Torres Quevedo, C/Maria de Luna 3, 50018 Zaragoza, Spain.*

## Highlights

- Proposal of the maximum infiltration rate in warm climates for residential nZEB.
- The infiltration impact on the air conditioning demand depending on the climate has been obtained.
- Values for $n_{50}$ are proposed for residential nZEB in warm climates.
- Recommended value for correlation factor to convert $n_{50}$ to $n_{average}$ for nZEB has been obtained.

[*] Corresponding author. *Silvia Guillén-Lambea*. *University Center of Defense, Ctra. Huesca, s/n, 50090, Zaragoza, Spain.*
*Email address: sguillen@unizar.es, tel. +34 976 739838*