TESIS DE LA UNIVERSIDAD DE ZARAGOZA

2017

86

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Residential nZEB in southern Europe: analysis and optimization of the parameters related to air ventilation systems to reduce air conditioning energy demand

Departamento

Ingeniería Mecánica

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ISSN 2254-7606

Prensas de la Universidad
Universidad Zaragoza

ISSN 2254-7606

Universidad Zaragoza
1542

Tesis Doctoral

RESIDENTIAL NZEB IN SOUTHERN EUROPE: ANALYSIS AND OPTIMIZATION OF THE PARAMETERS RELATED TO AIR VENTILATION SYSTEMS TO REDUCE AIR CONDITIONING ENERGY DEMAND

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ECCN residenciales en el sur de Europa: Análisis y optimización de parámetros relacionados con el sistema de ventilación para reducir la demanda energética de climatización

DOCTORAL THESIS

by

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Zaragoza, May 2017

Agradecimientos

Mi más sincero agradecimiento a mis directores de tesis, José Mari Marín y Beatriz Rodríguez. Gracias José Mari por tus sabios consejos, por enseñarme millones de variadas cosas, gracias por ser siempre mi profesor y sobre todo gracias por tu confianza en mi trabajo. Gracias Beatriz por tu inestimable ayuda, por tus recomendaciones, gracias por tu positivismo y sobre todo gracias por tus abrazos en los momentos bajos.

Gracias a Jesús Martínez Patiño, gracias por tu ayuda, por tu confianza e implicación en mi estancia de investigación y gracias a la Universidad de Guanajuato por acogerme.

Gracias al Centro Universitario de la Defensa por haberme permitido iniciar y concluir este proyecto.

Gracias a mis compañeros de EG-DAO por su alegre compañía en este sinuoso camino, gracias Jorge por escucharme y por ayudarme a superar mis caóticos momentos, gracias Marcos por tus sinceros ánimos y gracias Myriam por compartir tus risas conmigo.

Gracias a mis padres por su amor incondicional y por todo lo que me han enseñado.

Gracias a Fernando, mi amor, gracias por hacer mis proyectos los nuestros, gracias por ayudarme a hacerlos posibles.

Abstract

The construction sector is responsible for approximately 40% of energy consumption and greenhouse gas emissions at a worldwide level. Two-thirds of these emissions come from residential and commercial buildings. Building policies worldwide are becoming more demanding in terms of improving the energy performance of buildings to ensure that the target for nearly-zero energy buildings (nZEB) will be reached in 2020.

The construction methodology Passivhaus has been adopted throughout northern and central Europe as a reference for the drafting of regulatory changes aimed at adapting buildings to nZEB. However, the implementation of such changes in areas with warm climates is still under study. The main objective is the reduction of air conditioning energy demand, whose limit value is regulated all over the world. Those parameters with the greatest impact for improving air conditioning demand are subject to continuous and important improvements. Such improvements are: to increase thermal insulation, to increase the airtightness of the building envelope and to reduce the energy losses due to air ventilation. However, regulatory changes in southern Europe aimed at reducing air conditioning energy demand to achieve the nZEB targets are mainly focused on improving building envelope thermal insulation. They do not include the influence of airtightness and the energy losses due to air ventilation, especially in residential buildings.

On this basis, we present the following doctoral dissertation whose main objective is the optimization of air ventilation systems for residential nZEB in the south of Europe. First, the main regulations concerning the ventilation of residential buildings in several countries, as well as the requirements set by the Passivhauss standard, are studied and compared. Secondly, the suitability of heat recovery in mechanical ventilation systems is investigated depending on the climate data. The advisability of choosing a heat or an energy recovery ventilator depending on the potential energy to be recovered is also demonstrated. Finally, optimal control strategies for Energy Recovery Ventilators (ERV) are proposed, supported by a quantitative analysis of the air conditioning demand.

Moreover, for dwellings with mechanical ventilation systems, especially those with heat or energy recovery, airtightness may be a determining factor for the performance of the system. This doctoral dissertation aims to demonstrate that the maximum value for air infiltration set for Europe by the Passivhaus standard may be unduly restrictive for residential buildings located in warm climates and proposes a limit for infiltrations depending on the climatic zone.

Additionally, the impact of comfort parameters on the heating and cooling energy demand for residential nZEBs following the Passivhaus standard has been quantified. This dissertation provides recommendations for the development of further standards concerning energy efficiency in buildings and air quality indoors.

Keywords: air ventilation, building energy demand, residential nZEB, heat recovery ventilator, energy recovery ventilator, Mediterranean climate, energy recovery strategies, European regulations, Passivhaus, air infiltrations, envelope airtightness, thermal comfort, energy efficiency.

Resumen

El sector de la construcción es el responsable de aproximadamente el 40% del consumo de energía y de las emisiones de gases de efecto invernadero a nivel mundial. Dos tercios de estas emisiones provienen de edificios residenciales y comerciales. Las normativas y regulaciones referentes a la construcción en todo el mundo son cada vez más exigentes en la mejora del rendimiento energético de los edificios para garantizar que se alcanzará, en el año 2020, el objetivo de edificios de consumo de energía casi nulo (ECCN, nearly zero energy buildings nZEB).

La metodología constructiva Passivhaus se ha extendido por el norte y el centro de Europa como referencia para la definición de los cambios normativos destinados a la adaptación de los edificios a nZEB, sin embargo su aplicación e implementación en climas cálidos del sur de Europa, todavía está en estudio. El objetivo principal es la reducción de la demanda de energía de climatización, cuyo valor límite se impone en las normativas de los diferentes países. Los parámetros que tienen más impacto en la optimización de la demanda energética del sistema de climatización están sujetos a importantes mejoras continuas. Estas mejoras son: el aumento del aislamiento térmico, aumento de la estanqueidad de la envolvente y la reducción de las pérdidas de energía debidas a la ventilación. Las modificaciones normativas para disminuir la demanda energética con el fin de alcanzar los objetivos nZEB se centran en los países del sur de Europa en mejorar aislamientos, dejando a un lado el estudio de las infiltraciones y el sistema de ventilación, sobre todo en edificación residencial.

Sobre esta base, presentamos la siguiente tesis doctoral, cuyo objetivo principal es la optimización del sistema de ventilación de aire para nZEB residenciales, específicamente los localizados en climas cálidos como el sur de Europa. Para ello, se analizan y comparan en profundidad las principales normativas relativas a la ventilación de edificios residenciales en varios países, así como los requisitos establecidos por el estándar Passivhauss. En segundo lugar, se investiga la adecuación de la recuperación de calor en el sistema de ventilación mecánica en función de los datos climáticos. También se demuestra la conveniencia de elegir un recuperador de calor o de energía dependiendo de la energía potencial disponible en el aire y finalmente se proponen estrategias de control para el funcionamiento óptimo de los recuperadores de energía (ERV) basados en los resultados de un análisis cuantitativo de la demanda energética del acondicionamiento del aire.

Además, para las viviendas que cuentan con sistema de ventilación mecánica, especialmente aquellas con recuperación de calor o energía, la estanqueidad al aire puede ser un factor determinante del rendimiento del sistema. Por lo tanto, esta tesis doctoral analiza si el valor máximo de infiltración establecido para el norte y centro de Europa por el estándar Passivhaus puede ser demasiado restrictivo para los edificios residenciales situados en climas cálidos, proponiendo un límite para las infiltraciones dependiendo de la zona climática.

Adicionalmente, se ha cuantificado el impacto de los parámetros de confort en la demanda de energía de calefacción y refrigeración para nZEB residenciales siguiendo el estándar de Passivhaus, proporcionando recomendaciones para el desarrollo de normativas adicionales referentes a la optimización energética sin olvidar la calidad del aire interior.

Palabras clave: sistema de ventilación, demanda energética de edificios, residencial ECCN, recuperador de calor, recuperador de energía, clima mediterráneo, estrategias de recuperación de energía, normas europeas, Passivhaus, infiltraciones de aire, estanqueidad de la envolvente, confort térmico y eficiencia energética.

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List of abbreviations

AC	Air Conditioned Building
ACH	Air change per hour
BEPS	Building Energy Performance Simulation
BPIE	Buildings Performance Institute Europe
CTE	Technical Building Code (Spain)
DB-HE	Basic document for energy saving
DB-HS	Basic document for health standards
ECCN	Edificios de Consumo Casi Nulo
EES	Engineering Equation Solver
EISA	Energy Independence and Security Act
ELA	Effective Leakage Area
EPBD	Energy Performance of Buildings Directive
ERV	Exhaust Recovery Ventilator
EU	European Union
HRV	Heat Recovery Ventilator
IDAE	Spanish Institute for Energy Diversification and Saving
IWEC	International Weather for Energy Calculations
LBL	Lawrence Berkeley Laboratory
LC-ZEB	Life Cycle Zero Energy Buildings
MRT	Mean Radiant Temperature
MV	Mechanical Ventilated Building
NV	Naturally Ventilated
nZEB	Nearly Zero Energy Building
PEP	Passivhaus Spanish Platform-Plataforma de Edificación Passivhaus
PH	Passivhaus
PHPP	Passivhaus Projecting Package
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
RH	Relative Humidity
SWEC	Spanish Weather for Energy Calculations
TESS	Thermal Engineering System Especialist
TMY	Typical Meteorological Year
TRNSYS	Transient System Simulation Tool

Chapter 1

Introduction

1. Introduction

1.1. Legislative context

Many reasons can be found to justify efforts to reduce energy consumption, the most important being the fight against global warming and the protection of the environment. Other not negligible reasons are the finite reserves of fossil fuels and high energy costs.

The Kyoto protocol [1], signed on December 1997, comes under the United Nations Framework Agreement on Climate Change and has as a target the reduction of the emission to the atmosphere of six greenhouse gases. The signatory countries commit themselves to develop and to apply policies *to improve the energy efficiency in the highest consuming sectors of their national economies* and to guarantee that greenhouse gas emissions do not surpass the levels established in annex B of the agreement. The specific target was to decrease the total amount emitted by at least 5% between 2008 and 2012 in relation to 1990 levels.

Aware that the measures included in the Kyoto protocol were not enough to stop climate change, in March 2007 EU leaders adopted an *integrated approach to climate and energy policy to combat global warming and to raise the energy security and competitiveness of the EU.* To start this process, the heads of the States and Governments agreed a set of targets which must be met by 2020, known as 20-20-20 [2,3]. This means:

- A reduction of greenhouse effect gas emissions by at least 20 % of 1990 levels.
- 20 % of energy consumption should be supplied by renewable sources.
- A 20 % reduction of the primary energy consumption related to projection levels by means of energy savings.

In January 2008, the European Commission proposed compulsory legislation to implement the 20-20-20 targets. The European Parliament and the European Council eventually approved climatic and energetic legislative measures in December 2008 which became law by June 2009 [2,3].

In order to reach the 20-20-20 targets, the main routes focus on three sectors: industry, transportation and buildings. This last sector has a 40 % share of world energy consumption and CO_2 emissions [4,5]. In order to regulate the new requirements, the 2010/31/EU directive [6] known as the *Energy Performance of Buildings Directive* (EPBD) was published. Under its provisions, all EU members must take the necessary action to ensure that every public building is a nearly zero energy consumption building (nZEB) from 2018 onwards and all new buildings from 2020. This directive requires national energy plans to introduce the following items:

- A clear definition of a nZEB building according to the local conditions, including a quantitative primary energy consumption expressed in $\mathrm{kWh/(m^2 \cdot} year)$

- An intermediate demanding goal to improve the energy efficiency of new buildings (2015)

In Spain, the contribution of buildings to overall energy consumption and to greenhouse gas emissions is very significant. According to the latest estimations, this sector contributes 17 % of the total energy consumption and 25 % of the electricity demand [7]. Emissions of CO_2 are greater than 1 ton per year per dwelling. Several factors explain the increasing trends of these values, such as the increase in the number of dwellings, the greater degree of comfort required and the consequent increase in home appliances (Figure 1.1).

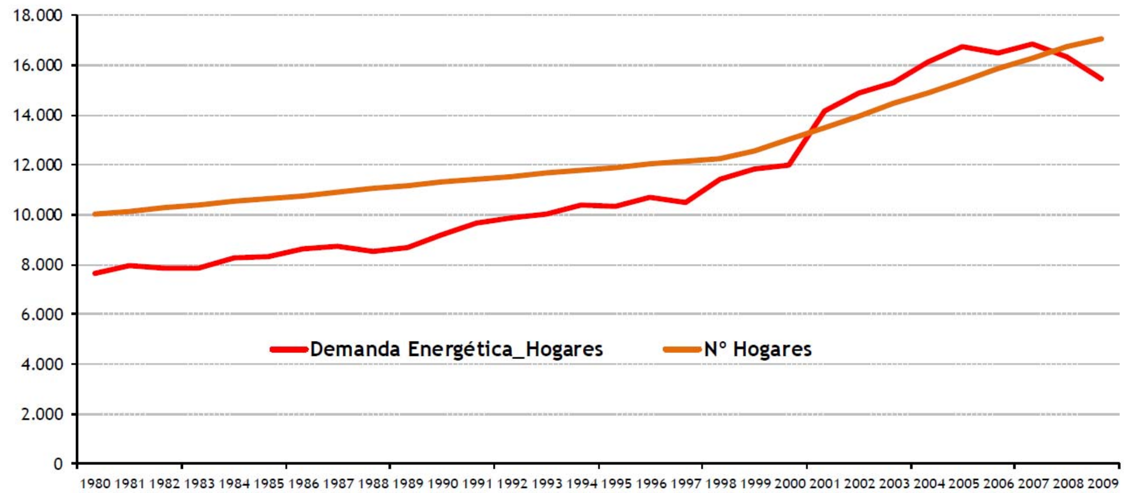


Figure 1.1. Energy consumption (ktep/year) of residential buildings [7].

The current energy situation in Spain is serious because of its high external dependence (about 80 %, much greater than the European average). Its limited resources together with continuous changes in energy legislation have the effect of constant increases in energy prices. Electricity prices are above the European average (Figure 1.2), being in fact the second most expensive within the whole EU.

Following the EU directives, in Spain the legal standard Real Decreto 314/2006 sets out the technical code for building (CTE) [8]. This code includes six basic documents of which the DB-HE [9] (basic document for energy saving) and DB-HS [10] (basic document for health standards) are those related to energy saving in buildings.

The aim of DB-HE is to establish procedures and rules to fulfill the requirement of energy saving and contains six basic documents: HE0 and from HE1 to HE5. These requirements regulate the thermal boundaries of buildings and the systems of energy generation. Their targets are twofold: the reduction of energy consumption and the use of clean energy sources. These documents have been updated twice, the last update being the legal Order FOM/1635/2013.

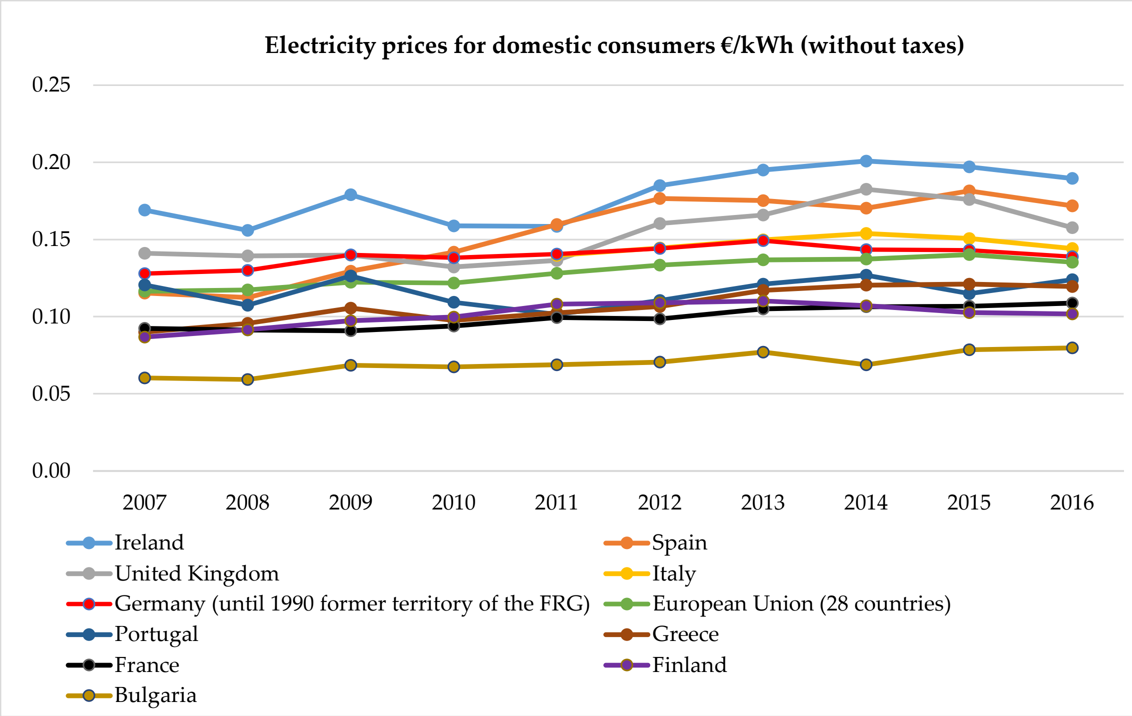


Figure 1.2. Electrical energy prices for domestic consumers, in €/kWh, without taxes. Prepared using EUROSTAT data.

A search into the most relevant European legal standards has also been undertaken and a detailed review carried out of standards relating to the air ventilation of buildings (3.2).

1.2. Nearly Zero-Energy Building (nZEB)

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 [11].

The prefix *n* preceding this term has different meanings- *nearly* in Europe and *net* in the USA- but the target is the same. The EPDB defines this concept as follows [12]:

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;" Annex I, article 1 stipulates that "The energy performance of a building shall be determined on the basis of the calculated or actual annual energy that is consumed in order to meet the different needs associated with its typical use and shall reflect the heating energy needs and cooling energy needs (energy needed to avoid overheating) to maintain the envisaged temperature conditions of the building, and domestic hot water needs." 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."

The term LC-ZEB (Life Cycle Zero Energy Buildings) should be added to the previous concepts to include not only the energy demand of the building when used, but also the energy needed to build and transport the building materials [13].

In 2012 the *National Global Change Research Plan 2012_2021: A Strategic Plan for the U. S. Global Change Research Program* [14] was published in the USA. Its remit was monitoring, searching and reporting the current situation of CO_2 emissions and energy consumption, and recommending measures to combat climate change. Notwithstanding, the document does not mention any commitment to any actual measure to reduce CO_2 emissions. In 2007, the Energy Independence and Security Act (EISA 2007) [15] established the goal that from 2030 onwards all buildings must guarantee a 100 % reduction in fossil fuel supply.

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 [16]. This situation has provoked considerable discrepancies in the reference values adopted by every country for energy consumption [17]. 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 [18] 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.

Different targets can be used to define nZEB, e.g. a very general one such as not to exceed a maximum amount of primary energy demand. Sometimes, this general target is used together with limitations that are more specific such as the heating and refrigerating demand in the Passivhaus standard [19] and other limits that ensure internal comfort.

In April 2015, the BPIE published a report on the situation of all the EU members plus Norway as regards the definition of nZEB buildings [20]. 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 [21]. 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. Several non-governmental associations have worked on implementing and spreading this concept; some examples are Passivhaus in Germany [19] (Passivhaus standard), Effinergie in France [22], Minergie in Switzerland [23] and CasaClima in Italy [24]. The best known is Passivhaus, possibly because it is the oldest having been devised in the 1990s.

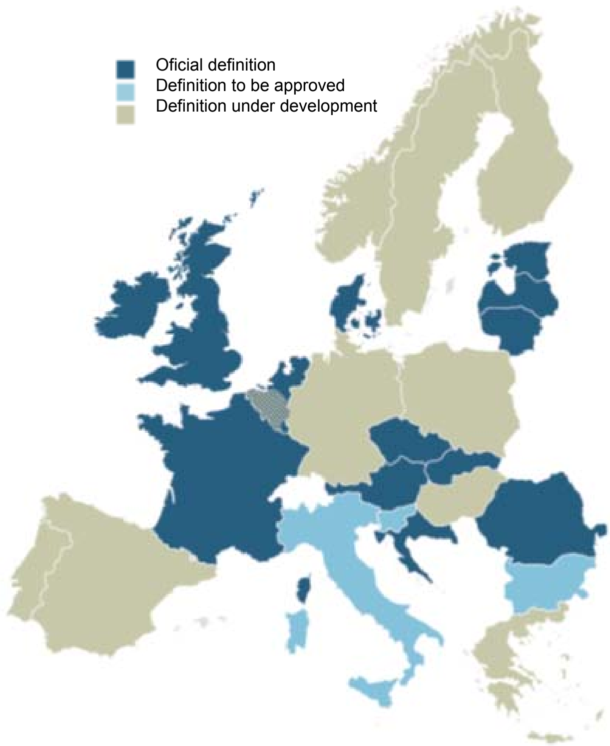


Figure 1.3. EU nZEB definition map for new buildings (2015). (Source: BPIE [20]).

1.3. Passives houses and the Passivhaus standard

The best known nZEB in central Europe is the Passivhaus (PH), devised by the Passivhaus-Institute of Darmstadt. This standard was formally formulated in 1988 and in 1990 the first project was carried out with the erection of four double houses in Darmstadt. The European commission has recommended the requirements of Passivhaus standards as an example of nZEB [18] definition. Currently, passive design in northern and central Europe is increasingly associated with PH standards, most countries adopting Passivhaus criteria as targets to be included in their legal standards for buildings. The situation is very different in southern Europe (Spain, Italy, Portugal and Greece) where the PH standard prescriptions are not optimized for their warmer climates.

The goals of passive design in winter are to maximize the heat gains and minimize the heat losses; in summer, the target is the reduction of solar gains. A passive house uses mainly passive systems to supply heat, cold, ventilation and illumination by controlling the natural energy fluxes surrounding the building such as sun and wind. There is a very wide range of passive technical solutions, many of them known since a long time ago, such as painting external walls in white so as to reduce the cooling demand and an appropriate sizing and orientation of windows to increase the entry of natural light and to reduce the heating demand. Passive architecture is therefore closely related to traditional architecture. It integrates active components with low energy consumption, for example pumps and fans which can be operated with renewable energy sources such as photovoltaic panels.

Passivhaus extends the passive house concept, providing a design procedure that allows the making of buildings with minimum energy consumption while maintaining thermal comfort by means of a sequence of steps and limitations in both the design and execution stages. The seven basic principles of the Passivhaus standard are as follows:

- A high degree of thermal isolation in the closures of the building (walls and windows). The required transmittance values are much lower than those included in the European standards.
- Removal of thermal bridges
- Infiltration control
- Mechanical ventilation with heat recovery. The heat exchanger is a key element in the operation of a passive house and its minimum efficiency should be 75 %.
- High performance windows and doors with double sealed frames and two or three low emissivity panes of glass in order to increase the thermal resistance of the closures.
- Optimization of solar gains and internal heating
- Energy modelling by means of a specific software package: the PHPP (Passivhaus Planning Package). This is a simple calculation program based on excel sheets and is used to do the thermal calculations of the building.

The dwellings built under the Passivhaus standard are distinguished by their low energy consumption. Their requirements are the following [19]:

- Maximum heating demand of $15\text{kWh}/(\text{m}^2 \cdot \text{year})$.
- Maximum cooling demand of $15\ \text{kWh}/(\text{m}^2 \cdot \text{year})$.
- For buildings heated and cooled by air, alternatively, the heating and cooling load can be less than $10\ \text{W}/\text{m}^2$.
- The airtightness must be verified by means of a pressurization test according to the standard EN 13829 [25], limiting the air renewals to 0.6 per hour under a pressure difference of 50 Pa.
- The total primary energy consumed by the building must not exceed $120\text{kWh}/(\text{m}^2 \cdot \text{year})$.
- The internal surface temperatures of the building in winter must be higher than $17\ ℃$.

Currently there are about 4000 buildings (and/or dwellings) [26] in Europe built and certified under the Passivhaus standards. Thirty-five of them are in Spain.

1.3.1. The Passivhaus standard for Mediterranean climates

The PH standard was originally devised for central European cold weather. PH has subsequently carried out extensive research to adapt its criteria to the warmer climates in southern Europe [27], although significant work still needs to be done.

Mediterranean weather has much higher temperatures and solar radiation and usually higher humidity than weather in central Europe. So, the question is not whether the PH requirements can be achieved in the Mediterranean area but rather how they can be achieved in the best possible manner. It is not known if the passive house, as conceived by PH, would offer the same comfort level in summer as the level offered in central Europe. The analysis of the ventilating system is especially important in order to establish its optimal design and operating point for Mediterranean countries.

In order to find an answer to these questions, several research groups were created in Europe, the most outstanding being the *Passive- On* project (2005-2007) [28]. The Intelligent Energy Europe (EIE) program funded this project, whose goal was the reformulation of the Passivhaus standard for warmer European climates. This adaptation implies a set of changes such as the removal of the obligation of installing active systems for ventilation and heat recovery, the requirement that summer comfort temperature does not exceed the limits defined in the standard EN 15251 [29] for adaptive comfort temperature, and the reduction of the airtightness limitations. However, this adaptation is very far from being finished.

In recent years many scientific papers have been published focused on the minimization of energy consumption in warmer buildings, not only for the south of Europe but also for several areas in China or the USA [30–39], where the PH building standard is spreading. Nevertheless, the most recent bibliography reflects the pioneering work carried out in central Europe on this topic. Most of the papers on heat exchangers used in air recovery are focused on sensible recovery (Heat Recovery Ventilators, HRV) [40,41]. Reference [42] is especially noteworthy because it reports a comparative study of three kinds of building (individual house, flat and office) for seven French towns with and without heat recovery. The simulations were made with TRNSYS [43] and very relevant results were obtained, although taking into account only the sensible heat recovery and the sensitivity of general ventilation parameters. The exchanger design parameters were not considered. Mardiana et al. [44] carried out a complete review of the existing HRV technologies.

Recently, a substantial number of publications [38,45–50] have studied the possibility of using enthalpy recovery devices, also known as membrane exchangers, that recover both sensible and latent energy (Energy Recovery Ventilators ERV). Mardiana et al. analyzed the most relevant ERV parameters in order to optimize the efficiency of the ventilating system [51].

In Spain, research is very scarce. Perez-Lombard et al. [52] carried out a review of the published energy consumption in buildings, but this work is now obsolete as it dates from 2007. More recently, the work by Fernández-Seara et al. [53] described a test in a membrane exchanger, reproducing the operating conditions of current systems.

1.4. Thesis motivation and justification

Two important issues have been identified in relation to the energy efficiency imposed by the European directives on buildings. The first is the search for a realistic definition of nZEB for the warmer climates of the Mediterranean area. The second is the adaptation of measures and requirements used in central and northern Europe to warmer climates in order to achieve low energy consumption with a suitable comfort level.

Restrictions on heating and cooling demand lead directly to an increase in the external thermal insulation of buildings in current legal standards. In consequence, the thermal loads due to mechanical ventilation amount to values of 50 % [54]. Therefore, it is necessary to rethink the suitability and optimization of ventilating systems with heat recovery to attain reduced energy consumption values in Mediterranean climates and, particularly, in Spain. It must be highlighted that the minimum ventilating flows in Spain are very high in relation to other countries (3.2.) and that energy recovery in ventilation is not compulsory. Therefore, the first step is to determine whether the requirements of energy demand in a nZEB dwelling can be achieved without heat recovery.

Once it is understood that the ventilating system is a key factor for accomplishing the nZEB requirements (in 2018 for public buildings and in 2020 for all buildings), it becomes clear that there is a need to widen the search to include the operating strategy optimization of ventilating systems for Mediterranean countries. It is vital to determine the most suitable kind of system, its design, its operation and, above all, its impact on the energy consumption of dwellings.

It is also clear that air infiltration control is necessary, which is not yet included in the legal standards because to date it has been considered that greater airtightness can increase the cooling load and not noticeably reduce the heating demand. As the infiltrated air is not treated by the recovery system, its influence on energy use in buildings in Mediterranean countries must be evaluated in order to establish some limitations in the legal standards of these countries.

To complete this research, the influence of the comfort parameters in a nZEB dwelling in a Mediterranean climate will be analyzed, in order to evaluate the potential savings of an optimized definition of these parameters while keeping comfort levels according to current European standards. The influence of adaptive models on energy demand in nZEB dwellings with heat recovery in the ventilating system will be studied.

1.5. Objectives

The purpose of this Ph. D. is to investigate whether the requirements, parameters and operating processes of ventilating systems with heat recovery defined in accordance with the Passivhaus standards for nZEB dwellings in central Europe are suitable and capable of being optimized for the milder climates of Mediterranean Europe (Spain, Italy, Greece and the south of France).

This suitability and optimization needs to achieve the energetic demands that the heating and cooling of the nZEB dwellings must fulfill in 2020. Therefore, the ventilation flows, operating strategies of the recovery system (HRV and ERV), airtightness of the external walls and comfort parameters will be analyzed.

In order to reach the final target, the following specific goals are pursued:

1) To establish the state of the art of the standards and regulations in Europe, USA and Passivhaus concerning ventilation air for residential buildings and more specifically for those with mechanical ventilation systems. The results of the research should determine whether the requirements of nZEB heating and cooling energy demands can be achieved with current ventilation strategies.
2) The evaluation of the energy savings of recovering the sensible, the latent or both energies from the ventilation air depending on the climate data for Mediterranean cities.
3) To establish the effectiveness of several control strategies for ventilation air systems including ERV with the aim of optimizing the air conditioning energy demand of dwellings located in several cities in the south of Europe. The impact of the latent effectiveness on the air conditioning energy demand must also be studied.

4) The assessment of the impact of air infiltrations on the energy consumption in dwellings situated in Mediterranean countries in order to establish limits for these countries.
5) To evaluate the impact of comfort parameters on the air conditioning energy demand for residential nZEBs following the Passivhaus standard. The results should help southern European countries to define their thermal comfort parameters for nZEB, providing recommendations for the development of further standards and norms concerning indoor climate and energy calculations.

1.6. Organization of the Thesis

The remainder of this thesis is divided into eight chapters. A schematic of the organization of the thesis is shown in Figure 1.4.

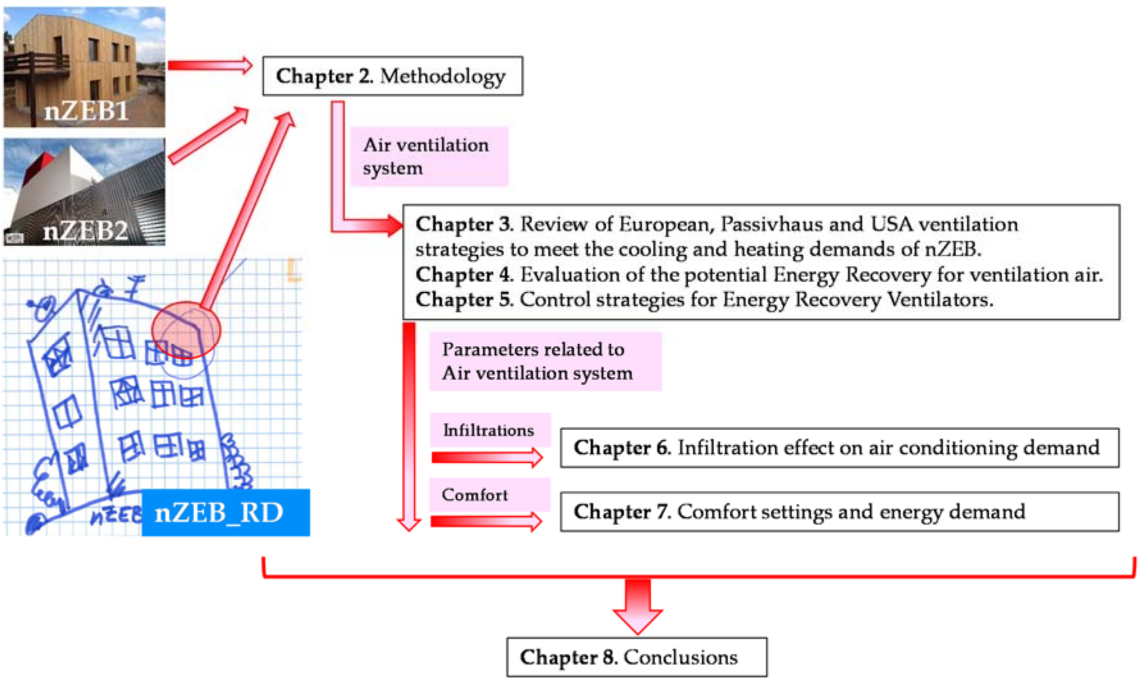


Figure 1.4. Organization of the Thesis.

The contents of each chapters are as follows:

The present chapter 1 introduces the most important features to be studied in this thesis, the current legal background and the motivation and justification of the thesis.

The methodology applied in this thesis is explained in chapter 2. The software and the selection of the dwelling are described and justified. A methodology for the TRNSYS model validation is also described and the results from of calibration and validation process are discussed.

In chapter 3, the state of the art of ventilation air flows and the strategies set out in the regulations in the USA, Germany, the UK, France and Spain are described, together with those established by the Passivhaus standard. Simulations have been performed using the dwelling TRNSYS model with the flow rates, ventilation strategies and envelope transmittances required by the regulations of each country. The simulations were performed in a total of 33 cities: 12 in Spain (one from each climate area), 7 in France, 2 in the UK, 2 in Germany and 10 in the USA. Secondly, simulations using the thermal envelope transmittances values recommended by Passivhaus standards have been made, maintaining the ventilation strategies of each country. The influence of the ventilation parameters in the heating demand was obtained moreover, the necessity to recover the waste heat coming from ventilation air depending on the climate to reach nZEB requirements was analyzed.

Chapter 4 describes a new methodology based on the analysis of a psychrometric chart applied to the climate data from 16 cities. Fourteen of these cities are located in different climate areas in Spain, one on the south coast of France, and one in Germany as an example of European continental climate for the purposes of comparison. Based on an in-depth analysis of the climatic data for several cities located in mild and warm climates in the south of Europe, this research proposes a methodology for evaluating the advisability of recovering the sensible, the latent or both energies from the ventilation air. The methodology calculates only real demands, identifying the season of the year for outside air conditions in order to make the appropriate decision as regards conditioning the ventilation air.

In chapter 5, possible control strategies for ventilation air systems including ERV have been analyzed for eleven cities located on the Mediterranean coast in southern Europe: 6 are located in Spain, 4 in Italy and 1 in France. Simulations were performed to check the suitability of including ERVs instead of HRVs in air ventilation systems. Possible control strategies have been analyzed to minimize the undesirable operation of ERVs which could otherwise increase the air conditioning energy demand for winter and summer seasons. Simulations for different levels of latent effectiveness while maintaining the sensible effectiveness invariable have been performed. Furthermore, simulations applying natural ventilation and free cooling have also been performed.

Chapter 6 is devoted to a study of the influence of air infiltrations through the building envelope on the heating and cooling demand, in order to recommend maximum values suitable for the national standards of nZEB dwellings in Mediterranean countries. Simulations have been performed for several levels of infiltration in the selected dwelling in twelve European cities, four of them located in northern Europe for the purposes of comparison.

Chapter 7 describes simulations performed to assess the impact of comfort parameters (temperature and air humidity) on the air conditioning energy demand for a residential nZEB dwelling. Fifteen cities located in southern Europe were selected for this study. Energy demand simulations have been carried out for a range of temperatures and different degrees of air humidity in order to calculate their impact depending on the climate area. Moreover, simulations have been performed following adaptive models where the comfort temperature depends on the running mean outdoor temperature.

The main conclusions of this research, together with a summary of the original contributions presented in this thesis and future lines of research, are set out in Chapter 8.

Chapter 2

Methodology

2. Methodology

Building energy performance models, most commonly known in the scientific field as BEPS (Building Energy Performance Simulations), play a key role in design and optimization from the point of view of energy efficiency.

The development of a BEPS model to evaluate and optimize the potential energy saving in residential buildings including sensible and enthalpy energy recovery ventilators is essential in order to analyze the influence of the operating parameters and thus to achieve the objectives of this doctoral dissertation.

For this purpose, the most commonly used energy simulation software programs in the scientific community were analyzed. Among them, the TRNSYS software ("TRaNsient SYstem Simulation tool") was selected. Secondly, a dwelling representative of those found in Spanish residential buildings was chosen and a TRNSYS model was built (nZEB_RD: Representative Dwelling). The model enables quantitative/parametric analyses to be performed of the different parameters relating to air ventilation systems which have a great influence on the air conditioning energy demands of a nZEB building.

Energy performance and operating data were collected from one existing single family house (nZEB1) located in Barcelona (Spain), which was certified under the Passivhaus standard. A nZEB1 TRNSYS model was prepared for calibration and validation with the measured data.

Furthermore, a single family house (nZEB2) was designed and built during 2016 in Zaragoza (Spain) under the Passivhaus standard. The calculations done during the design phase by a Passivhaus architect with PHPP software (Passivhaus Projecting Package) were available and were used to validate a new nZEB2 TRNSYS model.

The lessons learned from the construction of both TRNSYS models (nZEB1 and nZEB2) and from their calibration and validation processes carried out with the measured data and with the results from the PHPP tool were applied to the generation process of the TRNSYS model for the selected representative dwelling (nZEB_RD). This procedure avoided errors, as for example in the inlet parameters of the model, and resulted in a robust model able to achieve reliable results.

Finally, the energy demand of the nZEB_RD has been calculated using the PHPP tool. The results were used to validate the nZEB_RD TRNSYS model.

The nZEB-RD TRNSYS model provides the base for the parametric studies done for the most impacting parameters (relating to the air ventilation system) on the air conditioning energy demand (Chapters 3, 5, 6 and 7).

Figure 2.1 shows the thesis methodology and the content of the current chapter.

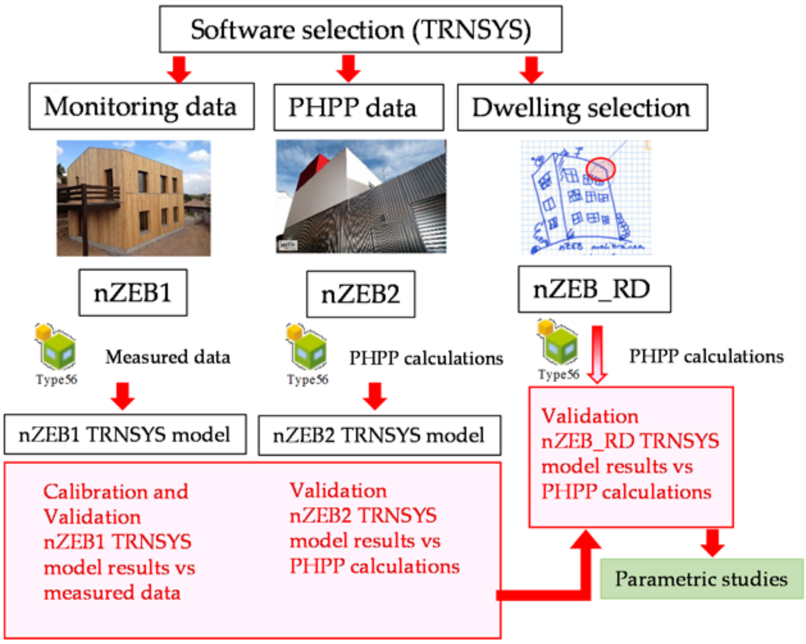


Figure 2.1. Doctoral dissertation methodology.

2.1. Software selection

Currently, a large variety of energy simulation programs are used in research and scientific projects for thermal simulation in buildings. In the USA, programs such as DOE2 and BLAST (Building Loads Analysis and System Thermodynamics) emerged as a result of the slow but steady investment by the American administration since 1970. Subsequently, DOE2 and BLAST were combined in a new program called Energy-Plus, whose use is widespread. Other programs like TRNSYS [55], developed by Wisconsin-Madison University (USA), are widely used in the university and scientific field.

In Europe, unlike the USA, there is no organization that centralizes the resources for the development of this kind of software. There are several programs developed by different member states with different approaches: commercial, free, open code, etc. Some examples are BSIM for building research developed by the Danes Institute, ESP-r (open code) by Strathclyde University in Glasgow or IDA-ICE (Sweden) which is a commercial program with different modules for diverse applications (the module for building is ICE-Indoor Climate and Energy) but with a common simulated (?) motor. There are also several programs created by enterprises, such as IISIBAT (by the French Scientific and Technical Center for Building- CSTB) which uses TRNSYS for engine calculation, or Design Builder (England) which generates the "idf" file for Energy-Plus calculations.

The technical guide of procedures and parameters for thermal simulations of buildings compiled by the Spanish Technical Association of Air Conditioning and Refrigeration (ATECYR) for IDAE (the Spanish Institute for Energy Diversification and Saving) includes a comparative review of the most commonly used programs at worldwide level for the thermal simulation of buildings [56].

In fact, there are numerous publications which compare the capacities of the energy simulation programs available on the market. Crawley et al. [57] make a complete comparative study of the 20 best programs. In more recent research, Wang et al. present a complete review of the advances of building related simulation and computation techniques between 1987 and 2014 [58]. Their paper focuses specifically on six different topics including ventilation performance prediction, whole building energy and thermal load simulation. Harish et al. [59] present a review of all the significant modeling methodologies which have been developed and adopted to model the energy systems of buildings. In their paper, simulation programs and software packages available for building energy modeling are presented and compared (Table 2.1).

Table 2.1.Summary of capability of different BEPS programs [60].

Modeling characteristics	Building energy simulation programs								
	BLAST	BSim	DeST	DOE-2.1e&2.2	ECOTECT	EnergyPlus	eQuest	ESP-r	TRNSYS
Simulation solution	PI	CI	PI	NI	NI	CI	CI	CI	CI
Time step approach	PI	PI	OI	NI	NI	CI	PI	CI	PI
Geometric description	CI	CI	CI	CI	CI	PI	CI	CI	CI
Simulteneous radiation and convection	CI	CI	CI	CI	NI	CI	CI	CI	CI
Combined envelope heat and mass transfer	CI	CI	NI	NI	NI	CI	NI	CI	CI
Solution method for conduction transfer of heat	TFM	NI	TFM	TFM	FDM	TFM	TFM	FiDM	TFM
Internal mass considerations	CI	CI	CI	CI	CI	CI	CI	CI	CI
Occupant comfort	CI	NI	NI	NI	PI	CI	NI	PI	PI
Solar gains, shading and sky considerations	NI	NI	PI	NI	CI	CI	PI	PI	CI
Variable construction element properties	NI	NI	NI	NI	CI	NI	NI	NI	NI
PCMs	NI	NI	OI	NI	NI	NI	NI	OI	OI
EIA	PI	NI	NI	PI	NI	CI	PI	PI	OI

Nomenclature: CI: Completely/wholly implemented (Issue is well addressed and backed by program's supportive documentation); PI: Partially implemented (Issue is partially implemented and is not fully addressed by the program); OI: Optionally implemented (Issue is addressed for research and is not included in the standard feature); NI: Not/Negligibly implemented (Issue is not included or only a very small part of it is implemented in the programs); TFM: Transfer Function Method; FDM: Frequency Domain Method; FiDM: Finite Difference Method.

Analyzing these publications, it can be concluded that DOE-2, EnergyPlus, TRNSYS and ESP-r are the most widespread and have the greatest computational capacity. For the development of this thesis, TRNSYS 17 [60] was selected as one of the most capable and widely used for scientific publications at worldwide level.

TRNSYS is a flexible tool used to simulate the behavior of transient systems based on graph models. The program is composed of two parts. One part is the calculation engine (called kernel) which reads and processes the entry files, solves the problem iteratively, determines the convergence and prints the system variables. Kernel also has utilities to calculate thermo-physical properties, to reverse arrays, to perform linear regressions, to interpolate data from external files, etc. The second part is an extensive library of components. TRNSYS has data bases containing the climatological data of many cities (including Spanish and European capital cities), physical-mathematical modules capable of representing the dynamic behavior of multiple typologies of equipment and facilities with their operating parameters, and controllers that manage the operations, exchange of information and graphical representation of variables.

2.1.1. The TRNSYS model

The TRNSYS dwelling model allows obtaining the energy demand to maintain the interior conditions required in the dwelling (temperature and relative humidity) under particular conditions (model inputs) such as climate data, occupancy, internal loads and air infiltrations. The heat balance is done in discrete time, usually for one year in one-hour intervals.

The TRNSYS modules are called Types and are linked together, relating the outputs of some with the inputs of others. As outputs, the model generates graphics and data files containing the results of calculations (monthly, hourly, annual balances, etc.).

The dwelling model was generated with TRNBuild2.0, the tool used for the building energy demand calculations [61]. This tool allows a building including many zones to be defined through the Type 56 *"multizone building"* component and subsequently the thermo-dynamical behavior of the dwelling is calculated by TRNSYS.

To generate a Type 56 for a dwelling (0.) it is necessary to define its geometry and spatial lay out, its constructive elements and its materials including the thermo-physical properties. Next, the thermal loads due to equipment and occupancy are included. The ventilation air flow rates, which usually depend on other module outputs defined in TRNSYS, the comfort parameters, and the climate data are incorporated into the model. A simplified operating scheme of the TRNSYS model is shown in Figure 2.2.

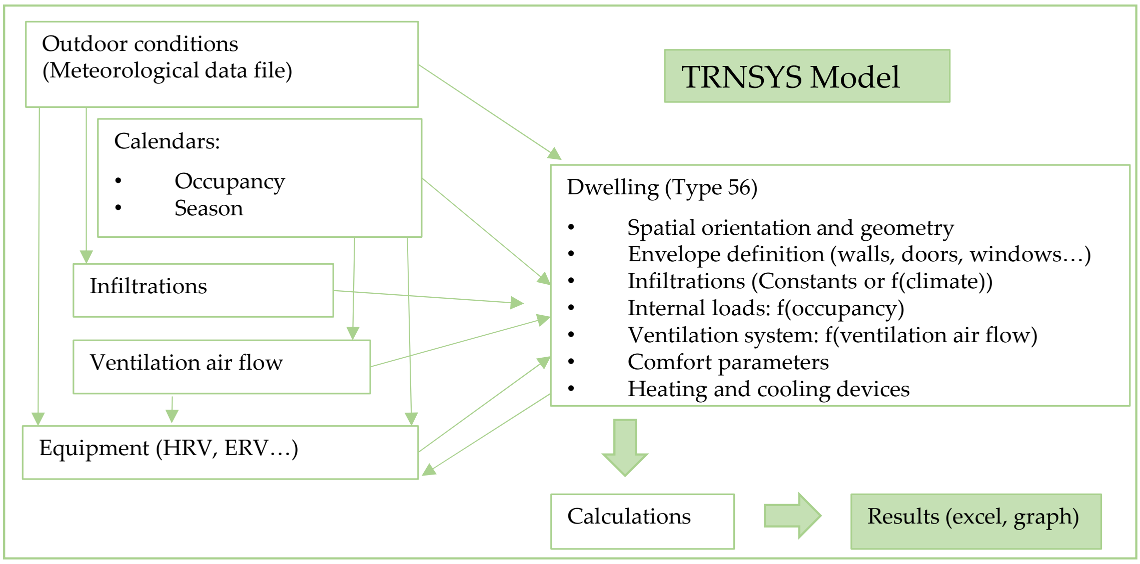


Figure 2.2. Simplified operating scheme of the TRNSYS model.

The simulation results for different constructive typologies and equipment operating modes enables the influence of the most relevant parameters to be defined in order to perform their optimization for energy demand reduction. Some of the relevant constructive parameters have been modified to evaluate their influence on the heating and cooling demand. For example, the envelope transmittances and the air flow rates have been modified in accordance with the regulations of the countries analyzed in chapter 3, and the nZEB dwelling has also been located in different cities to analyze its behavior depending on the meteorological conditions. Parametric studies of the comfort parameters, the air infiltration level and the optimization of ERV working strategies have also been carried out.

2.1.2. TRNBuild: type 56

Type 56 models the thermal behavior of a building divided into different thermal zones. In order to create this type, a separate pre-processing program called TRNBuild must be used. The TRNBuild program reads in and processes a file containing the building description and generates two files that will be used by the Type 56 component during a TRNSYS simulation, the (*.BLD) and (*.TRN) files.

TRNBuild has been developed to create the *.BUI file which contains the basic project information, and a description of the user thermal zones. Type 56 needs a substantial amount of building data to calculate the thermal behavior of the building, including geometric data, wall construction data, window data, etc. Furthermore, it needs information about factors such as occupancy which will help to define the gain from the occupants during the day. Additionally, it needs a weather data file containing information such as levels of radiation, ambient temperature, humidity, etc.

After creating the *.BUI file, which contains all the information required about the building, TRNBuild uses it to generate standard Type 56 files and several other files which are automatically generated every time the BUI file is saved:

- A file containing all the information about the building excluding the wall construction (*.BLD).
- A file containing the transfer functions for the walls (*.TRN).
- The information file (*.INF) which contains the processed (*.BUI) file followed by the values of the wall transfer function coefficients, and the overall heat transfer transmittance U (W/m^2.K). The information file provides a list of inputs required for Type 56 and also a list of selected outputs.

There are other files generated: the shading Matrix file called *.SHM and the insolation Matrix of a zone *_xxx.ISM (the triple X in the file's extension of the insolation matrix will be replaced with the zone’s number).

The common steps to define the TYPE56 of the three studied houses (nZEB1, nZEB2 and NZEB_RD) are detailed below.

<u>Building enclosure definition</u>

One of the most significant energy losses in buildings is through the building envelope. It is necessary to define the walls, roof and floor slabs (layers, materials and thickness) to calculate the heat transfer between inner spaces and outdoors. Each wall is defined in TRNBuild by the type and the category:

1) Type. The wall typology is defined by layers of elements: brick, concrete, insulation, etc.; its thickness and its thermo-physical properties.

2) Category. This indicates the class of the wall depending on its boundary conditions. The defined categories are:

- External: one of its surfaces is in contact with the outside and receives solar radiation depending on the building orientation.
- Internal: this is located in the interior of a space and does not transfer heat to other spaces. It is included to give the thermal inertia of building.
- Adjacent: this separates two adjacent rooms which can exchange heat.
- Boundary: this limits the model with other spaces or rooms. They transfer heat under conditions which are defined by the user.

Each dwelling zone is adjacent to other dwelling spaces and/or to the outside and/or to other dwellings or common building spaces (such as stairs and neighboring dwellings, for example). The boundaries between the spaces, the wall characteristics and the volume of each space are defined in TRNBuild. The enclosure typologies defined and used in the simulated houses are:

- EXT_WALL: external wall of building.
- INT_WALL: wall between interior spaces and neighboring dwellings which gives the thermal inertia. Temperatures for adjacent areas follow the Spanish legislation [9]: for adjacent homes 24ºC in summer and 18ºC in winter and unheated public areas 26ºC in summer and 12ºC in winter.
- FLOOR_PLANT: is the floor between floors for a block of houses.
- EXT-FLOOR: The external floor is used for floors in contact with the ground. This is the floor slab for a single family house.
- ROOF: Used for the roof of the building in contact with the outside.

To introduce the dwelling enclosures, it is necessary to create and define each layer. The values can be completed manually or by selecting the material available in TRNBuild libraries for this purpose. TRNSYS calculates and shows the global transmittance of each defined wall, using the surface thermal resistances at external and internal surfaces. The window parameters can be selected from TRNBuild libraries or can be introduced manually.

The values for the envelope thermal transmittances vary depending on the dwelling construction parameters. These are detailed for nZEB1, nZEB2 and n-ZEB_RD in (0), (2.3.2.2) and (2.3.3.1) respectively. Moreover, the envelope thermal transmittances for nZEB_RD will vary during this thesis depending on the climate area where the house is located for each specific study, as will be detailed in the corresponding chapter.

However, the thermal resistances are identical in the three TRNSYS models developed in this thesis and follow the values indicated by the Spanish regulations [62] (Table 2.2).

Table 2.2. Surface thermal resistances in contact with the air [64].

	Inner Surface R_{si} (m^2K/W)	**Out Surface R_{se} (m^2K/W)**
External wall	0.13	0.04
Internal wall	0.13	0.13
Floor	0.17	0.04
Roof	0.10	0.04

A shading factor as well as an exterior absorptivity coefficient for solar radiation and an exterior emissivity coefficient for thermal infrared radiation for each surface of the building are also entered.

The exterior solar absorptivity and emissivity coefficient of the external wall surfaces are 0.6 and 0.9, respectively. For nZEB2, specific values are included and detailed in Table 2.12. Low emissivity windows have been selected for the three models.

The shading factor for absolutely unshaded spaces is 0; this situation is especially true for roof surfaces. Walls of buildings located in rural or suburban areas, with few surrounding close buildings, would have a value of 0.7. Buildings located in the inner city should have a shading factor reduction factor of 0.4. A shading factor of 0 over the external wall has been included in the models. The shading factor over the windows depends on the season of the year, and the value varies for each dwelling.

The solar factor has also been defined for each window, varying between 0.47 and 0.6. The area of the window frame was considered to be 15%.

The thermal capacity, as a measure for heat storage in house components, is calculated by TRNSYS depending on the construction elements.

The energy losses produced by thermal bridges were not included in the models. These can be relevant for buildings with low quality architecture and construction. However, for a nZEB building where the envelope thermal losses are minimized thermal bridges are almost inexistent. The Passivhaus standard establishes rules to avoid or minimize thermal bridges [27]. If its linear thermal transmittance is less than 0.01 W/mK, the thermal bridge is not considered for building energy demand calculations because its effect is negligible.

Air ventilation system

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. The minimum acceptable heat exchanger sensible efficiency is 75%, which is a typical value for the heat exchangers currently available on the market. To reach this high performance, the heat exchanger usually works at crossflow, and its core is formed by a compact set of plastic plates (Figure 2.3 and Figure 2.4).

The heat exchanger has a by-pass valve controlled by the air temperature. During winter the by-pass circuit is closed and the air goes through the heat exchanger. However, during fresh summer nights if the outdoor temperature is lower than indoors the valve opens the bypass circuit and the air does not cross the heat exchanger.

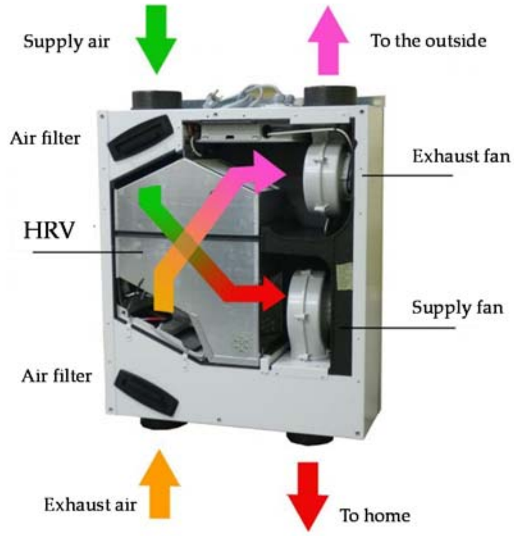


Figure 2.3. Heat exchanger in the air ventilation system (Zehnder Group Ibérica).

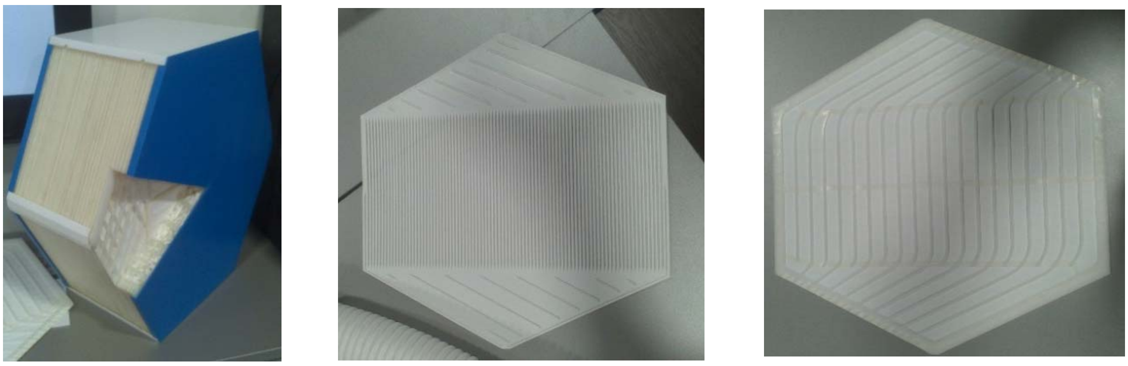


Figure 2.4. Heat exchanger core and plates (Zehnder Group Ibérica).

The European regulations indicate the procedure to calculate the minimum air flow rate for each room depending on its occupancy and/or its area. In this research, the ventilation air flow rate is one of the fundamental parameters under study. As a general rule, in the three simulated houses the air flow rates and their distribution through each room will follow the Passivhaus recommendations.

The air flow rate depends on the dwelling occupancy, taken into account by the schedules introduced in the TRNSYS model. The values have also been supervised by technical experts from Zehnder, a heat recovery equipment developer and manufacturer. The nominal ventilation flow recommended by Passivhaus is 30 m^3/h per person.

The operation mode of the energy recovery ventilator included in the air ventilation system is controlled by the Type 66 defined in TRNSYS [60]. This type also controls the by-pass by launching an algorithm programmed in Engineering Equation Solver (EES) [63]. The algorithm calculates the position of the by-pass (open or closed) depending on the air temperature, humidity and enthalpy of the air flows (Chapter 5).

The mechanical ventilation system pushes the air flow to the dry spaces (living room and bedrooms) and extracts air from the humid spaces (kitchen, bathroom and toilet). The air flow rates are balanced in the three simulated dwellings.

Heating and cooling systems

The heating system in the TRNSYS model has an independent temperature control for each zone. This temperature control turns on the heating system when the temperature of any room drops below the indicated winter set temperature. The cooling system works similarly and is working when the indoor temperature exceeds the temperature set for summer.

Building airtightness

The value of the air infiltration in a house is measured by the Blower Door test carried out according to EN 13829 [24]. The test is performed at a pressure difference of 50 Pa. This value is high enough to guarantee that the test result does not depend on the meteorological conditions at which it is carried out (see 6.2). The term most commonly used to refer to the air permeability of a dwelling is n_{50} (ACH or h^{-1}), which is obtained by dividing the air flow rate by the volume of air contained in the dwelling at 50Pa. The Passivhaus standard recommends a maximum value for n_{50} of 0.6 ACH. The study of the influence of the dwelling airtightness on the air conditioning energy demand constitutes a specific chapter (Chapter 6).

Internal thermal loads

The main internal loads in residential buildings are due to the lighting, equipment and home appliances and the metabolic activity of the occupants. The heat generation according to different degrees of activity follows the values detailed in ISO 7730: 2005 [19]. The nominal values applied to the models are shown in Table 2.3.

Table 2.3. Rates of heat gain from occupant spaces according to ISO7730.

	SENSIBLE LOAD (1 PERSON) (W)	LATENT LOAD (1 PERSON) (W)
Kitchen	75	95
Bedroom (x1) / Living room (x1)	60	40

For lighting and equipment a nominal load of 2.5 W/m² has been considered. The nominal latent and sensible loads are multiplied by a coefficient depending on the time of day related to the occupancy as indicated in Table 2.4.

Table 2.4. Coefficients of internal loads applied in the model depending on the time of day.

	TIME OF DAY- WORKING DAY					TIME OF DAY- WEEKEND				
	0-7	7-13	13-15	15-20	20-24	0-9	9-12	12-17	17-22	22-24
Occupancy	0.50	0.25	1.00	0.50	0.75	0.50	0.25	2.00	0.50	1.00
Lighting and equipment	0.00	0.50	0.00	1.00	0.50	0.00	0.50	1.50	1.00	0.50

2.2. Dwelling selection

The dwelling selected was previously used in the doctoral thesis written by Dr Beatriz Rodríguez Soria (faculty advisor of this thesis) in 2011 [64]. The housing censuses for the benchmarking of the housing stock carried out every ten years in Spain are done by the National Statistics Institute. The last census available is from 2011. Nowadays, due to the crisis in the construction sector, almost no variation is expected in the average data of Spanish housing stock.

The guide nº12: "Simplify option. Houses. Calculation report" produced by the Institute for Energy Diversification and Saving (IDAE) [65] has substantial data of building characteristics. It includes Figure 2.5 which shows the number of dwellings and their average area in Spain. The most common dwelling area is between 76 m² and 90 m². The dwelling has a living room, a kitchen, three double bedrooms and two bathrooms.

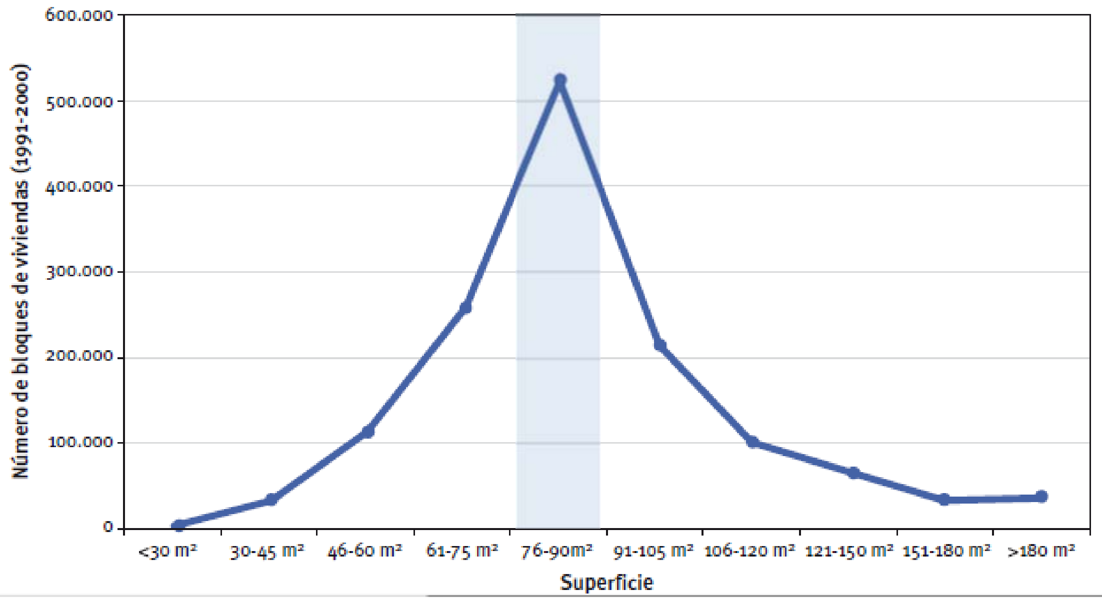


Figure 2.5. Spanish dwellings areas. IDAE. 2009 [67].

The final report of the SPAHOUSEC project (Analysis of the Energy Consumption in Spanish Households- IDAE) [7] gives information about the housing census and energy consumption. The report divides Spain into three climate zones: Atlantic (Pontevedra, La Coruña, Lugo, Asturias, Santander, Vizcaya and Guipúzcoa), Mediterranean (Gerona, Barcelona, Tarragona, Castellón, Valencia, Alicante, Murcia, Almería, Granada, Málaga, Cádiz, Huelva, Sevilla, Córdoba, Jaén, Islas Baleares and Islas Canarias), and Continental (the remaining provinces). It can be deduced from this report that more than 70% of Spanish homes are in blocks and their average surface area is 86.5 m² (Table 2.5 and Table 2.6).

Table 2.5. Quantity of dwellings depending on the construction type and climate zone [7].

	Single family house	Apartment/ dwelling in a block of houses	TOTAL
Atlantic	580.240	1.673.181	2.253.421
Continental	1.649.042	4.133.792	5.782.834
Mediterranean	2.867.948	6.295.427	9.163.375
TOTAL	5.097.230	12.102.400	17.199.630

Table 2.6. Dwelling average area (m²) [7].

	Single family house	Apartment/ dwelling in a block of houses	TOTAL
Atlantic	126,7	82,2	93,7
Continental	150,6	84,7	103,5
Mediterranean	136,8	88,7	103,8
TOTAL	140,2	86,5	102,4

The selected dwelling (nZEB_RD) is in a housing block included in a real construction project developed by the Construction Engineering Department of Zaragoza University (Figure 2.6).

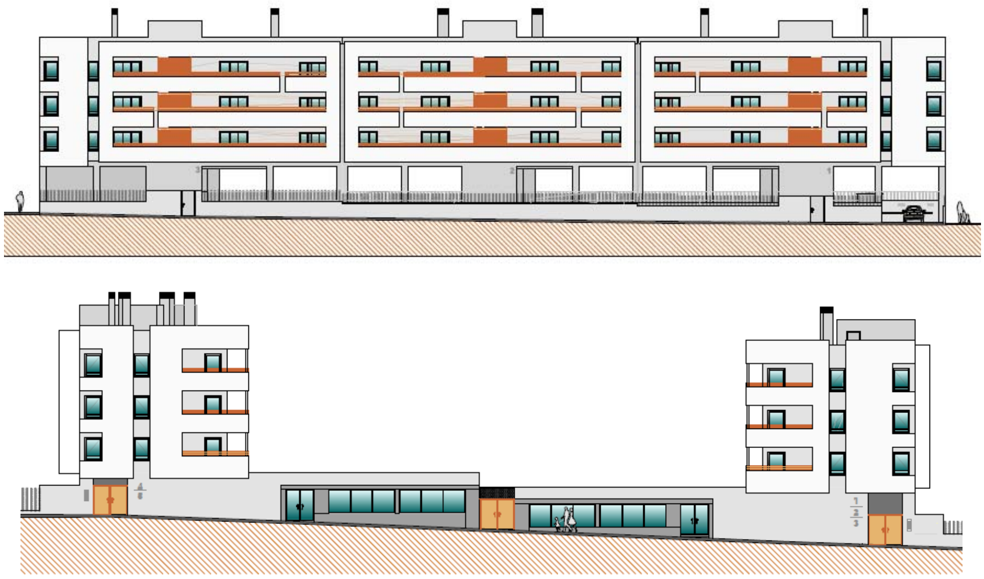


Figure 2.6. The selected housing block.

The nZEB_RD has a representative size and layout for a typical family composed of 4 persons. It has a kitchen, a living room, three bedrooms and two bathrooms and a net area of 81.51m². The ceiling height is 2.5m and the apartment is located on the top floor of a building of 4 floors. Regarding its orientation, the dwelling has windows on the north facade in the living room and in the double bedroom, and on the south facade in the kitchen, bathroom and two bedrooms. Only the hall and toilet have no exterior windows. The dwelling's layout is shown in Figure 2.7.

Figure 2.7. nZEB_RD layout.

Moreover, the selected dwelling fulfills the requirements defined by IDAE [65] 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). Also, the dwelling occupation, 4 persons (internal gains), is the ‘standard’ value in Spain. It is very important to select a ‘typical or standard’ dwelling in order to obtain comparative results which are representative. The specific construction characteristics included in the TRNSYS model developed are detailed in section 2.3.3.1.

2.3. TRNSYS model validation

The validation of building energy performance simulation (BEPS) models is a complicated challenge, mainly because there is no standard model calibration procedure or method valid for all typologies of buildings. Moreover, usually the dwelling under study has not yet been built, so there are no existing measured data for the model calibration. Unfortunately, the scarcity of housing blocks complying with nZEB requirements in Mediterranean climates means that there is no available experimental data.

In the scientific literature, model calibration refers to the creation of a simulation model which generates similar energy consumption results to those of measured data, enabling reliable conclusions to be drawn. Coakley et al. [66] review the most relevant methods for model calibration (energy performance) with measured data, detailing the importance of uncertainties in the calibration process. The BEPS model definition involves scores of inputs so that the calibration process can provide various solutions [67].

But what kind of errors can actually be made when using a reliable and checked tool such as TRNSYS? As remarked by Kaplan et al. [68], it will never be possible to identify the exact solution to the calibration problem and so sensitivity issues may be of primary importance in the calibration field. Besides, a true calibration requires a dynamic matching over one year between computed and measured values and not a static matching under one condition. These elements make the calibration of building energy simulation models very challenging.

Ten years ago, a model was calibrated by simply comparing the difference in percentage between the simulation results and the measured results in terms of energy [68,69]. However, Bou-Saada et al. [70] proposed the use of a statistical index to characterize the model behavior in a more appropriate way. Following their proposal, the compensation effect is avoided (over-estimates cancel out under-estimates). The acceptance criteria currently used are dependent on the MBE (%) (Mean Bias Error) and the CV-RMSE (%) (Coefficient of Variation of the Root Mean Square Error) shown in Table 2.7. These validation criteria can be applied exclusively over the energy demand (or energy consumption), never over the uncertainties of the input parameters (for example, the air outdoor temperature profile).

Table 2.7. Acceptance criteria for BEPS model calibration [72].

Standard/guideline	Monthly criteria (%)		Hourly criteria (%)	
	MBE	CVRMSE (monthly)	MBE	CVRMSE (hourly)
ASHRAE Guideline 14 [24]	5	15	10	30
IPMVP [25]	20	–	5	20
FEMP [26]	5	15	10	30

In the expert literature, it is advised to calibrate the models with the measurements taken during one year. Nevertheless, some publications conclude that the calibrations undertaken with data from a short period of time are equally acceptable, for example, during one week or one month (STEM- Short-term end-use monitoring) [71].

The building energy performance simulation (BEPS) models as used in building design are law-driven models which are used to predict the behavior of a complex system given a set of well-defined laws (energy balance, heat transfer…). TRNSYS is one of the main tools in the category of diagnostic law-driven simulation tools. Moreover, TRNSYS is one of the four most common simulation programs used today (DOE-2, EnergyPlus, ESP-r and TRNSYS).

According to Agami[72] *'Errors and uncertainties in building energy simulations programs arise from different sources: (1) improper input parameters that could be due to use-related lack of experience (or even negligence) and improper specification of material properties or system parameters; (2) improper model assumptions due either to the underlying physics of the phenomenon or to the use of semi-empirical model coefficients; (3) lack of robust and accurate numerical algorithms; and (4) error in writing the simulations code.'*

While verification deals with determining whether the equations are solved correctly (error 3 above), validation involves solving the right equations (error 2 above).'

Following the Agami definitions, errors number 2, 3 and 4 are related to the simulation program used and they are consequently discarded. So, the TRNSYS model for the case under study (nZEB_RD) could only contain uncertainties coming from error (1). The calibration and validation procedures carried out for the nZEB1 and nZEB2 models serve to eliminate this error, provided that the user has previous experience that can be applied to develop another similar model even if the dwelling is not the same.

In most cases, TRNSYS models reported in the most prestigious scientific journals are not validated, because the simulation results are used to compare or make sensitivity studies of one parameter or a set of parameters. Some examples have been selected mainly because the research in question is also based on simulation results and heat recovery systems. In [73] , the amounts of heating energy recovery in winter for a sample apartment in a residential building are analyzed quantitatively and compared under different operation conditions with the EnergyPlus program by Liu et al. The model is neither validated nor calibrated, and the authors conclude that the EnergyPlus program has been extensively validated through analytical, comparative, sensitivity, range, and empirical tests. Pineau et al. [74] present a comparison of the energy and environmental performances of six heating systems installed in a low energy house using the simulation results from a TRNSYS model of each heating system studied and a thermal TRNSYS building model. These models are based on performance parameters calibrated using laboratory test results and part-load characteristics defined in the French thermal building code 2012, but the building model is not validated or calibrated. Rasouli et al.[38] investigate the impact of ERV on annual cooling and heating energy consumption by modeling a 10-storey office building in four American cities using a TRNSYS simulation tool. El Fouih et al. [42] also present their results from simulations using TRNSYS for different building models and ventilation systems without any mention of model validation.

The TRNSYS model for the selected dwelling (nZEB_RD) has been constructed after the calibration and/or validation of the nZEB1 and nZEB2 TTRNSYS models. The lessons learned through the calibration, verification and validation of the models have been applied during the nZEB_RD model development in order to eliminate possible errors that could come from improper model parameter selection. The working stages are the following (Figure 2.1):

1) Calibration and validation of the nZEB1 TRNSYS model with the measured energy demand data for the existing single family house. The Type 56 of the nZEB1 house was calibrated using the measured heating demand and then validated with the measured air temperature profiles.

2) Validation of the nZEB2 TRNSYS model with the energy demand results obtained with the PHPP tool. The PHPP calculations were performed by Passivhaus experts from the Spanish platform (PEP). The Type 56 of the nZEB2 house contains identical inputs

(design and functional conditions) to those included in the PHPP tool for energy demand calculations.

3) Validation of the nZEB_RD TRNSYS model with the energy demand results obtained with the PHPP tool. The PHPP calculations were done during the course of this research. The Type 56 of the nZEB_RD house contains similar inputs (design and functional conditions) and TRNSYS types to those included in the nZEB1 and nZEB2 validated models. Furthermore, the lessons learned during the calibration and validation of the monitored houses have been implemented in the Type56 of nZEB_RD.

The applied working procedure enabled the first cause of errors in the BEPS models to be eliminated: the input parameters.

2.3.1. Calibration and validation of the nZEB1 model

A detached single family house, nZEB1, was designed and built following the Passivhaus standard and was subsequently certified by the institute. Therefore, nZEB1 meets the air conditioning energy demand target of a nZEB and it is thus appropriate for validating this TRNSYS model since its construction characteristics, its behavior and the comfort parameters will be similar to those of the representative dwelling in the block selected (nZEB_RD).

The house was monitored and measured every 15 minutes from September 2015 until September 2016. The monitored values were: air temperatures (ground and first floor), ambient temperature, total electrical energy consumption of the house, and electrical energy consumption due to the mechanical ventilation system and due to the electric radiators.

The occupancy of the house was analyzed and the months of December and January were rejected for the study, the former because the electric radiators were not in use and the latter because the family was away for ten days. Therefore, the study was performed for February 2016.

The calibration and validation procedure is as follows: first, the calibration of the model is carried out, adjusting the selected parameters (described below) until the measured heating energy demand during February is equal to that obtained with the TRNSYS model. Once the model has been calibrated, in a second step the validation is done comparing the measured air temperatures in the house and those obtained with the TRNSYS model to verify that both follow the same profile during 24h.

2.3.1.1. nZEB1 description and Type56.

The single family house (nZEB1) is located 70 Km north of Barcelona (Spain) (Figure 2.8), not on the coast. Two adults and two children live in the house whose habits have been taken into consideration when defining the internal gains due to the presence of the occupants. The house has a net area of 100 m^2 divided into two floors. The layout is shown in Figure 2.9. The house has the kitchen and the living room on the first floor and the bathroom, the toilet and two bedrooms on the ground level. It has a height of 2.5m.

Figure 2.8. Single family house: nZEB1.

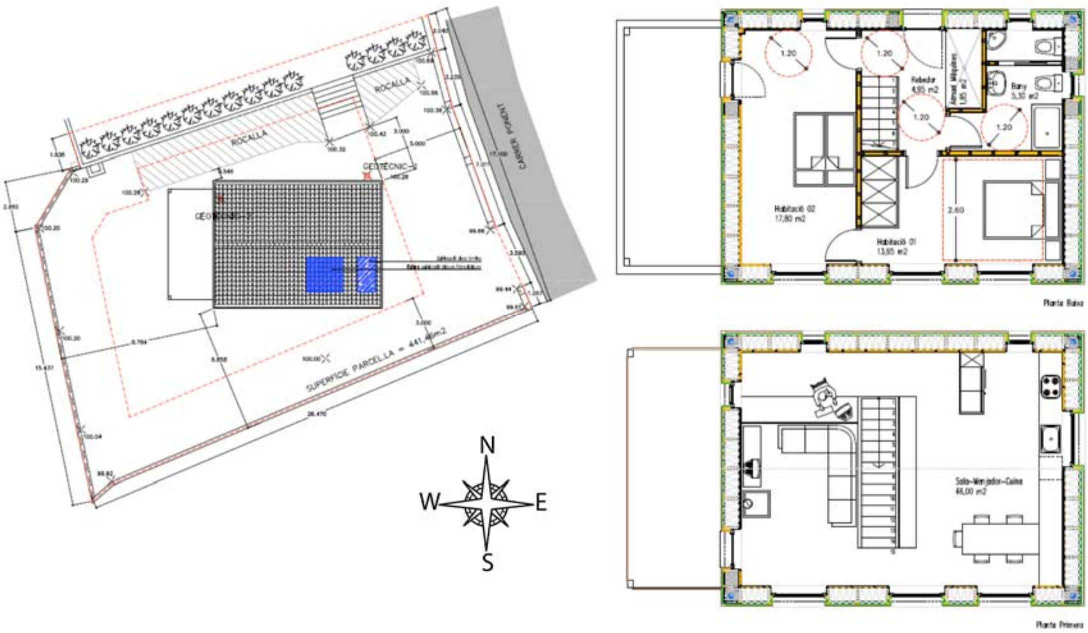


Figure 2.9. nZEB1 layout and orientation.

In the model, 4 zones and 4 air nodes are considered. Their dimensions, as well as their volume, are shown in Table 2.8.

Table 2.8. nZEB1 room dimensions and air volume.

Zone /Air node	Room/Zone	L1 (m)	L2 (m)	A (m2)	V (m3)
1/1	Kitchen	5.33	6.00	32.00	80.00
2/2	Bath and toilet	2.90	3.13	9.06	22.66
3/3	Bedrooms 1 and 2	8.33	6.00	40.94	102.35
4/4	Living room	3.00	6.00	18.00	45.00
	TOTAL			100.00	250.01

The characteristics of the house enclosure are given in Table 2.9

Table 2.9. nZEB_RD enclosure technical characteristics.

Building enclosure	Area (m²)***	U (W/(m²K)	Wall layers
External walls	North: 35.2 South: 27.8 East: 20.0 West: 25.1	0.127	(In-Out): Plasterboard (13 mm) + Installation chamber (35 mm) + OSB* (22 mm) + Straw (400mm) + Wood fiber (16 mm)
Floor	50.0	0.165	(In-Out): XPS** insulation (130mm) +Forged concrete (350mm) + Fiber wood insulation (80 mm) + Wood (22 mm)
Roof	50.0	0.122	(In-Out): Wood (15 mm) + OSB* (22 mm) + Straw (400mm) + Wood fiber (16 mm) + Roof tiles
Windows	North: 4.1 South: 13.9 East: 1.8 West: 4.9	1.060	Triple low-emissivity glass: 4/16 argon /4/16 argon /4
Main door (internal)	North: 2.3	1.000	Triple glass

OSB: oriented strand board ; **XPS: extruded polystyrene; * Including windows.*

The house has a mechanical ventilation system which includes a heat exchanger (HRV) supplied by Zenhder, model ComfoAir 350 (Figure 2.10). The HRV has a measured effectiveness of 0.84 at 120 m³ / h (nominal air flow).

Figure 2.10. Comfoair 350 heat exchanger from Zehnder.

The ventilation air flows are balanced and the air flow rate for each room is shown in Figure 2.11. The ventilation system is programmed to four operating modes:

1) Out of the house: minimum maintenance flow 50 m³/h;

2) Minimum flow (night): 70 m³/h;

3) Nominal flow rate (people in the house): 120 m³/h;

4) Party mode (guests at home): 240 m³/h.

From the analysis of the measured data, it was possible to obtain the mode of operation of the air ventilation system. During winter, the air ventilation flow was 120 m^3/h from 8:00 a.m. to 23:00 p.m. and 70 m^3/h from 23:00 p.m. to 8:00 a.m.

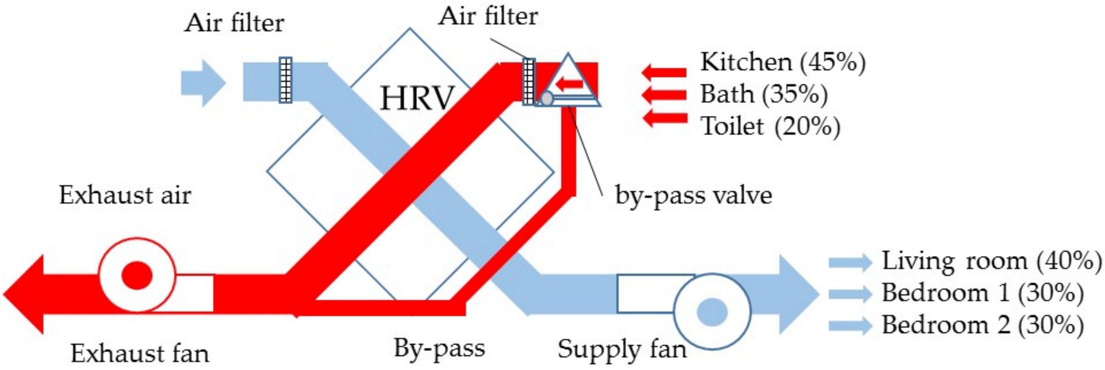


Figure 2.11. Air ventilation system for nZEB1.

The house has electric radiators in all the rooms and does not have any air conditioning equipment. The temperature control devices in the house are regulated to 19.5ºC in winter.

Concerning the house airtightness, the value of n_{50} measured in the house was 0.32 ACH. This low value indicates that the house is very airtight and has very low air infiltration. The difficulty is to transform the infiltration level from 50 Pa to a real operating average value (see 6.2.1). In the TRNSYS model, a constant value throughout the year of 0.022 ACH has been considered.

The internal loads have been obtained from the electrical energy consumption of the house. The model includes sensible and latent loads due to occupation. The nominal load is calculated by considering four people in the house: 1 adult in the kitchen, 1 adult in the bedroom and two children in the living room (two children having the same load as 1 adult). The nominal values applied to the model are shown in Table 2.3.

<u>Climate data</u>

The ambient air temperature was measured, processed and then included in the TNRSYS model. The measured data was collected every 15 min. The TRNSYS model calculates on an hourly basis, and reads the temperatures through Type62 (Excel reader). However, further climatological data were needed to perform the simulations (solar radiation loads) and therefore the data for Barcelona city (as the closest city) from the Meteonorm meteorological database were used. It was verified from the maps of the Spanish Meteorological Agency that the average global irradiance is similar [75].

2.3.1.2. Results and discussion

The heating demand was obtained through the electrical consumption of the radiators (heating source), being 74.02 kWh (for electrical radiators COP=1) for February 2016. This value is used for the TRNSYS model calibration.

The parameters adjusted in the TRNSYS model to achieve this result were: the control of the external shading protection (whose use depends exclusively on the user and therefore it is not measurable data) and the soil temperature (there are no existing measurements). Both parameters have an influence on the heating energy demand. Moreover, the heating energy consumption of the house is so low that inevitably any parameter has quite a noticeable impact.

Kusuda y Achenbach [76] found that the temperature of the undisturbed ground T (ºC) is a function of the time and the year and the depth below the surface , z (m), and could be described by the following correlation:

$$T = T_m - A_a \exp\left[- z \left(\frac{\pi}{365\,\alpha} \right)^{0,5} \right] \cos\left\{ \frac{2\,\pi}{365} \left[n - n_{min} - \frac{z}{2} \left(\frac{365}{\pi\,\alpha} \right)^{0,5} \right] \right\} \tag{2.1}$$

where

T_m (ºC) is the main surface temperature (average air temperature),

A_a (ºC) the amplitude of surface temperature (maximum air temperature minus mean air temperature),

n is the current day of the year,

n_{min} is the day of the year corresponding to the minimum surface temperature

α (m^2/day) is the thermal diffusivity of the ground (soil).

The trigonometric function argument is expressed in radians.

The thermal diffusivity can be obtained with the following equation (2.2) proposed by ASHRAE [77]:

$$\alpha = \frac{86{,}4\, k_s}{\rho_s \left[c_s + c_w (w/100) \right]} \tag{2.2}$$

where

k_s (W/(m·K)) is the thermal conductivity of the dry soil,

ρ_s (m^3/kg) the ground density,

c_s (kJ/(kg·K)) the specific heat;

c_w (kJ/(kg·K)) the liquid water

w (%, dry basis) is the ground humidity.

The thermal diffusivity varies significantly depending on the soil type. Kusuda and Achenbach obtain values between 0.018 and 0.094 m^2/day for the USA.

To apply equation (2.2) several hypotheses must be assumed:

1) The surface ground temperature is identical to the air temperature. The average annual temperature in Barcelona according to the Meteonorm database is T_m = 15.3°C.

2) The approximate temperature range is A_a = 15°C.

3) The day with the lowest ambient temperature is January 30, n_{min} = 30.

4) The depth of the ground in contact with the slab is between 1 and 2m.

Calculating for different depths and for a thermal diffusivity of α = 0.030 m²/day corresponding to dry soil [78], the soil temperature under the house will be between 9ºC and 14ºC for the month of February.

The model has been calibrated by varying the soil temperature. The soil temperature value obtained after the calibration during the month of February is 12ºC. The external shading factor has also been adjusted depending on the occupation (mobile external protection) and values vary between 0 and 0.75.

The heating demand for February obtained from the model was 73.70 kWh, thus the error obtained is 0.4%.

The measured and simulated air temperatures have been compared (for both the ground floor and the first floor), obtaining comparable values. Figure 2.12 shows the temperatures during one day in February. The measured and calculated values are similar.

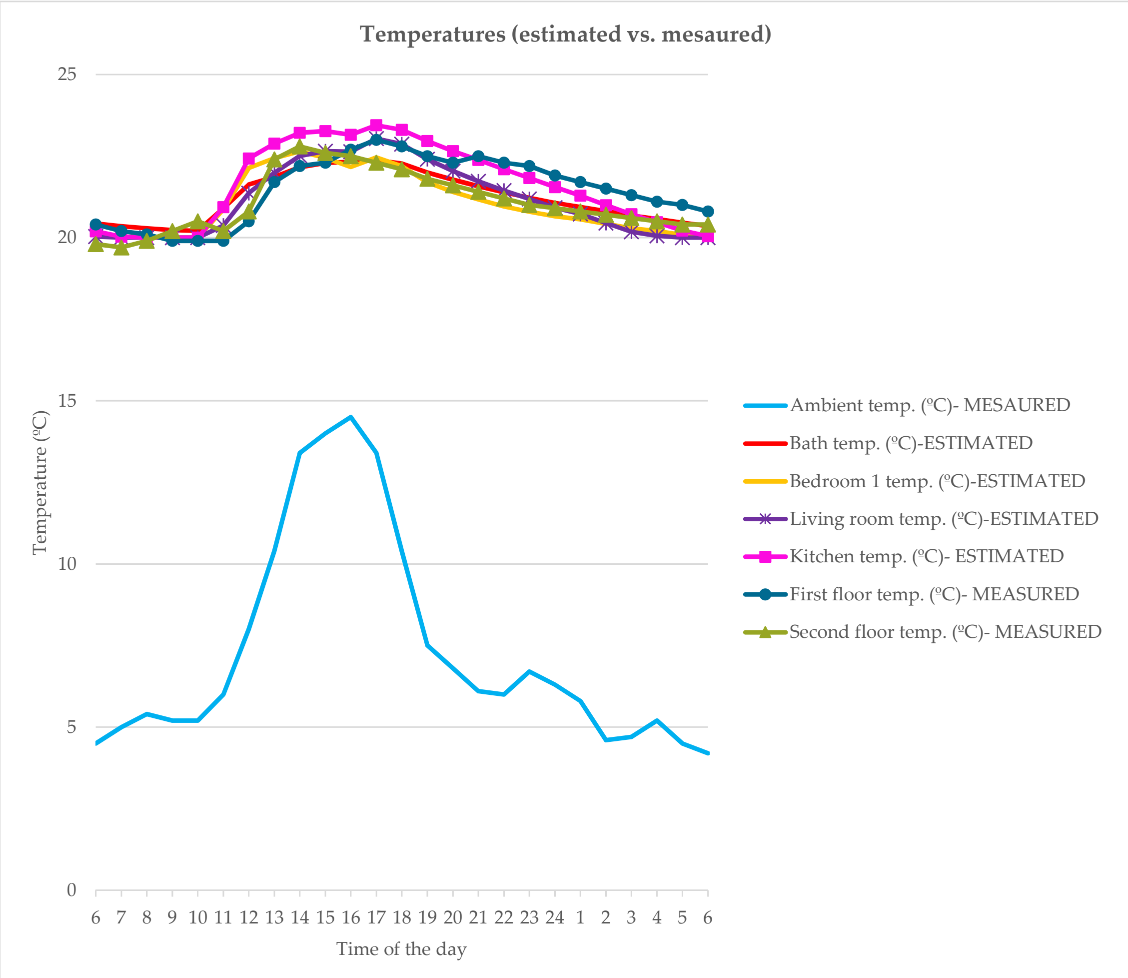


Figure 2.12. Air temperatures.

2.3.2. Validation of TRNSYS nZEB2 model.

During the development of this research, a single-family house (nZEB2) was built following the recommendations of the Passivhaus standard in Zaragoza city (Spain). Follow-up was carried out in the design and construction phases in addition to its start-up and subsequent operation. Therefore, the data from the design phase, such as the air conditioning energy demand obtained using the official Passivhaus calculation tool, the PHPP (Passivhaus Projecting Package), was available. The calculations were made by technical experts from the Spanish Passivhaus Platform (PEP). These data allowed us to verify that the results obtained with a TRNSYS model for nZEB2 are similar to those obtained with the PHPP tool and in consequence are suitable for validating the model.

The values and parameters for the calculation of the air conditioning energy demand for nZEB2 in the TRNSYS model are the same as those included in the PHPP tool. The construction and functional parameters are described below.

2.3.2.1. The PHPP tool

The PHPP is the standard tool developed by the Passivhaus Institute. It was introduced for the first time in 1998 and has been continually improved ever since [79]. The PHPP is based on Excel and is an easy- to- use planning tool for energy efficiency for use by architects and planning experts. It is continually being validated and extended on the basis of measured values and new research findings. The reliability of the calculation results and ease of use of this planning tool has already been experienced by several thousand users.

The tool is developed to calculate the energy demand for low energy buildings and is based on the monthly method in accordance with the norm EN ISO13790:2008 [80] for heating and cooling energy demand calculations. The calculations used for this thesis have been done with PHPP 8.5 (2013). The current PHPP version is the PHPP 9 (released at the end of 2016) which includes modifications in the design software and updates for nonresidential buildings in warm climates.

2.3.2.2. nZEB2 description: PHPP and Type56

The single family house was built in 2016 and has been inhabited since September 2016. The house has a net area of 73.4m^2 on two floors. On the ground floor there is a living room, a kitchen and a toilet, and on the first floor there is a studio, a bedroom and a bathroom (Figure 2.13).

There is a third floor where a workshop is located but this is outside the thermal envelope. In the calculations performed with the PHPP tool, the workshop is not part of the energy demand analysis. According to PHPP, if the building has an unheated attic, the intermediate ceiling should be treated as if it were adjacent to the outside air (i.e. as if the unheated attic did not exist). An auxiliary tool may be used in case of ventilated attics, but this extra option has not been applied to the current calculation. No solar radiation loads are applied to the roof which is under the attic.

Figure 2.13. Single family house nZEB2.

The family house has a first party wall with a neighboring house (kitchen, living room and the bedroom walls), and a second party wall with another neighboring house only on the ground floor (kitchen and toilet). The party walls are considered adiabatic in the PHPP tool, so the same consideration has been included in the TRNSYS model.

There are two exterior walls on the ground floor and three exterior walls on the first floor. The distribution and orientation of the dwelling can be seen in Figure 2.14. The main facade of the house is turned oriented 330° west.

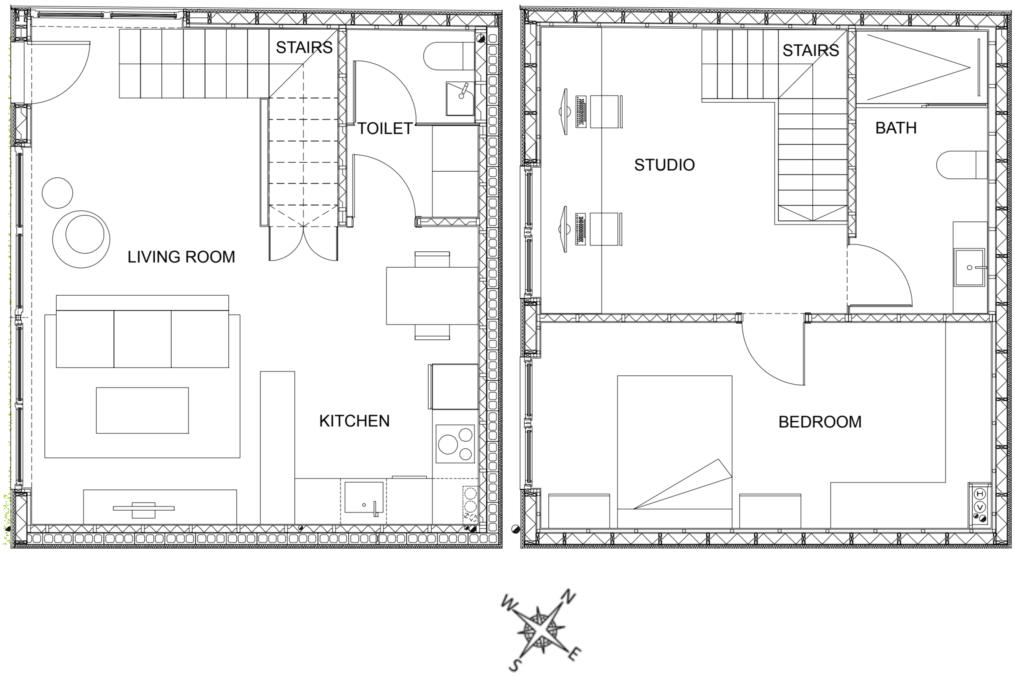


Figure 2.14. nZEB2 layout.

The TRNBuild model consists of five thermal zones and six air nodes (the kitchen and living room are within the same thermal zone). The area and volume of the rooms are listed in Table 2.10. The height of the roof is 2.5 m.

Table 2.10. nZEB2: room area and volume

Zone/Air node	Room/Zone	L1 (m)	L2 (m)	A (m^2)	V (m^3)
1/1	Living room	4.00	6.45	25.80	64.50
1/2	Kitchen	1.66	3.90	6.47	16.19
2/3	Toilet	1.66	2.60	4.32	10.79
3/4	Studio	4.00	3.70	14.80	37.00
4/5	Bedroom	5.90	2.69	15.87	39.68
5/6	Bath	1.66	3.70	6.14	15.36
	TOTAL			**73.40**	**183.51**

The house is built with a wooden framework and wool insulation. The external walls are covered with SATE (External Thermal Insulation system). The enclosure characteristics are given in Table 2.11. The total area of the windows and door is 18.3 m², including the entrance main door. The percentage of openings related to the net area of the dwelling is 24.93%.

Table 2.11. nZEB_RD enclosure technical characteristics.

Building enclosure	Area (m^2)	U (W/(m^2K)	Wall layers
External walls	North: 28.3 South: 32.1 East: 16.0	0.191	(In-Out): Plaster (13 mm) + Wood (10mm)+Double air brick (70 mm) + Wool insulation (140 mm) + Wood (10mm) + SATE* (60 mm)
External wall to neighbor	West: 16.1 South:28.3	0.251	(In-Out): Plaster (13 mm) + Reinforced partitions (80 mm) + Cement mortar (150 mm) + XPS** insulation (60 mm)
Floor	36.7	0.313	(In-Out): +Forged concrete (200mm) + XPS** insulation (100 mm)
Flat roof	18.7	0.117	(In-Out): Plaster (15 mm) + Wood (10 mm) + Wool insulation (240 mm) + Wood (10 mm) + XPS** (100mm) + Sand and gravel (50 mm)
Flat roof to workshop	18.0	0.156	(In-Out): Plaster (15 mm) + Wood (10 mm) + Wool insulation (240 mm) + Wood (15 mm)
Windows	North: 2.4 West: 13.7	0.897	Triple glass, low emissivity: 4/16 /4/16 /4
Main door	West: 2.2	1.000	Wood

SATE: External** *Thermal Insulation System¸* ****XPS:** *extruded polystyrene¸ Including windows*

PHPP uses the surface thermal resistances for the building envelope, in accordance with EN ISO 6946 [81]. The values can be found in Table 2.2. However, the thermal resistance for below ground construction is set at 0 for calculations in the PHPP, so the same value has been used in the TRNSYS model.

The exterior solar absorptivity and emissivity coefficient of the building elements surface are the same in both models. The solar absorptivity values are shown in Table 2.12.

Table 2.12. Solar absorptivity and emissivity values for building elements surface.

Building envelope	Exterior solar absorptivity	Exterior solar emissivity
Roof	0.4	0.9
Attic roof	0.9	0.83
Floor	0.4	0.9
External wall	0.1	0.15
External wall to neighbor	0.4	0.9

The thermal capacity is also included in the PHPP. Passivhauss states that its influence is insignificant compared with other influencing parameters. It could be calculated specifically, but a standard value is recommended. Al least 60 Wh/ m^{2}K is used, and an additional value of 24 Wh/ m^{2}K for each solid enclosing area of a typical room is added. TRNSYS calculates the thermal capacity depending on the construction elements.

nZEB2 has a mechanical ventilation system with HRV. The Zehnder model ComfoAir 200 heat exchanger installed in the nZEB2 (Figure 2.15) has an effectiveness of 0.825 for a flow rate of 60 m^3/h (nominal). These data come from a laboratory test conducted at Zehnder.

Figure 2.15. ComfoAir 200 installed in nZEB2.

Two people live in the house. The ventilation flows are balanced (inlet flow = return flow) and the distribution of air flow rates to the rooms in the TRNSYS model is shown in Figure 2.16. The ventilation system is programmed to four operating modes:

1) Out of the house: minimum maintenance flow 25 m^3/h;

2) Minimum flow (night): 35 m^3/h;

3) Nominal flow rate (all in the house): 60 m^3/h;

4) Party mode (guests at home): 90 m^3/h.

PHPP considers that the ventilation air flow is constant and continuous throughout the year, 64 m^3 h for the winter and 90 m^3/h for the summer season. It also considers an additional natural air ventilation caused by a window opening during summer nights during 4 hours. The extra ventilation air flow is 1.1 ACH.

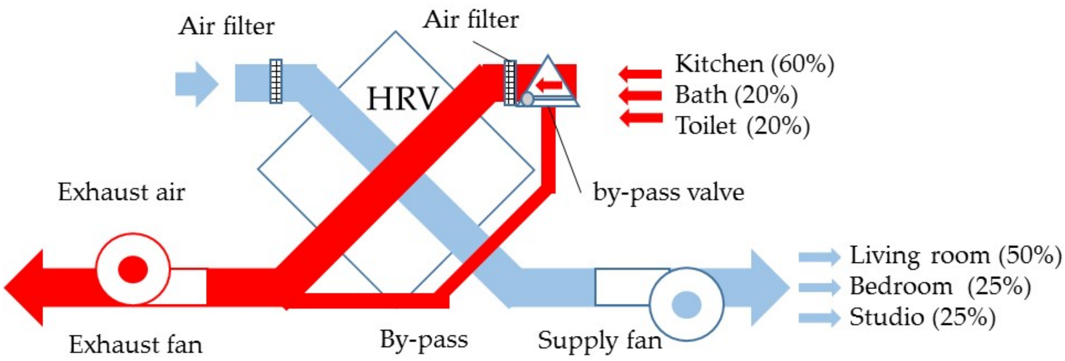


Figure 2.16. nZEB2 Air ventilation system.

Concerning the house airtightness, during the design phase Passivhaus uses Equation (2.3) to convert the limit value into an air flow under real operating conditions. This equation is a simple approximation which until 2008 was in the norm EN ISO 13790 [80]. The value obtained for the air flow infiltration is considered constant throughout the year.

In balanced ventilation systems with heat recovery, the infiltration air change rate depends on a coefficient e, which is the screening coefficient. Its values according to EN832 [82] are shown in Table 2.13. For this house the values are those corresponding to 'Moderate screening'.

$$n_{average} = \frac{V_{50}}{V} \cdot n_{50} \cdot e \tag{2.3}$$

where:

V_{50}/V is the ratio of theoretical air volume contained in the house and the air volume during the Blower Door Test. A value of 1.0 has been considered.

Table 2.13. 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 standard value for $n_{average}$ according to Passivhaus is 0.042 ACH (n_{50}= 0.6 ACH). This is also the value included in Type 56 for nZEB2.

<u>Climate data.</u>

PHPP calculates on a monthly basis. The energy balances are done using monthly average temperatures and monthly average solar radiation loads.

The PHPP contains a standard climate data set derived from typical Central European climate conditions. The list of available locations includes monthly average temperature and surface solar irradiance values for a horizontal surface and the four cardinal vertical surface orientations. The ground temperature is calculated from an independent algorithm based on the air temperature.

The climate data for PHPP calculations are shown in Table 2.14.

Table 2.14. Climate data.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ambient temp (ºC)	6.2	8.0	10.3	12.8	16.8	21.1	24.3	23.8	20.7	15.4	9.7	6.5
Ground temp (ºC)	12.2	10.6	10.5	12.0	14.6	17.7	20.4	22.0	22.0	20.6	18.0	14.9
Global radiation kWh/(m²month) PHPP	58	84	131	151	182	201	209	181	138	93	61	51
Global radiation kWh/(m²month) TRNSYS*	50	67	117	136	175	192	201	178	136	92	54	42

* Meteonorm monthly average. On hourly basis for TRNSYS calculation.

A Type62 (Excel) has been included in the TRNSYS model that allows us to enter the same values of the air ambient temperature and the floor temperature as those used in PHPP.

However, it is not possible to include in the TRNSYS model the simplified values of solar radiation. Therefore, the model in TRNSYS differs from PHPP in the thermal loads due to solar radiation. Table 2.14 shows the irradiation values of horizontal global radiation (kWh/m^2 month) used in both programs. Although those used in TRNSYS are on an hourly basis, the table shows the monthly average for the purposes of comparison. The solar irradiation values of the Meteonorm file used by TRNSYS are slightly lower than those used by PHPP, especially in winter.

The sensible thermal loads due to occupation and those caused by equipment (computers, domestic appliances, etc.) included in the PHPP tool and TRNSYS model are 2.1 W/m^2 in winter and 5.2 W/m^2 in summer.

Reduction factor for solar gains: shading and solar protection.

The nZEB2 house is located in an urban area. PHPP takes into account the shading caused by the adjacent buildings on the external surfaces of the walls and the solar radiation thermal loads on the windows. It does not take into account the use of blinds or interior curtains. Internal sunscreen elements can be integrated in TRNSYS.

The shading factor on the walls has been considered 0 for both calculation programs in order to compare results. However, the shading factors used by PHPP on the windows were maintained and introduced in TRNSYS through the use of internal protection.

PHPP applies a reduction factor (r) for solar gains on the windows, following equation 2.4.

$$r = r_{shading} \cdot r_{Dirt} \cdot r_{incidence\ angle} \cdot r_{Frame} \quad (2.4)$$

where

$r_{shading}$ is the reduction factor considering the shading from neighboring buildings, trees, overhangs, etc.The standard value is 0.75. PHPP calculates this value for every window and then uses the average value for each orientation. The average value is calculated for summer and for winter. For the west windows the value is 0.52 for winter and 0.65 for summer. The north windows do not have a reduction factor for shading.

r_{Dirt} is a reduction factor to take into account dirty windows. The standard value is 0.95. This reduction has also been included in the TRNSYS model.

$r_{incidence\ angle}$ is the reduction factor due to non-perpendicular radiation. The standard value is 0.85.

r_{Frame} is a reduction factor accounting for the area of the window frame (15%).

2.3.2.3. Results and discussion.

PHPPP calculates the heating demand by two methods: an annual heating method or a monthly method both in accordance with the norm EN 13790 [80]. The monthly method performs the energy balance for every month of the year. The results of the annual heating demand for both methods are comparable and in most cases very similar. Dissimilar results have been observed in buildings with large glazing areas and very low heating demand (considerably below the level required by Passivhaus). In these cases the monthly method should be used, as stated by PH.

The heating and cooling results obtained by the monthly method are used for validation of the TNRSYS model. Table 2.15**¡Error! La autoreferencia al marcador no es válida.** shows the monthly results. The winter months for heating demand are from January to May and from October to December.

Table 2.15. Air conditioning energy demand for nZEB2.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total heat	Total cool
PHPP	3.77	2.21	1.08	0.29	0.00	0.71	4.77	3.98	0.58	0.00	1.33	3.46	12.14	10.04
TRNSYS	3.55	2.53	1.03	0.08	0.00	2.07	4.37	3.52	1.06	0.00	1.61	3.39	12.19	11.03
%	-5.9	14.8	-5.2	-72.3	--	193.6	-8.4	-11.5	81.8	--	21.3	-2.1	0.4	9.8

The results obtained with the two tools are similar, especially in the annual air conditioning energy demand. The difference in heating demand is + 0.4% and in cooling demand + 10% for the TRNSYS calculations versus the PHPP calculations. Although the percentage differences for some months are important, as for example the month of June, this data is not representative since the cooling demand is very low. Figure 2.17 shows the monthly heating and cooling demand obtained for PHPP and TRNSYS.

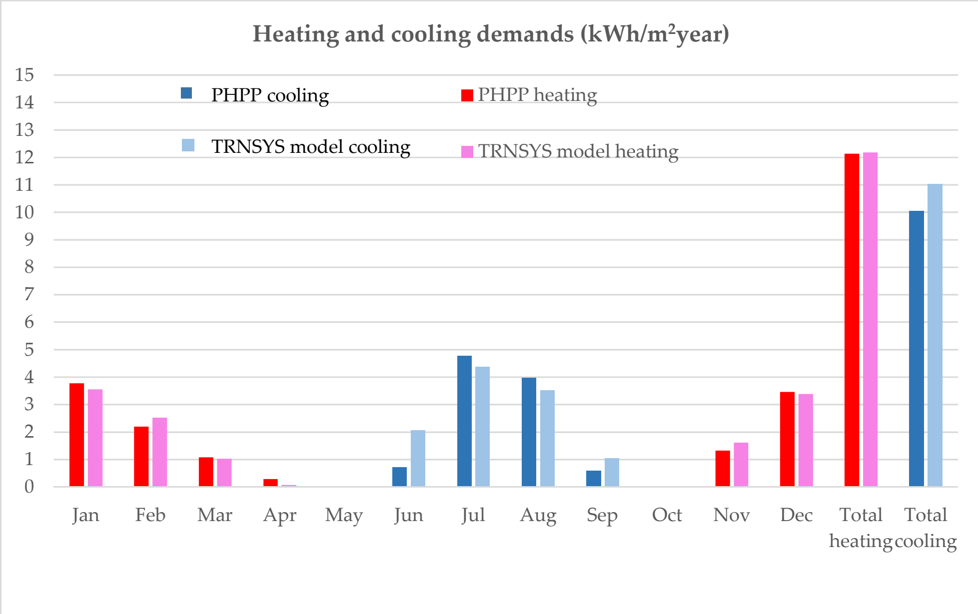


Figure 2.17. Monthly heating and cooling energy demand for nZEB2.

2.3.3. Validation of TRNSYS nZEB_RD model.

2.3.3.1. nZEB_RD description: PHPP and Type56

The construction and functional parameters used to define the representative dwelling in a block of houses, nZEB_RD, are detailed below. The dwelling layout is shown in Figure 2.7.

In the model, each room was considered as a zone and an air node. The dimensions of each room defined in TRNBuild, as well as their volume, are shown in Table 2.16.

Table 2.16. nZEB_RD room dimensions and air volume.

Zone/Air node	Room/Zone	L1 (m)	L2 (m)	A (m²)	V (m³)
1/1	Kitchen	3.40	2.70	9.18	22.95
2/2	Bath	2.00	1.70	3.40	8.50
3/3	Toilet	2.00	1.50	3.00	7.50
4/4	Bedroom 1	3.80	3.20	12.16	30.40
5/5	Bedroom 2	2.40	5.00	12.00	30.00
6/6	Bedroom 3	3.50	3.00	11.27	28.18
7/7	Living room	6.13	3.70	22.68	56.70
8/8	Corridor	6.13	1.10	7.46	18.65
	TOTAL			**81.15****	**202.87**

** The area of the dwelling is 81.51 m2 and in the model TRNBuild is 81.15 m2 due to adjustments in the definition of the model.

The dwelling in the block is built of brick and has XPS insulation (extruded polystyrene). The building has a flat roof. The characteristics of the envelope are given in Table 2.17.

The external building enclosure follows the Passivhaus recommendations regarding the thermal transmittance of the building envelope for southern Europe.

The total area of the windows and door in the dwelling is 21.16 m^2, including the entrance main door. The percentage of openings related to the net area of the dwelling is 26.07%.

Table 2.17. nZEB_RD enclosure technical characteristics.

Building enclosure	Area (m^2)***	U (W/(m^{2}K)	Wall layers
External walls	North: 24.1 South: 29.0 East: 20.0	0.340	(In-Out): Plaster (15 mm) + Double air brick (70 mm) + XPS** insulation (80 mm) + Cement mortar (10mm) + Brick facade (115 mm)
External wall to neighbor	West: 24.9	0.958	(In-Out): Plaster (15 mm) + XPS** insulation (10 mm) + Double air brick (100 mm) + XPS** insulation (10 mm) + Plaster (15 mm)
Floor to neighbor	81.15	0.843	(In-Out): Plaster (15 mm) +Forged concrete (300mm) + Mineral wool (20 mm) + Wood (15 mm)
Flat roof	81.15	0.260	(In-Out): Plaster (15 mm) + Forged concrete (300 mm) + Cement mortar (10mm) + EPDM* (5 mm) + XPS insulation (110 mm) + Sand and gravel (50 mm)
Windows	North: 8.4 South: 10.8	1.400	Tripe low-emissitvity glass: 4/16 /4/16 /4
Main door (internal)	West: 2.0	1.400	Wood

****EPDM:*** *Ethylene-propylene elastomer;* ****XPS:*** *extruded polystyrene; *** Including windows*

The air ventilation system has an HRV with an effectiveness at a nominal flow (120 m^3/h) of 0.85 (according to the manufacturer Zehnder). The air flow distribution remains unchanged in each room of the dwelling in all the TRNSYS simulations and is shown in Figure 2.18.

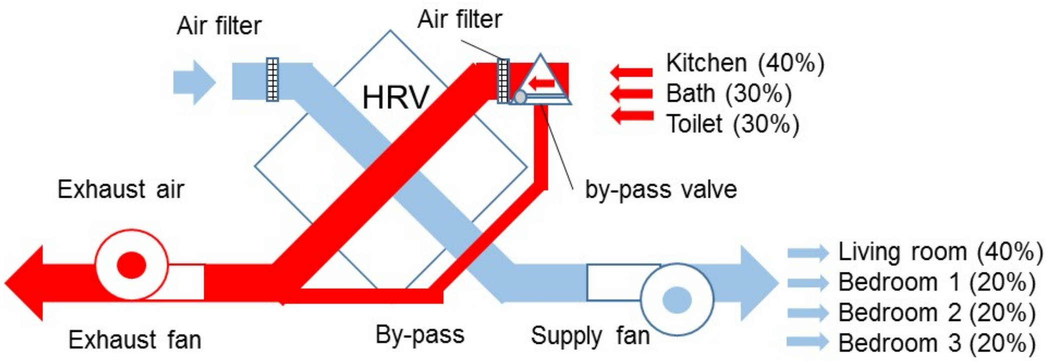


Figure 2.18. nZEB_RD air ventilation system.

PHPP calculations and TNRSYS model simulations have been done for an air ventilation flow of 120 m^3/h during winter and 180 m^3/h during summer. Extra natural ventilation is added during summer nights due to opening windows, which occurs during 4 hours with an air flow of 1.1 ACH.

Infiltrations, climate data, internal loads and comfort parameters are identical to the values used for nZEB2 validation. The shading factors and solar protection used are the same as for nZEB2 except the window shading factor which in this case is 0.25 during winter and 0.45 during summer.

2.3.3.2. Results and discussion.

The heating energy demand and cooling energy demand obtained by the monthly method with the PHPP tool are used for validation of the TNRSYS model. Table 2.18 shows the monthly results obtained by both tools. The winter months for heating energy demand are from January to May and from October to December.

Table 2.18. Air conditioning energy demand for nZEB_RD.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total heat	Total cool
PHPP	4.50	2.15	0.83	0.19	0.00	0.78	4.60	3.45	0.59	0.02	2.16	4.55	14.40	9.42
TRNS	4.43	2.80	0.76	0.03	0.00	1.09	3.72	3.20	1.28	0.00	1.62	4.69	14.33	9.29
%	-1.7	30.2	-8.6	-84.9	--	39.7	-19.2	-7.3	117.7	--	-24.7	3.1	-0.5	-1.4

The results obtained with the two tools are similar, especially in the total air conditioning energy demand. The heating demand is just -0.5% and the cooling demand is -1.4% for the TRNSYS model versus the PHPP calculations. Although the percentage differences for some months are important, as for example the months of April or September, this data is not representative since the demand for heating or cooling is practically negligible (spring and autumn months).

Figure 2.19 shows the monthly heating and cooling values obtained by PHPP and TRNSYS.

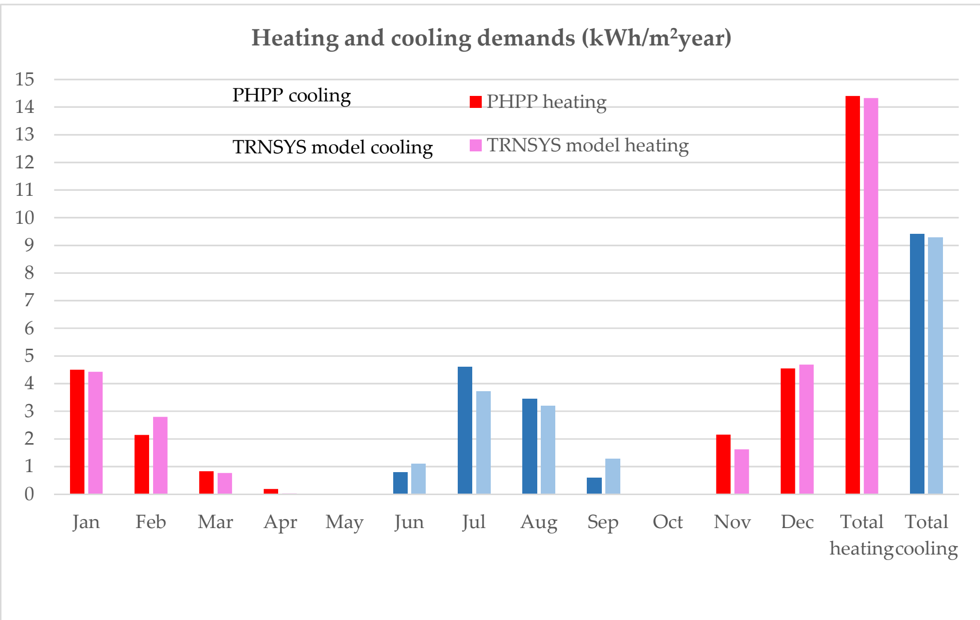


Figure 2.19. Monthly heating and cooling energy demands for nZEB_RD.

For the hottest months, July and August, the results obtained with TRNSYS are slightly lower although the difference is only 0.88 kWh/m^2 for July and 0.25 kWh/m^2 for August.

2.3.4. Conclusions

The errors obtained in the heating and cooling energy demand are shown in Table 2.19.

Table 2.19. Errors obtained in validation models.

Validation	Error obtained for Heating demand	Error obtained for Cooling demand
nZEB1 versus measured data	+0.4%(for February)	---
nZEB2 versus PHPP tool (done by PH specialist)	+0.4%	+10%
nZEB_RD versus PHPP tool (done by the author)	-0.5%	-1.4%

The uncertainties which could explain the difference between nZEB1 versus the measured values are:

- The global radiation data for the TRNSYS model is taken from Meteonorm.
- The real opening and closing of the door and windows is not included.

The differences obtained using TRNSYS and the PHPP tool may be justified due to the differences in some inlet parameters and calculation procedures, as listed below:

- The global radiation data for the TRNSYS model is taken from Meteonorm and for PHPP from its own climate data.
- The TRNSYS model calculates on an hourly basis and PHPP on a monthly basis.
- The thermal capacity of building elements in PHPP is not calculated specifically but a standard value is recommended.
- The shading reduction factor for windows in TRNSYS is considered as internal shading devices and in PHPH as shading created by the surroundings.

In conclusion, the differences in energy saving (%) obtained are small enough to ensure that the data obtained from the nZEB_RD TRNSYS model are sufficiently consistent to be able to reach solid conclusions throughout this doctoral dissertation.

Chapter 3

Review of European ventilation strategies to meet the cooling and heating demands of nearly zero energy buildings (nZEB)/Passivhaus. Comparison with the USA

3. Review of European ventilation strategies to meet the cooling and heating demands of nearly zero energy buildings (nZEB)/Passivhaus. Comparison with the USA

This chapter is based on the following published paper:

S. Guillén-Lambea, B. Rodríguez-Soria, J.M. Marín, *"Review of European ventilation strategies to meet the cooling and heating demands of nearly zero energy buildings (nZEB)/Passivhaus. Comparison with the USA."* Renew Sustain Energy Rev 2016;62:561-74. doi:10.1016/j.rser.2016.05.021.

Abstract

The parameters and conditions that govern the ventilation requirements in residential buildings under current regulations worldwide are not harmonized. The reduction in energy demand and the increase in the thermal comfort in dwellings are mainly conditioned by these parameters.

This article reviews and compares the ventilation flow rates in residential buildings in various countries: the United States of America, Germany, France, the United Kingdom, and Spain. It also compares the requirements of these countries with the requirements of the Passivhaus construction standard, which is recommended by the European Union as an example of nearly zero-energy buildings (nZEB).

Furthermore, a model for a dwelling is created using TRNSYS software.

First, simulations have been performed with the flow rates, ventilation strategies and envelope transmittance required by the regulations of each country. The cooling and heating demands have been obtained for representative cities in different climate zones. With these results, the impact of ventilation parameters in the heating demand of the proposed Spanish dwelling is analyzed. Secondly, the same dwelling has been simulated with the thermal envelope transmittance values recommended by the Passivhaus standard. The ventilation strategies of each country have been maintained. The influence of the ventilation can be observed uninfluenced by other design parameters.

It is found that with the current ventilation strategies, the heating and cooling demand values required by Passivhaus can be reached in only a few warm climates. In other cases, the ventilation strategies will need to change, and heat recovery ventilation will be required.

Keywords

Ventilation; European regulations; Passivhaus; Residential dwellings, Climatic zones

3.1. Introduction

A substantial percentage of the air conditioning consumption in buildings is due to ventilation systems in dwellings [83]. Various studies have examined the requirements of minimum ventilation flow rates in several countries [84–87]. Of special interest is the article [88] which reviews the ventilation flow rates in fifteen countries and later calculates the minimum air changes necessary in a Japanese housing type according to different regulations without including ventilation strategies. A more recent study [89] discusses ventilation standards in several European countries and analyzes the ventilation flow rate values obtained in different European dwellings. The report published by BPIE this year [90] outlines the ventilation rules in eight EU countries. However, none of these works includes American rules or the Passivhaus standard. Furthermore, they do not state whether the rules are adequate to meet nZEB requirements.

This article analyzes the main regulations concerning the ventilation of residential buildings in several countries. It assesses and quantifies how ventilation parameters and their regulation affect the heating and cooling energy demands of dwellings. The countries studied are: the United States of America, Germany, France, the United Kingdom and Spain. According to the *Implementation of the Energy Performance of Buildings Directive Country Reports 2008* [12], Germany, France and the United Kingdom are considered as references in the implementation of energy efficiency regulations in buildings. Spain is included as a Mediterranean Europe country for the purposes of comparison. In addition, the ventilation regulations of these countries are compared with the guidelines and conditions concerning ventilation recommended by Passivhaus [18,91,92]. The European countries selected are representative of the different climate zones of the European Union with one exception: the colder Northern climate. The reason for this is that Nordic countries have already implemented (like Finland [93]) or are in the process of implementation of the Passivhaus recommendations in its regulations. The USA has been included in the study for two reasons. First, because of the similarity between its climate zones and those of Europe (as supported by the standard ASHRAE 90.1-2013 [94] that identifies the equivalence between US and EU climate zones). And secondly, because the Passivhaus standard is well extended across the country [19].

Furthermore, a dwelling situated in a block of houses has been modeled in TRNSYS [43]. The conditions established by each country to meet the envelope and the ventilation system requirements according to the different rules under study have been applied. All other parameters which influence the heating and cooling demands such as indoor temperature [95], infiltration [96] and internal loads have been kept constant in all the simulations. The heating demand due to ventilation has been obtained for the different climate zones of each country.

Secondly, the same dwelling has been simulated with the thermal envelope transmittance values recommended by the Passivhaus standard. The ventilation strategies in each country have been maintained. The influence of the ventilation can be observed uninfluenced by other design parameters. Finally, simulations have been performed using the thermal transmittance and ventilation strategy recommended by Passivhaus for the same climate zones as the countries under study.

The main conclusion is the need to implement heat recovery in ventilation systems to meet the demands of the Passivhaus-nZEB. The results shows that the energy demand limit set by the Passivhaus standard is difficult to achieve by simply increasing the thermal insulation of the envelope.

3.2. Review of European and United States regulations governing ventilation in residential buildings

The main function of the ventilation is to ensure the indoor air quality ensuring extraction agents harmful to humans. CO_2 is a readily measurable agent, which has been established as reference of hygienic quality of the interior spaces. The air in the countryside has a CO_2 concentration around of 380 ppm and the air on the cities around of 450 ppm. The CO_2 concentration in interior spaces must be less than 1200 ppm [27]. The air ventilation flow should guaranty that the CO_2 concentration at the dwelling remains under this level.

Both the EU and the USA regulate ventilation systems through mandatory regulations indicating both quantitative flow rate values and ventilation strategies.

The regulations concerning ventilation in different countries and the conditions of energy efficiency of buildings are briefly explained below. These apply in the United States of America, Germany, France, the United Kingdom and Spain. The Passivhaus standard is also included.

For each analyzed country, an introduction to the rules is provided, describing how ventilation flows rates are imposed and detailing regulation strategy.

The full regulatory framework is reflected in Table 3.1.

Table 3.1. Regulatory framework in the countries under study. (Compiled by the author).

International	Entity	At the supranational level	Country or state		
			Country	General Construction regulations	Main regulations governing the ventilation factors under study
ISO 7730:2005. Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.	EU	European Directives: 2010/31/UE European Standard (EN) EN15251:2007	Germany	Energieeinspa rungsgesetz-EnEG	DIN 1946-2009 (part 6) DIN 18017-2009 (part 3)
			France	R. 111-20 du code de la construction et de l'habitation	Arrêté du 24 mars 1982 relatif à l'aeration des logements Arrêté 28 octobre 1983 relatif à l'aeration des logements
			U.K.	Building Act 1984 (England and Wales)	Building Regulations 2000: Approved Document F: Ventilation /2010
			Spain	Ley Ordenación de la Edificación	Código Técnico de la Edificación (CTE): DB HS-3
	USA	ASHRAE Standards Standard 62-1-2013 Standard 62-2-2013			

3.2.1. United States regulations

The "American Society of Heating, Refrigerating and Air-conditioning Engineers" (ASHRAE) publishes standards used worldwide as a reference for the calculation and design of air conditioning systems. Many European Standards (EN) on indoor air quality and air conditioning are based on this standard.

The ASHRAE 62.1.2013 Standard "Ventilation for Acceptable Indoor Air Quality" [97] defines ventilation in all conditioned spaces except for single family and multi-family low-rise residential buildings with less than three stories. In this standard, ventilation air flow in the "breathing areas" (internal volume of enclosures) is established at l/s per person or l/s per m2 of dwelling.

Otherwise, the ASHRAE 62.2.2013 standard: "Ventilation for Acceptable Indoor Air Quality in Low-Rise Residential Buildings" [98] regulates ventilation in single family and multi-family low-rise residential buildings with less than three stories. In this standard, intermittent and continuous ventilation are allowed. However, it recommends controlled and intermittent mechanical ventilation. The standard points out that continuous fan operation greatly increases energy consumption and introduces the same air amount under all conditions of use, even in extreme climates.

This standard includes infiltration in the calculation of the ventilation only if the infiltration has been measured. In this case, the recommended ventilation rate is reduced by the rate of infiltration only when the infiltration constitutes less than 2/3 of the total flow rate.

The minimum flow rates for continuous and intermittent ventilation are shown in Table 3.2.

3.2.2. European regulations

The European standard EN15251: 2007 'Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics' [29] was adopted by the CEN on 26/03/2007.

This standard provides ventilation flow rates for use if there are no national regulations. It sets out four categories of ventilation flow rates depending on the quality of the indoor environment. Class II represents a normal level of expectation regarding the indoor air quality of new and refurbished residential buildings.

Ventilation flow rates depend on the average use of the residence and can be adapted depending on the degree of occupation. In this standard, ventilation flow rates are recommended during the hours of occupation. The calculation procedure for Class II is as follows. First, the ventilation flow rate is calculated based on the floor area of the dwelling by applying a value of 0.42 l/sm2. Secondly, the supply flow is calculated based on the occupation using a value of 7 l/s per person (living room and bedrooms) and, thirdly, it is calculated depending of the floor area of the living room and bedrooms considering 1 l/sm2. The final ventilation flow should be the highest value of the three flow rates obtained. It is completed by adjusting the supply to the extract flow rates of the kitchen, bathrooms and toilets. These values are indicated in Table 3.2.

Concerning strategy, the standard explicitly recommends a minimum ventilation flow rate between 0.05 l/sm2 and 0.1 l/sm2 in residential buildings for vacancy periods. Furthermore, it indicates that ventilation systems with variable flow can control the air flow according to occupancy, the pollutant load or the production of moisture.

3.2.3. Spanish regulations

In Spain, the Technical Building Code (CTE) published in 2007 [99] establishes the requirements to be met by buildings in relation to the basic requirements of safety and habitability. It consists of various Basic Documents (DB). The most recent update of the Basic Energy Saving Document (hereinafter HE) [9] was published on 12 September, 2013. This document regulates the actions of the thermal envelope of the building and the systems and facilities that consume energy.

The Basic Health Document HS 3: Indoor Air Quality [10] (hereafter DB-HS 3), regulates the ventilation air flow and the design conditions of the ventilation system of dwellings.

The minimum ventilation air flows in residential buildings are defined for each type of enclosure, both dry and wet, and are shown in Table 3.2.

This document requires that the outdoor air enters the dwelling by inlet openings located in dry rooms, and is expelled by exhaust openings in wet rooms. Therefore, the sum of the flows into the dry rooms should be increased to be equal to the sum of the output flow from the wet rooms.

Concerning strategy, the ventilation, either hybrid or mechanically controlled, should operate with the same flow rates for 24 hours.

3.2.4. German regulations

In Germany the Energy Saving Act was adopted in 1976 (Energieeinsparungsgesetz-EnEG) and most recently revised in 2009 [100] .This law is the legal basis for the development of later regulations.

The Energy Conservation Ordinance - EnEV 2014 [101] regulates the requirements of energy saving buildings in terms of envelope and the installation of heating, cooling, ventilation, hot water and lighting, thus leaving all coordinated enforcement within the same regulation. The ventilation parameters in Germany are set out in the DIN 1946-6 Ventilation in residential buildings [102] and the DIN 18017-3 Ventilation in bathrooms and toilets without external windows [103]. Recommended values are indicated in Table 3.2.

The DIN1946-6 specifies four levels of ventilation, depending on the fan speeds to ensure sufficient air with different conditions of use and load: ventilation for protection from humidity, reduced ventilation, nominal ventilation and intensive ventilation. The norm states that the air changes per hour (ACH) required to reduce the content of carbon dioxide and water vapour from the air are between 0.5 (to avoid building damage caused by mould due to moisture when there are no occupants) and 1 for maximum occupancy.

Regarding the strategy, the German standard advocates mechanically controlled ventilation in an airtight building, to control energy losses and to act on them.

3.2.5. English regulations

In the UK, each constituent country (England and Wales, Scotland, and Northern Ireland) publishes its own regulations, which dictate the ultimate objectives of energy efficiency and the numerical values that specific energy factors must achieve. The law common to England and Wales was selected for this study. In England and Wales, the definitions, procedures, and performance levels that should be met by buildings are included in the 1984 Building Act and subsequent amendments [104]. These performances parameters are developed under a compendium of documents, which are known as the Building Regulations of 2000. Of these, the document governing the energy efficiency of residential buildings is the “Approved Document L1A: Conservation of fuel and power- New dwellings, 2010 edition” [105] and the document outlining the basis for ventilation systems is the “Approved Document F: Ventilation, 2010 edition” [106].

The latter document indicates that uncontrolled air infiltration should be minimized since it cannot be acted on and that it should be replaced by controlled ventilation. Thus, it calculates the required ventilation considering that the building has no infiltrations. If the air permeability of the building is greater than 5 m3/h at 50 Pa, it assumes an infiltration of 0.15 ACH, and decreases the ventilation flow required.

The air extraction ventilation is performed in wet rooms and is called "Extract Ventilation". The air supply is provided through both wet and dry rooms and is called "Whole Dwelling Ventilation". The Extract Ventilation flow rates required are tabulated in the norm depending on the room and if ventilation is continuous or intermittent. For dry rooms, the Whole Dwelling Ventilation flow rates required are tabulated in the norm depending on the number of rooms in the house, considering two occupants for a double room and one occupant for the rest.

Ventilation flow rates are calculated for the winter period. If additional ventilation is required in the hot months, “Purge ventilation” comes into operation.

These values can be found in Table 3.2.

The document explicitly states that both continuous and intermittent extraction are allowed, the latter being considered more efficient not only energetically but also for indoor air quality. It further indicates that ventilation flows can vary when the building is unoccupied. To compensate for this lack of ventilation when the building is occupied again, "Purge Ventilation" is performed by opening the windows.

Both manual and mechanical controls are specified as valid. The control can be based on any of these three parameters: occupancy, humidity and air pollution evaluated by measuring the CO_2.

3.2.6. French regulations

In France the law R.111-20: Building Code and habitability ("Code de la construction et de l'habitation") [107] sets out the general conditions that must be met by residential buildings. The ventilation of dwellings in France is regulated by the "Order of 24 March 1982 on provisions for ventilation of dwellings" [108] and its subsequent amendments on 27 March of the same year and 28 October 1983. This order indicates that ventilation must be permanent only when the outside temperature obliges windows to be kept closed. It further specifies that if there is a hood in the kitchen, the ventilation flow rate can be decreased in the kitchen. The air supply must enter through dry rooms and be extracted from wet ones.

The permanent ventilation flow rates required for wet rooms by French regulations are based on the number of main rooms (living rooms and bedrooms) regardless of the number of occupants of the dwelling. The flow rates are listed in Table 3.2.

French legislation encourages ventilation control through individual measurement devices. If these are installed, the ventilation rates can be reduced. In this case, the legislation regulates the minimum total flow that must be extracted from the kitchen in m3/h and the total minimum flow in housing.

Likewise, it also allows for a mechanical device that automatically modulates the ventilation flow to reduce the airflow at times when it is not needed. Therefore, the total minimum flows are further reduced. It also allows the use of CO2 and humidity measuring devices that are responsible for regulating the progress of fan operation.

3.2.1. Passivhaus recommendations

The Passivhaus standard defines a ‘passive house’ as follows [19]: "A passive house is one that can ensure climatic comfort providing energy for heating and / or cooling only through the ventilation air."

In the Passivhaus standard, the ventilation rate must be the minimum necessary to ensure the hygiene of the interior rooms, considering this value to be between 8.3 l/s and 8.9 l/s per person (for residential use) [27]. It also recommends regulating the exchange rate depending on the activity. Ventilation must be mechanically controlled via a heat exchanger to avoid introducing air at ambient temperature. The use of heat recovery systems in the ventilation circuit is required by the Passivhaus standard.

Houses built under this standard have an average heating demand lower than 15 kWh/m^2 a year, which involves a maximum consumption of approximately 10 W/m^2.

Table 3.2.Ventilation regulations and standards in the countries under study.

Table 3.2.Ventilation regulations and standards in the countries under study.

COUNTRY/ STATE	STANDARD/ NORM	VENTILATION AIR Whole dwelling ventilation rates	TYPE OF VENTILATION	EXHAUTS AIR FLOW RATES			SUPPLY AIR FLOW RATES	
				Kitchen	Bathroom	Toilet	Bedroom	Living room
USA	ASHRAE Standard 62-1-2013	Minimum ventilation rates in breathing zone: 2.5 l/s person or 0.3 l/s m^2. Occupancy [a]	CONTINUOUS VENTILATION	Min f l o rate b: 25 l/s	Min f l o rate c: 12.5 l/s	Min f l o rate c: 12.5 l/s	--	--
			INTERMITENT VENTILATION	Min f l o rate b: 50 l/s	Min f l o rate c: 25 l/s	Min f l o rate c: 25 l/s	--	--
	ASHRAE Standard 62-2-2013	The total required ventilation rate (Qtot) shall be as specif i e in a table depending on the f l oo area or, alternatively, calculated using the equation: Qtot=0.15 AFLOOR+3.5 (NBR+1) Qtot total required ventilation rate (l/s) Af l oo dwelling f l oo area (m^2) Nbr number of bedrooms (not to be less than 1) Exceptions [d]	CONTINUOUS LOCAL VENTILATION	5 ACH	10 l/s	10 l/s	--	--
			DEMAND-CONTROLLED LOCAL VENTILATION	50 l/s [e]	25 l/s	25 l/s	--	--
EUROPE	UNE EN 15252	During occupancy continuous f l o rate should be at least the biggest of the following values: 1) 0.42 l/s m^2 2) 7 l/s person at living and bedroom 3) 1 l/m^2 for living and bedroom f l oo areas During not occupancy ventilation rate could be reduced between 0.05 l/sm^2 and 0.1 l/sm^2	CONTINUOUS OR DEMAND-CONTROLLED VENTILATION. Ventilation rates could be reduced depending on the occupancy.	Min f l o rate: 20 l/s	Min f l o rate: 15 l/s	Min f l o rate: 10 l/s	--	--
SPAIN	DB HS3	Continuous ventilation 24hours per day	CONTINUOUS VENTILATION	Min f l o rate: 2 l/s m^2 + 50 l/s for appliance hood	Min f l o rate: 15 l/s	Min f l o rate: 15 l/s	5 l/s per person	3 l/s per person
GERMANY	DIN1946-6	Mechanical ventilation is required if the necessary air volume f l o for moisture-proof i n exceeds the air volume f l o caused by inf iltrati on Demand controlled ventilation specify 4 levels for fan air f l o w Pos 1: Protection against humidity. From 4.16 l/s (15 m^3/h) for 30 m^2 to 23.6 l/s for 210 m^2 (85 m^3/h) depending on f l oo area. Pos 2: Reduced ventilation. From 11.11 l/s (40 m^3/h) for 30 m^2 to 41.66 l/s for 210 m^2 (150 m^3/h) depending on f l oo area. Pos 3: Nominal ventilation. From 15.27 l/s (55 m3/h) for 30 m2 to 59.72 l/s for 210 m^2 (215 m^3/h) depending on f l oo area. Pos 4: Intensive ventilation. From 19.44 l/s (70 m3/h) for 30 m2 to 79.16 l/s for 210 m^2 (285 m^3/h) depending on f l oo area.	NATURAL OR FAN ASSISTED VENTILATION	Nominal ventilation in case of mechanical ventilation: 12.5 l/s (45 m^3/h)	Nominal ventilation in case of mechanical ventilation: 12.5 l/s (45 m^3/h)	Nominal ventilation in case of mechanical ventilation: 7 l/s (25 m^3/h)	--	--
	DIN18018	Applies for ventilation of bathrooms and toilets without windows Air f l o requirements only related to exhaust air rooms, not to the entire house	CONTINUOUS VENTILATION (minimum high rate)	11.11 l/s (40 m^3/h) during a Min of 12 hours	5.55 l/s (20 m^3/h) during a Min of 12 hours	5.55 l/s (20 m^3/h) during a Min of 12 hours	--	--
			INSTANTANEOUS VENTILATION (minimum rate)	16.66 l/s (60 m^3/h)	8.33l/s (30 m^3/h)	8.33l/s (30 m^3/h)	--	--

Table 3.2. Ventilation regulations and standards in the countries under study.

COUNTRY/ STATE	STANDARD/ NORM	VENTILATION AIR Whole dwelling ventilation rates	TYPE OF VENTILATION	EXHAUTS AIR FLOW RATES Kitchen	Bathroom	Toilet	SUPPLY AIR FLOW RATES Bedroom	Living room
UK	Approved Doc. F Ventilation 2010	From 13 l/s (for 1 bedroom dwelling) to 29 l/s (for a 5 bedroom dwelling). Whole ventilation f l o rate always higher than 0.3 l/s m^2. Occupancy [f] If dwelling permeability is 5 m^3/(h m) a 50 Pa, takes 0'15 ACH as inf iltrati o rate which will be reduced from the total ventilation rate.	CONTINUOUS EXTRACT VENTILATION (minimum f l o rate)[g]	13 l/s	8 l/s [h]	6 l/s [i]	--	--
			INTERMITTENT EXTRACT VENTILATION (minimum f l o rate)	30 l/s + appliance hood f l o rate or 60 l/s	15 l/s [h]	6 l/s [i]	--	--
FRANCE	Arrêté du 24 Mars 1982 Modif i par arrêté du 28 octobre 1983	Whole dwelling ventilation during winter: continuous ventilation has to be assured. With regulation control device, the total minimum f l o assured for whole dwelling from 9.72 l/s (35 m^3/h) for 1 room dwelling to 37.5 l/s (135 m^3/h) for 7 room dwelling [j] With mechanical ventilation and control device, the total minimum f l o assured for whole dwelling from 2.77 l/s (10 m^3/h) for 1 room dwelling to 9.72 l/s (35 m^3/h) for 7 room dwelling.	CONTINUOUS EXTRACT VENTILATION (minimum f l o rate)	From 20.8 l/s (75 m^3/h) for 1 room dwelling to 37.5 l/s (135 m^3/h) for a 5 or more room dwelling	From 4.16 l/s (15m^3/h) for 1 room dwelling to 8.33 l/s (30 m^3/h) for a 5 or more room dwelling	4.16 l/s (15m^3/h)	--	--
			DEMAND CONTROLLED VENTILATION BY REGULATION DEVICES (total minimum f l o rate)	Regulation device: From 5.55 l/s (20 m^3/h) for 1 room dwelling to 12.5 l/s (45 m^3/h) for a 7 room dwelling	--	--		
PASSIVHAUS	Standard Passivhaus	From 8.33 l/s to 8.88 l/s (30-32 m^3/h) per person Controlled ventilation depending on the occupancy	--	--	--	--	--	--

[a] Default occupancy for dwelling units shall be two persons for studio and one-bedroom units, with one additional person for each additional bedroom.

[b] For continuous system, the lower rate may be used. Otherwise use the higher rate.

[c] Rate is for a toilet room intended to be occupied by one person at a time. For continuous system operation during normal hours of use lower rate may be used. Otherwise use the higher rate.

[d] Whole-building mechanical systems are not required if window operation is a locally permissible method of providing ventilation and provided that at least one of the following conditions is met: the building has no mechanical cooling and is in zone 1 or 2 of the climate zone or the building is thermally conditioned for human occupancy for less than 876 h per year.

[e] Vented range hood (including appliance-range hood combinations) required if exhaust fan f l o rate is less than 5 kitchen ACH.

[f] This is based on two occupants in the main bedroom and a single occupant in all other rooms. This should be used as default value. If a greater level of occupancy is expected add 4 l/s per occupant.

[g] Total extract rate should be al least the whole dwelling ventilation rate

[h] Bath room and utility room

[i] For sanitary accommodation

[j] For France, no dif ference between bedrooms and living rooms apply

3.3. Computational Simulation of energy demand due to ventilation in a standard dwelling for the countries under study

3.3.1. Dwelling description and parameters of the model

The dwelling (nZEB_RD) is described on Chapter 2 (2.3.3.1).

The input parameters considered in the model and that remain constant in all the simulations are listed below. They remained unchanged in all the simulations, even if the requirements in the regulations of each country vary. The objective is to evaluate only the impact of the norms and standards regarding ventilation in dwellings as described in the first part of this chapter. The input parameters unchanged in all the simulations are as follows:

• The dwelling occupation and its associated thermal loads. These are detailed in section 3.3.1.1.

• The infiltration due to opening windows is as required by Spanish law [9]. Opening windows occurs during summer months (July to September) between 1 and 8 hours, inclusive. It is assumed that the living spaces have air infiltration caused by opening windows of 4 air changes per hour.

• The set temperature is the same for all simulations although these values also differ depending on the country regulations. The simulations were performed with a room temperature set at 21°C for heating and 25°C for cooling. These temperatures meet all the requirements of the international standards analyzed [109].

• Temperatures for adjacent areas follow Spanish legislation [9]: for adjacent homes 24ºC in summer and 18ºC in winter and unheated public areas 26ºC in summer and 12ºC in winter.

The input parameters of the model which vary depending on the country where the dwelling is located and its current regulations are as follows:

• The transmittances of the envelope are those required in the regulations depending on the climatic zone of the country where the dwelling is located. The values are shown in Table 3.3.

Table 3.3. Average envelope transmittance limit values depending on climatic zone.

Table 3.3. Average envelope transmittance limit values depending on climatic zone.

	Average transmittance limit depending on the location of the building enclosure (W/(m2K))																	
Location	**SPAIN**					**GERMANY**	**UK**	**FRANCE**		**PASSIVHAUS**		**USA**						
Norm	*DB-HE1*					*EnEV 2009*	*Approved Document L1A*	*Ordre 24 mai de 2006*		*Provides different values for Central & North of Europe and Mediterranean locations.*		*ASHRAE 90.1-2013*						
Climatic zone	A	B	C	D	E	--	--	H3	H1-H2	CENT&NORTH	MEDIT.	1	2	3	4	5	6	7-8
External Walls	0.94	0.82	0.73	0.66	0.57	0.20	0.18	0.40	0.36	0.15	0.34	0.86	0.67	0.59	0.51	0.45	0.40	0.40
Floors	0.53	0.52	0.50	0.49	0.48	0.28	0.13	0.36	0.27	0.15	0.26	1.83	0.49	0.42	0.29	0.29	0.29	0.24
Roofs	0.50	0.45	0.41	0.38	0.35	0.20	0.13	0.25	0.20	0.15	0.26	0.15	0.15	0.15	0.12	0.12	0.12	0.10
Windows/ doors	4.10	3.25	2.48	2.48	2.48	1.30	1.40	2.10	1.80	0.80	1.40	2.84	2.27	1.99	1.99	1.81	1.81	1.81

• The ventilation flow rate and strategy follows the regulations. In some cases, the ventilation flow rate is affected by occupation of the dwelling. Occupation profiles are detailed in section 3.1.2.

• The model uses the climatic data of the city in which it is located for calculating energy demands. Details can be found in section 3.3.2.

The simulations provide instant energy demand for heating and cooling throughout the simulation period considered (1 year) including the energy required to heat the ventilation air during the winter months. In the results tables (Table 3.8 and Table 3.9), the energy demand required for cooling the ventilation air during the summer season is not included because this is negligible compared to the overall demand throughout the year. According to the Savings and Energy Efficiency Plan (Plan de Ahorro y Eficiencia Energética PAEE 2012-2020) [110] in Spain, heating represents 41.7% of the total energy demand in a residential building whereas cooling represents only 0.4%.

3.3.1.1. Internal loads

The internal loads generated by occupancy, lighting and the use of equipment taken into account in the model are those defined in DB HE1 of the Spanish legislation [9].

In the case of sensible and latent loads due to occupation, the nominal load is calculated by considering three people in the house, with a heat generation equivalent to being seated in a restaurant according to ISO 7730: 2005 [111]. This nominal load is reduced by a factor of occupancy listed in Table 3.4.

For internal sources, a load of 5 W/m^2 has been considered multiplied by a reduction coefficient depending on the time of day, also indicated in Table 3.4.

Table 3.4. Reduction coefficients of internal loads applied in the model depending on the time of day.

		TIME OF DAY			
		1-7	**7-15**	**15-23**	**23-24**
Sensible & Latent Loads	Working day	1.00	0.25	0.50	1.00
	Weekend	1.00	1.00	1.00	1.00
Lighting	Every day	0.09	0.26	0.26	0.44
Equipment and devices	Every day	0.09	0.26	0.26	0.44

3.3.1.2. Flow and ventilation strategies.

Ventilation air rates included in the model are shown in Table 3.5.

For countries with intermittent ventilation flow rates, the values in the table are the maximum rates. To simulate ventilation strategies, two occupancy calendars have been defined with reduction coefficients depending on the day of the week and the time of the day.

Germany is the only country which includes in its regulations a strategy depending on the occupation. Therefore, the first calendar is based on the strategy recommended in that legislation (called Occupational Germany). The second gathers the recommendations of European standard EN 15251: 2007 (called Occupational Europe).

Table 3.5.Ventilation flow rates included in the model according to the regulations of each country.

COUNTRY/STATE		USA	EUROPE	SPAIN	GERMANY	UK	FRANCE	PASSIVHAUS
Norm/Standard		ASHRAE Standard 62-1-2013	UNE EN 15252	DB HS3	DIN18017	Approved Doc. F Ventilation 2010	Arrêté du 24 Mars 1982	Standard Passivhaus
ROOM	Area (m^2)[a]	Q (l/s)	Q Max (l/s)	Q (l/s)	Q Max (l/s)	Q (l/s)	Q Max (l/s)	Q Max (l/s)
Kitchen	9.18	25.7	26.6	18.2	25.0	13.5	33.4	17.6
Toilet	3.40	12.5	19.5	14.9	15.7	8.3	8.2	13.2
Bathroom	3.00	12.5	13.0	14.9	15.7	8.3	4.1	13.2
Bedroom 1	12.16	10.6	12.4	10.1	11.9	6.3	9.6	9.2
Bedroom 2	12.00	10.6	12.4	10.1	11.9	6.3	9.6	9.2
Bedroom 3	11.27	10.6	12.4	10.1	11.9	6.3	9.6	9.2
Living room	22.68	18.8	21.8	17.7	20.8	11.1	16.9	16.3
Whole dwelling		50.7	59.0	48.0	56.4	30.0	45.8	44.0
Type of ventilation		Continuous	Intermittent: Occupational Europe	Continuous	Intermittent: Occupational Germany	Continuous	Intermittent: Occupational Germany	Intermittent: Occupational Europe
Qv TOTAL (m^3/day)		4380	2908 (wd) 2591 (we)	4147	2008 (wd) 2617 (we)	2592	1633 (wd) 2128 (we)	2168 (wd) 1932 (we)

[a] Corridor area 7.56 m^2

wd: working day

we: weekend

The coefficients in the two occupation profiles are shown in Table 3.6.

Table 3.6.Coefficients for the two occupation profiles defined.

		TIME OF DAY									
		0-7	**7-8**	**8-9**	**9-10**	**10-13**	**13-15**	**15-18**	**18-20**	**20-22**	**22-24**
OCCUPATIONAL GERMANY	Working day	0.50	0.50	0.50	0.20	0.20	0.50	0.20	0.50	0.50	0.50
	Weekend	0.50	0.50	0.50	0.50	0.20	0.50	0.20	0.20	1.00	1.00
OCCUPATIONAL EUROPE	Working day	0.50	1.00	1.00	0.17	0.17	1.00	0.17	1.00	1.00	0.50
	Weekend	0.50	0.50	1.00	1.00	0.17	1.00	0.17	0.17	1.00	0.17

For the definition of the reduction coefficients in Occupational Germany, the values are those prescribed in DIN1946-6 [102]. The norm specifies that the ventilation flow rate should be between 0.5 and 1 ACH, depending on the use and the load. Furthermore, in the case of the existence of a flow regulator in the dwelling, the fan can operate at four speeds according to the reduction coefficients below:

1) Ventilation for protection against humidity: 0.2 ACH (11.3 l/s for the simulated dwelling nZEB_RD).
2) Reduced ventilation: 0.2 ACH (11.3 l/s for the simulated dwelling).
3) Nominal ventilation: People at home: 0.5 ACH (29.5 l/s for the simulated dwelling nZEB_RD).
4) Intensive ventilation: Guests at home ACH (56.4 l/s for the simulated dwelling nZEB_RD).

The French regulation requires a ventilation flow rate of 45.8 l/s for the simulated dwelling in the case of not having control devices. However, these flows can be reduced to 25.0 l/s if the housing has individual control devices (for every room) and down to 5.6 l/s in the case of having mechanical ventilation devices with automatic modulation. The French legislation does not refer to any ventilation strategy based on occupation. Due to the large number of possibilities and in order not to create distortion in the results, the Occupational German calendar has also been applied in the simulations at French locations. This calendar's coefficient resulted in an average flow rate of 20.1 l/s, which largely meets the French legislation.

English law requires a flow rate of 29 l/s for continuous ventilation and a minimum flow rate of 60 l/s for intermittent operation. The simulations were performed with continuous ventilation since the regulation does not recommend a strategy to follow in case of intermittent ventilation. Furthermore, the mean reduction coefficients for the Occupational Germany calendar are 0.41 for working days and 0.54 for weekends. This implies that both strategies with continuous or intermittent flow would give similar results.

In the case of Spain, continuous ventilation has been used because this is required by its own regulations. Continuous ventilation has also been chosen for the USA because the American legislation does not indicate or recommend strategies. Besides, as with the

English regulations, for intermittent flow ventilation the flow rates are doubled. Thus, implementing reduction coefficients from the Occupational Germany calendar would give similar results.

The second calendar includes the recommended strategy of the European standards, based on the recommended minimum flow for unoccupied hours where the air flow rate should range between 0.05 l/sm^2 and 0.1 l/sm^2. A coefficient of 0.5 for sleeping hours has also been considered. This calendar was used to perform the simulations with the Passivhaus-recommended transmittances and air flows for all the cities studied.

3.3.2. Climate data.

Representative cities from each of the climatic zones defined in the countries surveyed have been selected. Table 3.7 lists the cities selected in each country for performing the simulations. The climatic zones defined in each country are also detailed.

Table 3.7.Representative cities from each of the climatic zones defined in the countries surveyed.

Country/ State	Climatic Zone	City	Country/ State	Climatic Zone	City
SPAIN	A4	Almería	**FRANCE**	H3	Nice
	A3	Málaga		H2C	Bordeaux
	B4	Sevilla		H2B	Nantes
	B3	Valencia		H2A	Brest
	C4	Jaen		H1C	Lyon
	C3	Granada		H1B	Strasbourg
	C2	Barcelona		H1A	Paris
	C1	Santander	**USA**	8	Bethel (AK)
	D3	Madrid		7	Juneau (AK)
	D2	Segovia		6A	Brookings (SD)
	D1	Vitoria		5A	Oakland (MI)
	E1	Burgos		5B	Denver (CO)
UK	--	Belfast		4A	Baltimore (MD)
	--	London		3B	Los Angeles (CA)
GERMANY	--	Munich		3C	San Francisco (CA)
	--	Berlin		2A	Houston (TX)
				1A	Miami (FL)

3.3.2.1. USA.

The ASHRAE 90.2-2013 standard divides the American territory into three geographical zones based on the humidity level: A-Moist, B-Dry and C-Marine. It also distinguishes 8 geographical areas based on the severity of the winter climate from 1 (mild climate) to 8 (the coldest). A total of 16 climatic zones are distinguished in the USA. 8 cities were selected for the study, one for each winter climate zone.

The climate files for the simulations in American cities are in TMY3 format (Typical Meteorological Year 3) [112].

3.3.2.2. European climatic zones

In Spain, the Technical Building Code (CTE) in its Basic Document HE1 [9] distinguishes five geographical areas depending on the severity of the climate in winter (from lowest to highest: A, B, C, D and E) and four geographical areas depending on the climate severity in summer (from lowest to highest: 1, 2, 3 and 4). For each Spanish climate zone a letter indicates the severity of the winter climate and a number the severity of the summer climate. A total of 12 climatic zones are distinguished in the Spanish mainland. A representative city from each climatic zone has been selected for the study.

The climate files for simulations in the Spanish cities are in SWEC format (Spanish Weather for Energy Calculations) [113].

Germany and the UK do not distinguish climate zones. The energy requirements and associated parameters are the same throughout these countries. Two cities in each country have been selected.

In France, the regulation divides the country into three geographical areas according to the climatic severity in winter (from lowest to highest: H3, H2 and H1) and four geographical areas according the climatic severity in summer (from lowest to highest: a, b, c and d). A total of 8 climatic zones are distinguished in France. Seven representative French cities have been selected.

The climate files for simulations in Germany, the UK and France are in IWEC format (International Weather for Energy Calculations) [114].

3.3.3. Output parameters.

TRNSYS takes the heat balance for each thermal zone. The model calculates the energy demand for heating and cooling for a period of one year. In addition, the percentage of this demand due to ventilation is obtained. The energy balance for each room and the whole dwelling is governed by the following equation:

$$\dot{U}_{AIR} = Q_{HEAT} - Q_{COOL} + Q_{INF} + Q_{VENT} + Q_{COUP} + Q_{TRANS} + Q_{GINT} + Q_{SOL} + Q_{SOLAIR} \quad (3.1)$$

Where:

$\dot{U}_{AIR}$ Change of internal energy in the zone (KJ/h)

Q_{HEAT} Power of heating

Q_{COOL} Power of cooling

Q_{INF} Infiltrations gains

Q_{VENT} Ventilation gains (negative value for ventilation gains indicates losses due to ventilation).

Q_{COUP} Coupling gains

Q_{TRANS} Transmission into the surface

Q_{GINT} Internal gains (convective and radiative)

Q_{SOL} Absorbed solar gains on all inside surfaces of zones

Q_{SOLAIR} Convective energy gain of zone due to solar radiation transmitted through external windows which is transformed immediately into a convective heat flow to internal air.

Negative values indicate losses instead of gains.

3.4. Results

3.4.1. Results according to country regulations

Table 3.8 shows the results of the energy consumption in the selected cities.

In Spain, the heating demand due to ventilation varies between 40% and 51 %, being very similar in the different climatic zones. In contrast, the cooling demand in the hottest zones, such as Almeria, can be double that of the cooler zones, such as Burgos.

The ventilation losses in Barcelona are more than double those of Nice due to the Spanish regulations that require continuous ventilation while the French regulations allow discontinuous ventilation. Thus, in spite of having similar maximum ventilation flows, - 48 l/s for Spain vs. 45.8 l/s for France-, the daily air volume entering into the house is 4147 m3 in Barcelona and 1744 m^3 in Nice. The ratio of energy consumption due to ventilation and the total energy consumption is very close in both cities, but the total energy demands are very different because the wall transmittance is greater in Spain than in France.

A comparison of the results obtained for towns with colder climates, Strasbourg and Munich, shows different values for the ventilation losses. The explanation is that, although an identical occupancy profile is applied to both cities, the maximum ventilation flow is greater in the German town (56.4 l/s vs 45.8 l/s). Notwithstanding, the heating demand is similar in both towns due to the greater restrictions on the wall transmittance in Germany than in France. The results for heating demand due to ventilation cannot therefore be directly compared.

In LA city, the ventilation losses of the dwelling are greater than its heating demand because of its high solar gains (eq. 1). If there were no ventilation losses, a heating system would not be necessary. For example, reducing the ventilation flow by half reduces the heating demand to 11.7 kWh/m2·year. Removing the ventilation system reduces the heating demand to 3.8 kWh/m2·year and the heating system would only have to work in the months of December and January.

Table 3.8.Heating and cooling demands according to country regulations.

		ENERGY DEMAND (KWh/m²year)				
Country/ State	**Climatic zone/ City**	**QHEAT**	**QCOOL**	**QTOTAL**	**QVENT**	**%**
SPAIN	A4_Almeria	58.76	11.26	**70.02**	-25.76	44%
	A3_Aalaga	66.23	7.22	**73.45**	-27.48	41%
	B4_Sevilla	65.56	14.16	**79.72**	-29.59	45%
	B3_Valencia	79.90	3.89	**83.79**	-32.89	41%
	C4_Jaen	72.80	14.48	**87.28**	-37.38	51%
	C3_Granada	92.49	3.13	**95.62**	-44.07	48%
	C2_Barcelona	80.08	1.37	**81.44**	-38.84	48%
	C1_Santander	95.02	0.00	**95.02**	-38.84	41%
	D3_Madrid	101.18	2.58	**103.76**	-46.33	46%
	D2_Segovia	133.85	0.05	**133.91**	-56.21	42%
	D1_Vitoria	136.42	0.05	**136.48**	-55.12	40%
	E1_Burgos	145.04	0.00	**145.04**	-62.25	43%
FRANCE	H3_Nice	40.04	2.73	**42.77**	-16.12	40%
	H2C_Bordeaux	45.89	0.31	**46.20**	-19.53	43%
	H2B_Nantes	43.80	0.31	**44.11**	-21.13	48%
	H2A_Brest	50.32	0.00	**50.32**	-20.72	41%
	H1C_Lyon	57.94	1.81	**59.74**	-23.12	40%
	H1B_Strasbourg	67.67	0.46	**68.13**	-25.25	37%
	H1A_Paris	59.91	0.24	**60.15**	-23.31	39%
UK	Belfast	53.44	0.00	**53.44**	-38.19	71%
	London	60.14	0.05	**60.18**	-36.50	61%
GERMANY	Munich	67.14	2.46	**69.60**	-36.95	55%
	Berlin	62.93	4.58	**67.52**	-32.67	52%
USA	8_Bethel_AK	216.26	0.00	**216.26**	-117.54	-54%
	7_Juneau_AK	152.86	0.00	**152.86**	-84.97	56%
	6A_Brookings_SD	149.63	1.53	**151.16**	-89.13	60%
	5A_Oakland_MI	122.53	3.53	**126.06**	-73.98	60%
	5B_Denver_CO	100.97	1.76	**102.73**	-71.97	71%
	4A_Baltimore_MD	83.43	6.91	**90.35**	-59.65	71%
	3B_Los Angeles_CA	21.43	0.00	**21.44**	-29.35	137%
	3C_San Francisco_CA	44.43	0.00	**44.43**	-39.80	90%
	2A_Houston_TX	31.41	25.88	**57.28**	-27.24	87%
	1A_Miami_FL	6.99	36.73	**43.71**	-3.01	43%

3.4.2. Results according to Passivhaus transmittances and optimized ventilation flows

To compare the ventilation losses in the cities under study and to deduce the ventilation strategies required, simulations have been undertaken in two steps:

1. First, the transmittances are given the values according to the Passivhaus standards, while keeping the ventilation levels in line with each country's regulations to avoid the interpretation distortions observed in the previous section. The Passivhaus transmittances have been introduced in the following ways:
   For Spain, climatic zones from A to D.
   For France, climatic zone H3.
   For the USA, climatic zones from 1 to 3.
   For the other countries, the transmittance values are those corresponding to the Passivhaus standard for the centre and north of Europe (Table 3.3).
2. In a second step, besides applying the same Passivhaus values for the transmittances, the same values for the ventilation flows have been used for every city according to Passivhaus recommendations and to the flow regulation strategy recommended by the European standard EN 15252 explained in section 3.1.2.

The following conclusions can be drawn from the results, shown in Table 3.9.

If the transmittance values are reduced, resulting in a better-isolated dwelling, the ventilation losses represent almost its total thermal loads. It is more efficient to recover the ventilation energy than to increase the thermal isolation. This can be seen by comparing, in Table 3.8 and Table 3.9, the results of the towns belonging to the UK because of its very demanding isolation regulations.

By comparing again the cities of Barcelona and Nice, -which have very similar Mediterranean climates and whose heating demands are very similar (14.5 % less for Barcelona) if the same ventilation flows and wall transmittances are used (part 2 in Table 3.9) - the initial results showed a heating demand for Barcelona twice that of Nice, due only to the differences in French and Spanish ventilation strategies (30 % greater for Spain).

In the Spanish case, the results obtained when using the Passivhaus transmittance values indicate that the winter heating demand due only to ventilation surpasses the limit allowed by the standard DB HE1 (Table 3.10).

In the colder towns where the more relevant parameters have been optimized (Table 3.9, part 2), in spite of assuming no infiltrations by the building closures, the values obtained are very far from those required by the Passivhaus standard (15 kWh/m^{2}year, Figure 3.1)) and, as a consequence, by the nZEB model.

Table 3.9. Heating and cooling demands according to Passivhaus transmittances and optimized ventilation flows.

			ENERGY DEMAND PASSIVHAUS TRANSMITANCES (KWh/m^{2}year)					ENERGY DEMAND PASSIVHAUS TRANSMITANCES & VENTILATION FLOW RATES OCCUPATIONAL (KWh/m^{2}year)				
COUNTRY/ STATE	CLIMATIC ZONE/CITY	PASSIVHAUS	QHEATING	QCOOLING	QTOTAL	QVENT	QVENT %	QHEATING	QCOOLING	QTOTAL	QVENT	QVENT %
SPAIN	A4_ALMERIA	PH MEDIT	21.15	8.84	**29.99**	-27.60	130%	12.13	8.22	**20.35**	-15.59	129%
	A3_MALAGA		24.49	5.74	**30.24**	-29.08	119%	14.22	5.41	**19.63**	-16.17	114%
	B4_SEVILLA		27.89	10.20	**38.10**	-31.07	111%	16.75	8.74	**25.49**	-17.21	103%
	B3_VALENCIA		34.37	3.52	**37.89**	-33.82	98%	20.90	3.45	**24.35**	-18.49	88%
	C4_JAEN		41.07	10.70	**51.77**	-37.72	92%	25.46	9.26	**34.73**	-20.41	80%
	C3_GRANADA		53.27	1.89	**55.16**	-44.03	83%	33.64	1.42	**35.06**	-23.49	70%
	C2_BARCELONA		45.15	1.05	**46.20**	-38.88	86%	28.36	1.21	**29.57**	-20.94	74%
	C1_SANTANDER		54.74	0.00	**54.74**	-38.69	71%	36.96	0.01	**36.97**	-20.50	55%
	D3_MADRID		63.35	1.81	**65.16**	-51.02	81%	42.23	1.60	**43.83**	-24.40	58%
	D2_SEGOVIA		85.85	0.02	**85.88**	-55.77	65%	59.41	0.06	**59.47**	-29.33	49%
	D1_VITORIA		87.85	0.00	**87.85**	-54.66	62%	61.91	0.00	**61.91**	-28.75	46%
	E1_BURGOS	PH NORTH	70.09	0.00	**70.09**	-61.93	88%	41.15	0.00	**41.15**	-32.75	80%
FRANCE	H3_NICE	PH MEDIT	26.35	8.63	**34.98**	-16.62	63%	30.66	3.92	**34.59**	-21.34	70%
	H2C_BORDEAUX	PH NORTH	20.44	0.41	**20.85**	-20.30	99%	25.45	0.33	**25.78**	-25.94	102%
	H2B_NANTES		18.70	0.85	**19.55**	-22.41	120%	23.75	0.61	**24.35**	-28.60	120%
	H2A_BREST		24.12	0.14	**24.26**	-21.75	90%	29.42	0.06	**29.48**	-28.04	95%
	H1C_LYON		29.38	2.27	**31.65**	-24.39	83%	35.13	2.03	**37.16**	-31.27	89%
	H1B_STRASBOURG		34.76	1.06	**35.83**	-26.10	75%	41.61	0.84	**42.44**	-33.72	81%
	H1A_PARIS		26.41	3.95	**30.36**	-16.57	63%	36.08	0.45	**36.53**	-31.36	87%
UK	BELFAST	PH NORTH	46.87	0.00	**46.87**	-38.26	82%	41.55	0.01	**41.56**	-32.37	78%
	LONDON		53.44	0.10	**53.54**	-36.48	68%	48.41	0.16	**48.57**	-30.97	64%
GERMANY	MUNICH	PH NORTH	48.24	0.39	**48.62**	-36.95	77%	50.46	0.35	**50.81**	-39.26	78%
	BERLIN		46.04	1.69	**47.73**	-32.69	71%	48.06	1.68	**49.74**	-34.80	72%
USA	8_BETHEL_AK	PH NORTH	160.71	0.00	**160.71**	-117.48	-73%	101.20	0.00	**101.20**	-58.29	-58%
	7_JUNEAU_AK		113.29	0.00	**113.29**	-84.78	75%	71.10	0.00	**71.10**	-42.43	60%
	6A_BROOKINGS_SD		106.35	0.88	**107.23**	-88.80	84%	63.21	0.78	**63.99**	-44.88	71%
	5A_OAKLAND_MI		84.86	2.37	**87.22**	-73.72	87%	48.70	2.12	**50.82**	-37.14	76%
	5B_DENVER_CO		68.79	0.82	**69.61**	-71.58	104%	36.09	0.65	**36.74**	-37.24	103%
	4A_BALTIMORE_MD		56.15	6.04	**62.18**	-59.56	106%	29.09	5.58	**34.67**	-30.88	106%
	3B_LOS ANGELES_CA	PH MEDIT	17.78	0.00	**17.78**	-28.50	160%	8.82	0.05	**8.87**	-15.84	180%
	3C_SAN FRANCISCO_CA		39.01	0.00	**39.01**	-39.15	100%	21.83	0.00	**21.83**	-20.32	93%
	2A_HOUSTON_TX		22.71	24.97	**47.68**	-27.65	122%	12.92	21.72	**34.64**	-15.30	118%
	1A_MIAMI_FL		0.93	31.76	**32.69**	-13.58	1464%	0.21	28.49	**28.70**	-8.67	4127%

Table 3.10.Heating and cooling demands allowed by Spanish regulations depending on the climatic zone for the simulated dwelling.

Winter Climate Zone	Heating demand (KWh/m^2year)
A/B	15.0
C	32.3
D	51.7
E	77.0
Winter Climate Zone	**Cooling demand (KWh/m^2year)**
1/2/3	15.0
4	20.0

As mentioned, all the simulations were performed with a room temperature set at 21°C for heating and 25°C for cooling. Moreover, finally additional simulations have been done with a temperature set at 20ºC for heating, value according to the UK, Germany and USA standards [109]. The results obtained for Jaen, as a representative warm climate city, are: 19.57 kWh/m^2year for heating demand (vs 25.46 kWh/m^2year) and -18.89 kWh/m^2year for heating demand due to ventilation (vs -20.41 kWh/m^2year). The results obtained for Berlin, as a representative central European city, are: 41.91 kWh/m^2year for heating demand (vs 48.06 kWh/m^2year) and -32.93 kWh/m^2year for heating demand due to ventilation (vs -34.80 kWh/m^2year). The new energy demand obtained do not reach the objetive of nZEB energy demand either.

As mentioned, all the simulations were performed with a room temperature set at 21°C for heating and 25°C for cooling. Moreover, finally additional simulations have been done with a temperature set at 20ºC for heating, value according to the UK, Germany and USA standards [109]. The results obtained for Jaen, as a representative warm climate city, are: 19.57 kWh/m^2year for heating demand (vs 25.46 kWh/m^2year) and -18.89 kWh/m^2year for heating demand due to ventilation (vs -20.41 kWh/m^2year). The results obtained for Berlin, as a representative central European city, are: 41.91 kWh/m^2year for heating demand (vs 48.06 kWh/m^2year) and -32.93 kWh/m^2year for heating demand due to ventilation (vs -34.80 kWh/m^2year). The new energy demand obtained do not reach the objetive of nZEB energy demand either.

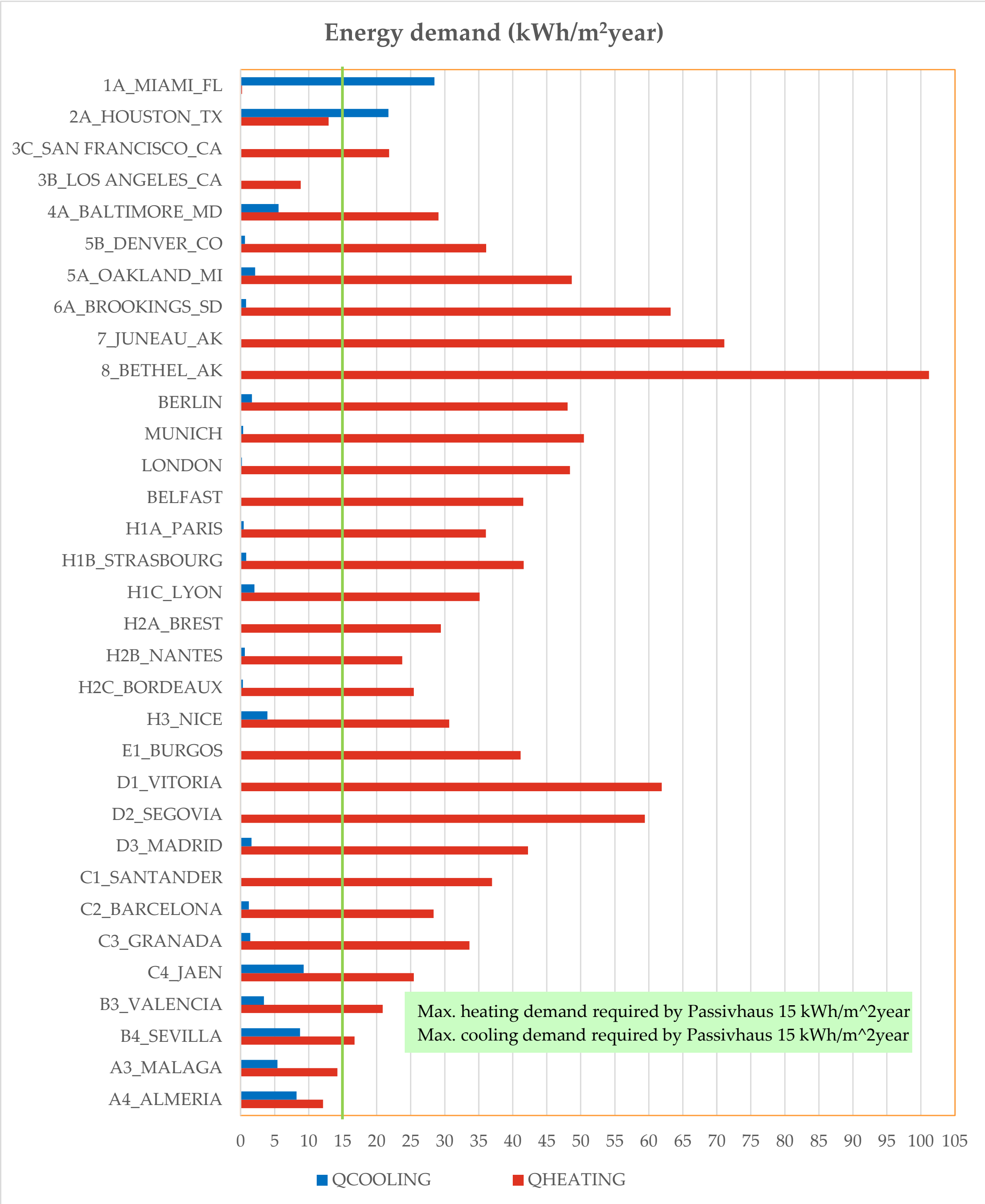


Figure 3.1.Heating and cooling demands compared to Passivhaus requirements.

3.5. Conclusions.

All over the world, national regulations require a steady reduction in thermal transmittance values, which involves ever-increasing airtightness in buildings. Consequently, the regulations recommend controlled ventilation systems in houses, while Spanish regulations specify continuous ventilation 24 hours a day.

In this research, the ventilation flows and strategies set out in the regulations of the USA, Germany, the UK, France and Spain have been compared, together with the Passivhaus standard. It is concluded that the maximum ventilation flows are similar but the control procedures are very different. The study also analyzes whether the requirements of nZEB for heating and cooling energy demands can be achieved with current ventilation strategies.

The results suggest that in cooler climates these limits cannot be achieved without heat recovery. In milder climates, if the transmittance values are reduced, the ventilation losses can almost be the equivalent of the entire heating demand of a dwelling. Buildings located in the warmest places, such as the south of Spain and parts of the USA, are the only ones capable of fulfilling the heating and cooling demands of nZEB without recovering the waste heat coming from ventilation.

Chapter 4

Evaluation of the potential Energy Recovery for ventilation air in dwellings in the South of Europe.

4. Evaluation of the potential Energy Recovery for ventilation air in dwellings in the South of Europe.

This chapter is based on the following published paper:

S. Guillén-Lambea, B. Rodríguez-Soria, J.M. Marín, *"Evaluation of the potential Energy Recovery for ventilation air in dwellings in the South of Europe* Energy Build. 128 (2016) 384-393. doi:10.1016/j.enbuild.2016.07.011.

Abstract

Heat recovery in ventilation systems for dwellings in cold and mild climates is needed in order to meet the requirements of nearly zero-energy buildings (nZEB) in terms of energy demand. These requirements can be met without heat recovery systems in only a few European areas with warm climates.

The energy recovery potential for warm Mediterranean cities located in the south of Europe has not been investigated in sufficient depth.

This article proposes a new methodology to analyze the climate data using the psychrometric chart to determine in which cases it is of interest to recover heat only or to recover the latent energy.

The study covers several cities in southern Europe and the results are compared with northern European cities in terms of recovery strategies.

The result demonstrates the necessity to establish different energy recovery strategies in cities located in similar latitudes. The appropriate strategy can be established with the climate data analysis methodology proposed. In some cities, the convenience of recovering latent energy to meet nZEB energy requirements has been demonstrated.

Keywords

Ventilation; South of Europe climatic area; Residential dwellings, Energy recovery strategies

4.1. Introduction

Several works have demonstrated that heat recovery is a necessity for severe climatic conditions (in north and central Europe). Fehrm et al. [115] conclude that heat recovery can reduce the primary energy consumption by a minimum of 20% for Germany and Sweden.

The current heat exchangers mounted on ventilation systems have a sensible efficiency in the range 65-95% (depending on the airflow rate and pressure drop of the system). Passivhaus requires a minimum of 75% for heat exchanger efficiency [27] for nominal working conditions.

With the aim of reducing the air-conditioning demand even further, energy recovery systems which recover not only the sensible energy also the latent energy have been studied in depth during recent decades. This is mainly because, depending on the climate conditions, the latent load constitutes a large fraction of the total thermal load in the HVAC system [116]. In one research article [117], an energy analysis shows that enthalpy heat exchangers (latent and sensible) reduced the total energy consumption by 8% compared to conventional air conditioning systems in tropical climates and by 4% in a moderate climate. In a study of a building in four American cities, Rasouli et al. [38] demonstrate that by using energy recovery the reduction in the annual heating energy consumption could reach 40%, which is 5% higher than the heat recovery, and estimate a 20% reduction in the cooling energy consumption if the ERV is well controlled.

Current heat exchangers for ventilation systems have a latent effectiveness in the range 55-60% [44] which is lower than the effectiveness of sensible heat exchangers.

The selection of the optimal recovery system is further complicated because the use of membrane-based materials to transfer both moisture and heat simultaneously could have the disadvantage of lower thermal conductivity compared to the well-known plate heat exchangers.

The present study focuses on the south of Europe, where warm and high humidity climate conditions could justify the use of energy recovery systems rather than heat-only recovery systems.

For this purpose, an in-depth analysis of the climatic data for cities located in humid areas (all around the Mediterranean coast) has been carried out. From this analysis, different psychrometric chart regions have been defined in order to evaluate the maximum energy recovery from ventilation systems and, finally, an optimized strategy in terms of sensible heat recovery or latent energy recovery is proposed.

The objective of this research is to indicate the advisability of choosing a heat or an energy recovery device depending on the potential energy to be recovered, as well as to identify some critical areas where the latent and sensible energy should be recovered to comply with the Spanish, European and nZEB regulations concerning the energy demand in buildings.

4.2. Background: Sensible and latent loads due to ventilation air flow.

The air flow supply to a dwelling at the outside temperature and humidity is equal to the air flow leaving the dwelling under indoor conditions, in cases where the ventilation system is balanced. This thermal load due to the ventilation air flow is an important energy demand (heating or cooling demand depending on the ambient conditions). The total power has to be added to the ventilation air flow for the air conditioning system can be calculated using Equation (4.1).

$$\dot{Q} = \dot{m}_{vent} \cdot (h_{out} - h_{in}) \tag{4.1}$$

Where

$\dot{Q}$ is the total energy demand due to the ventilation air (kW)

$\dot{m}_{ven}$ is the mass flow of ventilation dry air (kg $_{\text{dry-air}}$ /s)

h_{out} is the enthalpy of the outside air (kJ/kg $_{\text{dry-air}}$)

h_{in} is the enthalpy of the internal air (kJ/ kg $_{\text{dry-air}}$)

From the enthalpy definition Equation (4. 2)

$$h = C_{pair} \cdot T + w(C_f + C_{pv}T) \tag{4.2}$$

Where

C_{pair} is the dry air specific heat capacity at constant pressure (1.006 kJ/kg·K)

C_f is the water heat vaporization at 0ºC (2501 kJ/kg)

C_{pv} is the water vapor heat capacity (1.86 kJ/kg·K)

Substituting (4. 2) in (4.1) gives Equation (4.3)

$$\dot{Q} = \dot{m}_{vent} \cdot \left[(C_{pair} + C_{pv} \cdot w_{in})(T_{out} - T_{in}) + (C_f + C_{pv}T_{out})(w_{out} - w_{in}) \right] \tag{4.3}$$

Where

T_{out} is the outside air temperature (ºC)

T_{in} is the inside air temperature (ºC)

w_{out} is the outside air specific humidity (kg/kg$_{\text{dry-air}}$)

w_{in} is the inside air specific humidity (kg/kg$_{\text{dry-air}}$)

There is a sensible thermal load due to the temperature change and a latent thermal load due to the change of humidity. These values correspond to the two terms in Equation (4.3), resulting in Equation (4.4) and Equation (4.5), respectively.

$$\dot{Q}_s = \dot{m}_{vent} \cdot (C_{pair} + C_{pv} \cdot w_{in})(T_{out} - T_{in}) \cong \dot{m}_{vent} \cdot C_{pair}(T_{out} - T_{in}) \tag{4.4}$$

$$\dot{Q}_l = \dot{m}_{sup} \cdot (C_f + C_{pv}T_{out})(w_{out} - w_{in}) \cong \dot{m}_{vent} \cdot C_f(w_{out} - w_{in}) \tag{4.5}$$

Where

$\dot{Q}_s$ is the sensible energy demand due to the ventilation air (kW)

$\dot{Q}_l$ is the latent energy demand due to the ventilation air (kW)

4.2.1. Heat Recovery Ventilators (HRV)

The HRV includes in the system a heat exchanger used to heat the outside air before supplying it to the dwelling, transferring the heat from the inside air before expelling it outside. During summer the outside air is cooled by the same process. These heat exchangers only transfer the sensible energy between the two air streams. The energy transferred is the energy recovered by the ventilation air before being supplied to the dwelling.

Heat recovery depends on the heat exchanger sensible efficiency and can be calculated using Equation (4.6)

$$\dot{Q}_{s,rec} = \varepsilon_{sens} \cdot C_{min} \cdot (T_{sup,in} - T_{exh,in}) \quad (4.6)$$

Where

$\dot{Q}_{s,rec}$ is the sensible energy recovered (kW)

C_{min} is the minimum capacitance of the air stream, which is the lesser product of the mass flow rate and specific heat for each of the two streams (supply and exhaust)

$T_{exh,in}$ is the exhaust air temperature at the inlet of the heat exchanger, which is the dwelling temperature (ºC)

$T_{sup,in}$ is the supply air temperature at the inlet of the heat exchanger, which is the outside temperature (ºC)

ε_{sens} is the sensible effectiveness of the heat exchanger (-) defined by Equation (4.7), supposing that $Cmin = C_{sup} = Cexh$

$$\varepsilon_{sens} = \frac{(T_{exh,in} - T_{exh,out})}{(T_{exh,in} - T_{sup,in})} \quad (4.7)$$

Where

$T_{exh,out}$ is the temperature of the exhaust air after passing through the heat exchanger (ºC)

An extensive review of heat exchanger technologies for building applications can be found in the research article [44].

4.2.2. Energy Recovery Ventilators (ERV)

The ERV includes in the system a heat exchanger where an amount of air from the outside crossing the heat exchanger is separated by a permeable membrane from the exhaust air that allows not only heat to transfer from one stream to the other but moisture to transfer as well. Heat recovery depends on the heat exchanger sensible effectiveness and can be calculated using Equation (4.6). The moisture recovery depends on the latent effectiveness which can be calculated using Equation (4.8).

$$\dot{Q}_{l,rec} = \varepsilon_{lat} \cdot G \cdot (w_{sup,in} - w_{exh,in}) \quad (4.8)$$

Where

$\dot{Q}_{l,rec}$ is the latent energy recovered (kW)

$w_{exh,int}$ is the outside air specific humidity ($kg/kg_{dry-air}$)

$w_{sup,in}$ is the inside air specific humidity ($kg/kg_{dry-air}$)

$G \equiv \dot{m}_{vent} C_f$

ε_{lat} is the latent effectiveness of the heat exchanger (-) defined by Equation (4.9).

$$\varepsilon_{lat} = \frac{(w_{exh,in} - w_{exh,out})}{(w_{exh,in} - w_{sup,in})} \quad (4.9)$$

Energy recovery ventilators recover the total energy (sensible+latent) following Equation (4.10).

$$\dot{Q}_{TOT,rec} = \dot{Q}_{s,rec} + \dot{Q}_{l,rec} = \varepsilon_{sens} \cdot \dot{Q}_s + \varepsilon_{lat} \cdot \dot{Q}_l \quad (4.10)$$

The total recovered energy depends on two parameters: the potential energy which can be recovered and the heat exchanger sensible and latent effectiveness. This research focuses on calculating the potential energy to be recovered depending on the climate parameters and proposing an optimized strategy to recover sensible or latent energy, or both, or to by-pass the heat exchanger depending on the climatic data.

The second parameter, which is not investigated in this research, depends on the heat exchanger technology. An extensive review of membrane heat exchanger technologies for air conditioning systems can be found in [45]. Values for the sensible efficiency of current heat exchangers for ventilation systems vary from 65% to 95% depending on the air temperatures and air flow rates. The heat exchanger effectiveness for latent energy is lower, current values being around 55-60% [44].

4.3. Methodology

In this section, firstly the comfort parameters are analyzed and selected due to their high impact on the energy demand. Secondly, a psychrometric chart is divided into regions depending on the ambient air temperature and humidity in order to establish a recovery strategy. Finally, the climate data treatment is presented.

The comfort parameters selected for this study are 20-26ºC for temperature and 30-60% for RH. The selected intervals are very conservative. If the interval is reduced, the potential energy to be recovered will increase.

4.3.1. Analysis of the psychrometric chart

For ventilation systems without energy recovery, the outside air is introduced into the dwelling at the outside conditions. The air temperature and humidity hourly data are available from climate data files. Depending on these values, the outside air is located in different chart regions on the psychrometric chart (Figure 4.1).

The climatic data analyzed are taken from the Meteonorm meteorological database on an hourly basis [118]. As additional information, Table 4.1 shows the monthly mean ambient temperature and relativity humidity for the selected cities.

Depending on the location, the ventilation air energy demand of the air conditioning system will be sensible, latent or both. Under some conditions the air will not need to be conditioned before entering the dwelling. First, the amount of energy required for the ventilation air must be determined. In addition, it is highly advisable to assess the amount of heat, the humidification and the dehumidification energy required in order to decide whether heat recovery will be needed or whether latent energy recovery is also required.

For this purpose, the psychrometric chart has been divided into several regions: A, B, C, D, E, F, G, H, I and J for the analysis of the energy demand due to the ventilation air depending on the air humidity and temperature (Figure 4.1). The regions are defined depending on the comfort parameters selected. Each region corresponds to a different air treatment needed to reach comfort area, depending on whether the air must be heated/cooled or/and humidified/dehumidified.

The psychrometric chart is changing city by city according to altitude or atmospheric pressure. On Figure 4.1 the psychrometric chart is used as a sample, it corresponds to a barometric pressure of 94900Pa and an altitude of 594m (Madrid).

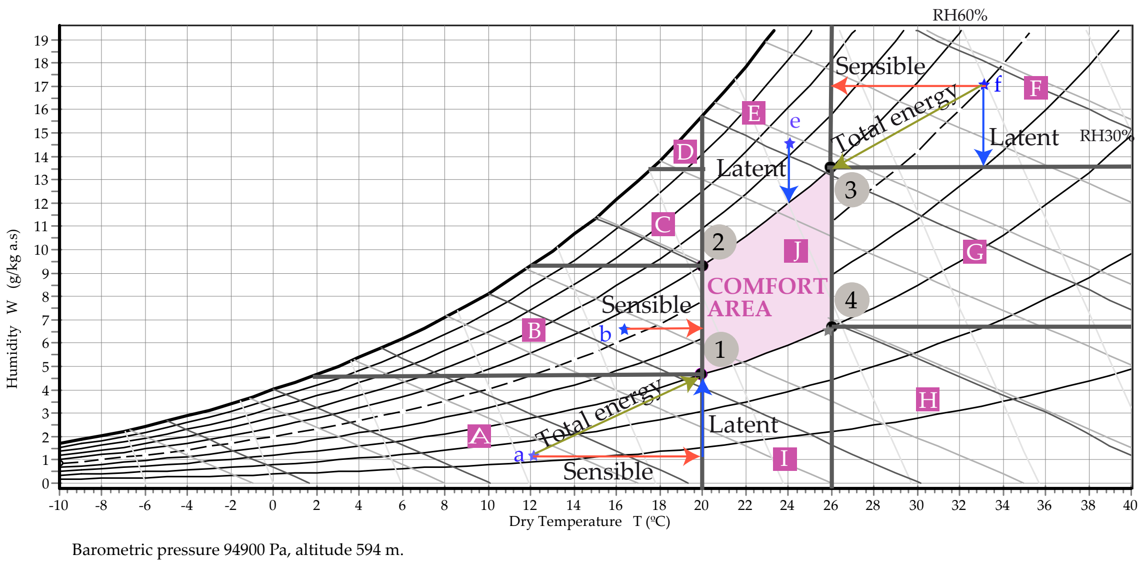


Figure 4.1. Psychrometric chart regions.

Table 4.1. Mean monthly air temperature and mean monthly relative humidity. Meteonorm.

Cities	Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
ALICANTE	T (ºC)	11,6	12,4	13,7	15,7	18,6	22,1	25,1	25,5	23,3	19,2	14,9	12,1	17,9
	HR (%)	68	66	69	63	70	69	69	74	68	74	69	69	69
ALMERIA	T (ºC)	12,5	13,0	14,6	16,1	18,8	22,3	25,4	26,0	24,1	19,9	16,2	13,3	18,5
	HR (%)	75	75	75	72	75	72	69	74	71	77	72	76	74
AVILA	T (ºC)	3,0	5,3	7,5	9,7	13,1	18,2	22,5	21,6	17,6	12,7	7,2	3,7	11,8
	HR (%)	81	70	63	56	59	49	40	44	51	66	73	80	61
BARCELONA	T (ºC)	8,8	9,5	11,1	12,9	15,9	19,7	22,9	23,0	21,0	17,1	12,5	9,7	15,3
	HR (%)	79	77	81	76	82	79	77	82	73	81	73	74	78
BILBAO	T (ºC)	8,6	9,4	10,5	11,8	15,3	18,0	20,2	20,5	19,1	15,9	11,3	9,2	14,2
	HR (%)	75	75	73	70	73	71	74	77	68	72	75	74	73
GERONA	T (ºC)	6,9	8,0	9,9	11,8	15,6	19,7	23,1	22,7	20,1	15,4	10,4	7,7	14,3
	HR (%)	79	74	74	71	74	68	63	68	66	80	76	78	73
LAS PALMAS DE GRAN CANARIA	T (ºC)	17,5	17,6	18,4	18,7	19,9	21,4	23,3	24,1	23,8	22,5	20,4	18,3	20,5
	HR (%)	77	76	72	75	77	77	72	75	76	77	76	82	76
MADRID	T (ºC)	5,5	7,0	9,3	11,6	15,5	20,4	24,3	23,8	20,3	14,5	8,9	5,9	13,9
	HR (%)	76	72	65	66	63	57	50	50	57	68	75	78	65
MALAGA	T (ºC)	12,2	12,8	14,0	15,7	18,8	22,0	24,8	25,3	23,1	19,1	15,1	12,6	18,0
	HR (%)	69	67	70	61	62	61	58	59	60	69	70	73	65
MURCIA	T (ºC)	10,6	11,4	12,6	14,5	17,4	21,0	23,9	24,6	22,7	18,7	14,3	11,3	16,9
	HR (%)	78	78	78	77	75	76	75	76	78	77	78	78	77
PALMA DE MALLORCA	T (ºC)	9,4	10,0	11,1	12,8	16,7	20,6	23,9	24,4	21,7	17,8	13,3	10,6	16,0
	HR (%)	80	78	78	78	75	73	72	74	78	79	79	80	77
SANTA CRUZ DE TENERIFE	T (ºC)	17,9	18,0	18,6	19,2	20,5	22,1	24,5	25,1	24,4	22,9	20,8	18,8	21,1
	HR (%)	67	64	64	63	64	65	60	63	65	68	65	71	65
SEVILLA	T (ºC)	10,7	11,9	14,0	16,0	19,6	23,4	26,8	26,9	24,4	19,5	14,3	11,1	18,2
	HR (%)	73	72	66	67	64	60	55	56	58	65	72	74	65
VALENCIA	T (ºC)	11,0	11,6	13,5	15,2	18,4	21,5	24,4	24,9	22,7	18,8	14,5	11,8	17,4
	HR (%)	67	63	64	60	68	70	70	74	66	69	64	65	67
BERLIN	T (ºC)	-0,4	0,6	4,0	8,4	13,5	16,7	17,9	17,2	13,5	9,3	4,6	1,2	8,9
	HR (%)	82	80	74	67	63	67	67	70	76	81	83	85	75
NICE	T (ºC)	8,7	9,4	10,9	13,2	16,4	19,9	22,9	23,0	20,5	17,0	12,4	9,6	15,3
	HR (%)	66	66	68	72	74	72	71	71	73	73	69	67	70

Depending on the region where the hourly values for the outside air temperature and humidity are on the psychrometric chart, their hourly energy demand should be treated as follows:

<u>REGION A</u>

The outdoor conditions for region A are mostly registered during cool and dry winter days. The outdoor air entering the dwelling through the ventilation system should be heated to at least 20ºC (sensible energy demand from the heating system) and humidified to 30% RH. This air flow (point a, Figure 4.1) should be treated at least to reach point 1.

It is very important to identify whether there is any registered value during the summer in this region, because during the summer season the heating is not working and the ventilation air should be used to cool the dwelling. However, the humidification always needs to be carried out.

REGION B

When the outside air is located in this region during the winter season (point b, Figure 4.1), only sensible heat has to be added to the air in order to reach the low set point temperature. The treated air will reach the comfort area at the comfort humidity, so latent energy is not needed.

For the summer season, no sensible heat has to be added to the air, but if the RH is higher than 60% the air should be dehumidified. The final absolute humidity (w) has to be calculated to obtain the latent energy demand applying Equation (4.5), using Equation (4.11):

$$w(T) =\cdot 0.623 \cdot \frac{RH \cdot P_V(T)}{P_{atm} - RH \cdot P_V(T)} \tag{4.11}$$

where P_{atm} is the atmospheric pressure and P_v (T) is the vapor pressure saturation which can be calculated using the Antoine equation (Equation (4.12)). This is a simple 3-parameter fit to experimental vapor pressures measured over a restricted temperature range:

$$logP = A - \frac{B}{T+C} \qquad \text{(P in bar)} \tag{4.12}$$

Where:

A, B, and C are "Antoine coefficients" that vary from substance to substance [119]. For water and a temperature range of 0ºC to 100ºC these values are A=5.11564; B=1687.537 and C=230.17.

T is the air temperature (ºC).

REGIONS C AND D

The air should be heated and dehumidified before reaching the dwelling in the winter season and only dehumidified in the summer season. The air humidity has to reach point 2 on Figure 4.1 for the winter season but has to reach the 60% RH curve for the summer season. In this case the final absolute humidity (w) has to be calculated depending on the temperature using (4.11).

REGION E

The outside air temperature is located within the comfort interval, therefore only latent energy has to be added to dehumidify the air. The air should reach 60% relative humidity (RH) (point e, Figure 4.1). The final absolute humidity (w) has to be calculated using (4.11) and (4.12).

REGION F

The air should be cooled to 26ºC and dehumidified to 60% RH before reaching the dwelling in the summer season (point f, Figure 4.1). Accordingly, sensible and latent energy has to be added to the ventilation air to reach the comfort area. For winter season, if the humidity is higher than 60% RH, the air should be dehumidified.

REGION G

When the outside air conditions are located in this region, for the summer season, the cooling system has to reduce the air temperature in order to reach the high set point temperature. The cooled air will reach the dwelling at a relative humidity within the comfort area, hence there is no latent energy demand.

REGION H

The registered values for outdoor conditions in the H region are registered during summer days. For warm and humid climates, no points located in this region are expected because such outside air conditions are rare for Mediterranean climates.

The outdoor air entering the dwelling through the ventilation system should be cooled to at least 26ºC and humidified to 30% RH. This air flow should be treated to reach point 4 on Figure 4.1. Latent and sensible energy is required.

REGION I

The outside air has a dry temperature within the comfort interval, so only latent energy has been added to humidify the air. The air should reach 30% relative humidity and the absolute humidity should be calculated using (4.11) and (4.12), in the same way as the points in region E.

REGION J

The points in region J are within the comfort interval, therefore the ventilation air does not need to be treated. If there is an ERV on the ventilation system, the air should by-pass the heat exchanger.

4.3.2. Climate data treatment.

Representative cities from humid and hot zones in the south of Europe and from cold areas in central Europe have been selected for the purposes of comparison. Figure 4.2 shows the cities under study.

The climate data for each city has been classified first depending on the air dry temperature. The temperature range has been divided into intervals of 1ºC. The number of hours registered for each interval has been counted.

For the interval T< -7ºC all the registered data with dry temperatures below -7ºC are counted, and for the interval T>41ºC the registered hours with a temperature above 41ºC are grouped.

The frequency of each interval temperature (n) is the total number of hours for which the air dry temperature is within a range. The frequency has been divided into summer frequency (n_{summer}) and winter frequency (n_{winter}) because the control strategy applied may be different. For example, for the interval 17ºC to 18ºC, there are some registered data during the winter season where the ventilation air should be heated but there are also some data registered during the summer season (cool summer nights or mornings).

Figure 4.2. Representative cities selected

During these hours the ventilation air does not need treatment but must enter the dwelling at ambient conditions (used to cool down the house during the hot Mediterranean summers: free cooling).

The dry temperature for each interval is the arithmetic average of the dry temperatures registered in the corresponding interval (T_{med}). The relative humidity (RH_{med}) and the absolute humidity (w_{abs}) are the arithmetic average of the humidity values registered for each interval.

Figure 4.3 shows the frequencies for the temperature intervals for Alicante (Spain) as an example. The values are represented separately for summer and for winter as the strategy differs. The sections are colored blue for winter and red for summer.

The time value t for equations (4.4) and (4.5) depending on the air conditions of the region on the psychrometric chart are as follows:

- For A region t=n= n_{winter} as n_{summer} =0, because the outside air is not at these conditions during any summer hours.
- For B region, t =n_{winter} for sensible heat (equation 4). No latent energy is demanded during winter. However, during the summer season the air has to be dehumidified in case RH>60%, then t= n_{summer} if RH>60%.
- For C and D regions, t =n_{winter} for sensible heat (equation (4.4)). However, t= n for latent energy (equation (4.5)). The latent energy is calculated separately for summer and winter, as the final absolute humidity is not the same.
- For E region t =n for equation (4.5). No sensible heat is required by the ventilation air.
- For F region t =n_{summer} for sensible heat and latent heat ((4.4) and (4.5)). If there is any winter hour in this region and the HR is higher than 60%, the air will be dehumidified and t= n_{summer}+ n_{winter} (only hours with RH>60%).

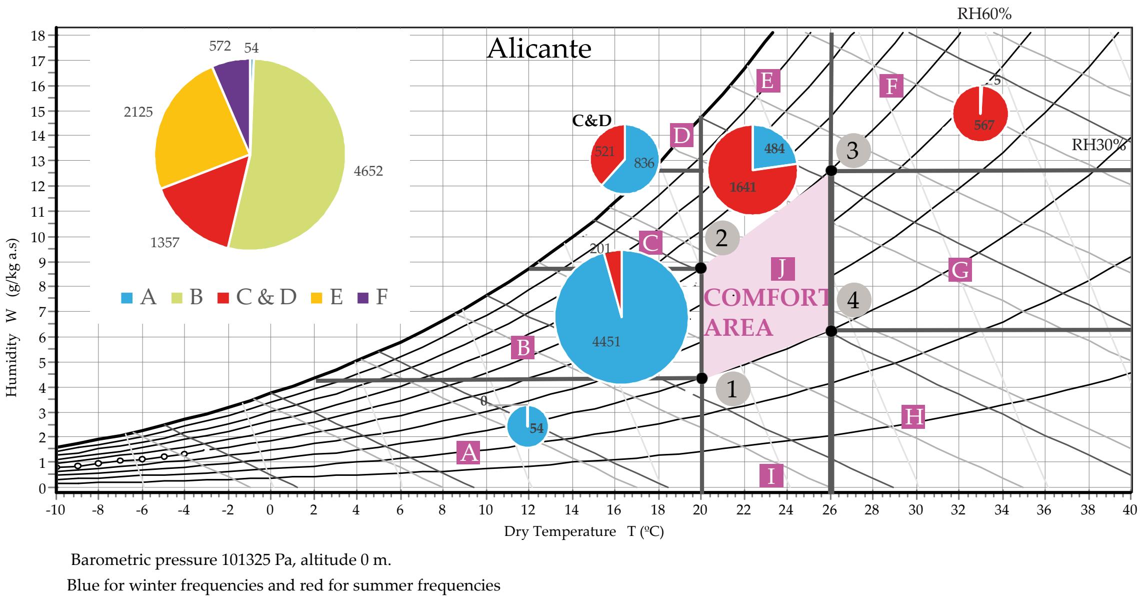


Figure 4.3.Frequencies for temperature intervals on the psychrometric chart sections for Alicante.

4.4. Results and discussion.

For Alicante the sensible demand is 68% and the latent demand is 32% of the total energy demand occasioned by the dwelling ventilation. Assuming a dwelling of 80 m^2 (the typical size for an apartment of 4 people) and a ventilation air flow of 120 m^3/h, the energy demand due to ventilation is 20.8 kWh/m^2 for sensible energy (20.3 kWh/m^2 for heating and 0.5 kWh/m^2 for cooling) and 9.8 kWh/m^2 for the latent energy (99.7% is dehumidification). The dehumidification demand is 8.3 kWh/m^2 during summer and 1.5 kWh/m^2 during winter.

The heating demand due to the dwelling ventilation flow (21.8 kWh/m^2) does not meet the maximum heating demand indicated by the Passivhaus standard (15 kWh/m^2) as a reference for the nZEB definition, therefore sensible heat should be recovered. The cooling demand due to the dwelling ventilation flow (8.8 kWh/m^2), however, still leaves room for other demands. Therefore it seems that the cooling demand requirement indicated by the Passivhaus standard could be met (15 kWh/m^2).

Table 3.10 (Chapter 3) shows the heating and cooling demands allowed by Spanish regulations depending on the climatic zone for a dwelling of 80 m^2. Alicante is located in the B4 Spanish climatic zone. Taking into account that the minimum ventilation flow rate imposed by Spanish regulations [10] is 172.8 m3/h, the energy demand due to ventilation is 30.0 kWh/m^2 for sensible energy (29.3 kWh/m^2 for heating and 0.7 kWh/m^2 for cooling) and 14.1 kWh/m^2 for the latent energy. The dehumidification demand is 12.0 kWh/m^2 during summer and 2.1 kWh/m^2 during winter. The heating demand due to ventilation air (31.4 kWh/m^2) does not meet the maximum heating demand established in the current Spanish regulations. The cooling demand due to the dwelling ventilation flow (12.7 kWh/m²) meets the requirements indicated by the current Spanish regulations. However, it leaves little scope for other demands, and therefore it seems that the cooling demand requirement will barely be fulfilled without an energy recovery system.

Calculations have been done for the cities selected. Figure 4.4 shows the percentage of sensible and latent demand due to the ventilation air.

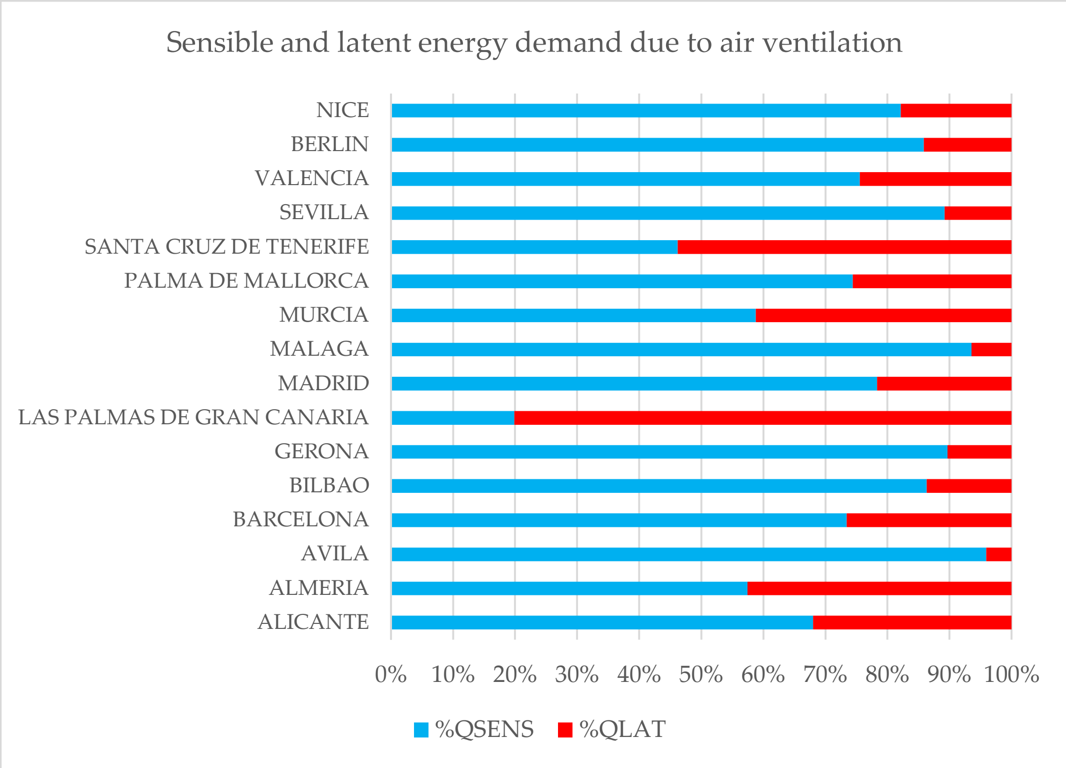


Figure 4.4.Sensible and latent energy demand due to ventilation air for each city

Las Palmas de Gran Canaria and Santa Cruz de Tenerife, both located in the Canary Islands, have a latent demand higher than the sensible demand. Almeria and Murcia are the Mediterranean cities which have more than 40% of latent energy demand. For Valencia, Palma, Barcelona and Alicante, all of them located on the Spanish Mediterranean coast, the latent energy demand due to ventilation air is between 20% and 40% of the total energy demand. For Gerona and Nice, cities located at the north of the Mediterranean sea, the latent energy represents less than 20% of the total energy. The latent energy for those cities is at the same level as for continental cities such as Madrid or Berlin.

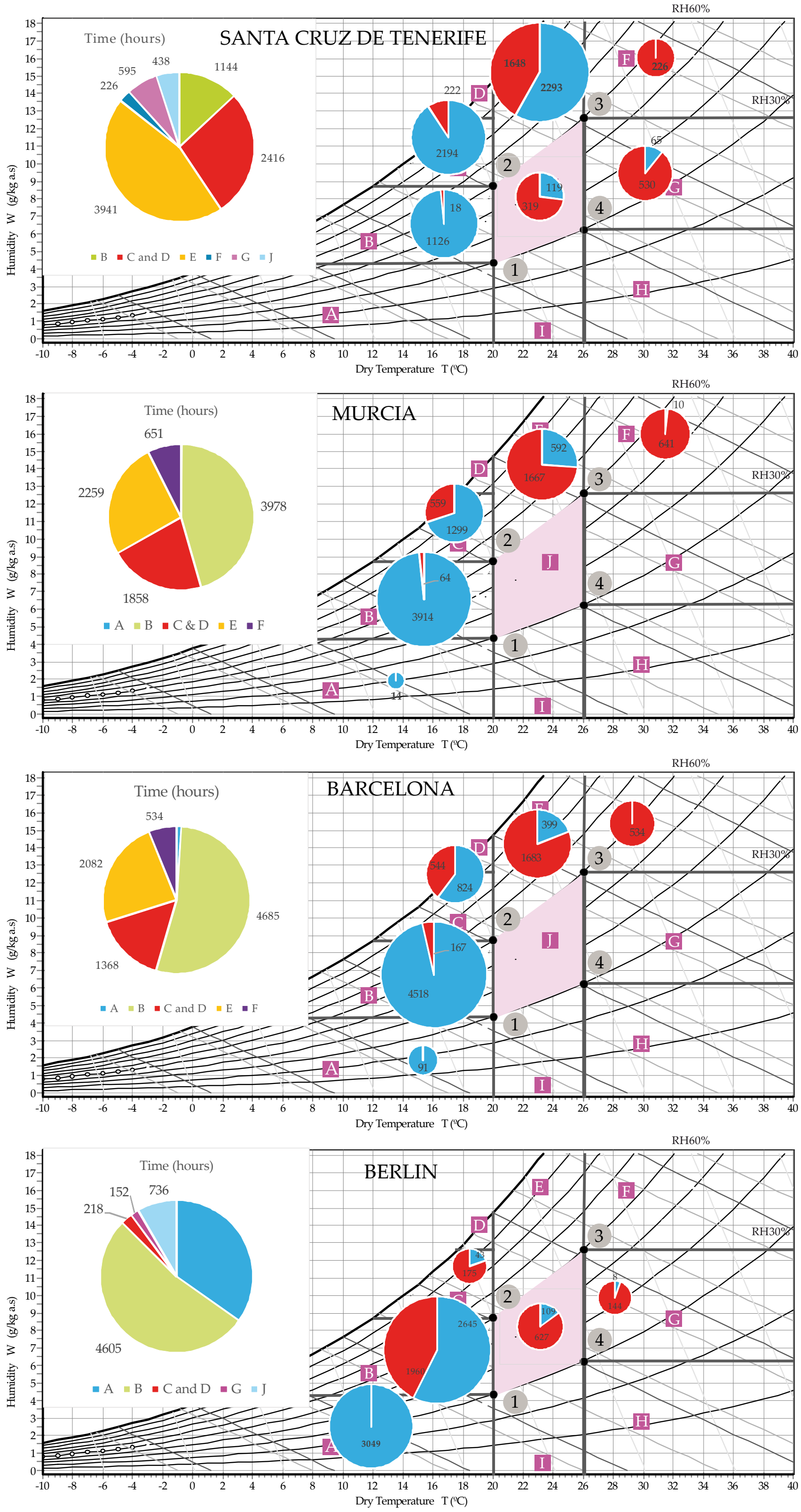
Table 4.2 shows the percentage of hours of the year for the different outside air conditions in the psychrometric regions. Region A is important for cold cities such as Berlin and Ávila, one of the coldest Spanish cities (winter climatic zone E). No frequencies for warm Mediterranean cities appear in this region. Region B has the highest frequency of almost all the studied cities except those in the Canary Islands. The next step should be to determine if the frequency is during winter (only sensible energy can be recovered) or during summer, as the strategy differs. The cities located in the Canary Islands have the highest frequencies in region E where only latent energy can be recovered. It is interesting to see that region J, which is the comfort area, has the highest frequencies for cold cities (Berlin and Avila) and for Málaga as a warm city. However, the frequencies occur during summer for the former and mostly during winter for the latter.

Table 4.2.Percentage of the hours of the year for ambient conditions in the psychrometric regions.

	Psychrometric regions						
CITY	A	B	C&D	E	F	G	J
ALICANTE	0.6%	53.1%	15.5%	24.3%	6.5%	0.0%	0.0%
ALMERIA	0.0%	43.9%	17.6%	26.7%	11.8%	0.0%	0.0%
AVILA	18.5%	62.9%	0.0%	0.0%	0.0%	5.8%	12.9%
BARCELONA	1.0%	53.5%	15.6%	23.8%	6.1%	0.0%	0.0%
BILBAO	4.1%	62.7%	14.4%	15.5%	0.4%	1.7%	1.2%
GERONA	7.8%	55.8%	12.3%	15.5%	3.5%	3.1%	2.0%
LAS PALMAS DE GRAN CANARIA	0.0%	1.2%	44.2%	50.5%	4.1%	0.0%	0.0%
MADRID	1.6%	54.1%	15.0%	20.8%	8.5%	0.0%	0.0%
MALAGA	0.0%	57.8%	5.7%	14.5%	2.2%	8.6%	11.3%
MURCIA	0.2%	45.4%	21.2%	25.8%	7.4%	0.0%	0.0%
PALMA DE MALLORCA	1.6%	54.1%	15.0%	20.8%	8.5%	0.0%	0.0%
SANTA CRUZ DE TENERIFE	0.0%	13.1%	27.6%	45.0%	2.6%	6.8%	5.0%
SEVILLA	1.2%	50.7%	9.2%	15.1%	10.1%	7.3%	6.4%
VALENCIA	3.0%	52.1%	10.2%	25.2%	9.5%	0.0%	0.0%
BERLIN	34.8%	52.6%	2.5%	0.0%	0.0%	1.7%	8.4%
NICE	4.7%	55.5%	15.1%	21.4%	3.2%	0.0%	0.0%

For a quick interpretation of the results, Figure 4.5 shows the frequencies for each region distinguished by season, as the recovery strategies are different. The sections are coloured blue for winter and red for summer. In Figure 4.5, the localization of the climate data for 4 cities with very different climatic data reflects the results obtained regarding the percentage of the sensible versus latent energy in the ventilation air.

Santa Cruz de Tenerife, which has 46% sensible energy demand versus 54% latent energy demand, has the highest frequency of ambient conditions located in region E (45% of the time over the year) where only latent energy demand occurs. Murcia, with 59% sensible energy demand, has the highest frequency in region B (45% of the time over the year) while Barcelona with 53% of the time in region B, consequently their percentage of sensible energy is increased till 73%. Berlin, where the latent energy demand is very low (14%), has no frequency of ambient conditions located in region E. Its highest frequencies are located in regions B and A. The result for region A indicates that the latent energy in Berlin is due to humidification, in contrast to the other cities where the latent energy is due to dehumidification.



The psychrometric chart is changing city by city according to altitude or atmospheric pressure.
On figure 5, the psychrometric chart is used as a sample, it corresponds to a barometric pressure of 94900Pa and an altitude of 594 m.

Figure 4.5. Frequencies for temperature intervals on the psychrometric chart sections for 4 cities.

Figure 4.6 represents the number of hours during a year when ventilation air requires energy from the air conditioning system as follows:

- Time Sens (h) is the number of hours that the air conditioning system will transfer only heat to the ventilation air.
- Time Lat (h) is the number of hours that the air conditioning system will need to dehumidify or humidify the air to reach the comfort area.
- Time Both (h) is the number of hours that the air conditioning system will transfer heat and humidity.
- Time By-pass is the number of hours that no treatment is needed, and the ventilation air should by-pass the energy recovery unit.

In cases where a heat exchanger is placed on the ventilation system, Figure 4.6 shows the time that the heat exchanger will work recovering the energy. This result will help to select the appropriate kind of heat exchanger. It is worth noting that for all the cities the period of time for transferring both heat and humidity simultaneously is not the longest. Most of the time, either heat recovery or humidity recovery is needed, but not at the same time. This result indicates that the best configuration seems to be having both heat exchangers working in parallel.

If the level of latent energy is significant, as for example in Murcia, the optimised configuration proposed will be a heat exchanger with a sensible core and a latent core which can work in dual mode for the period of time when sensible and latent energy can be recovered simultaneously.

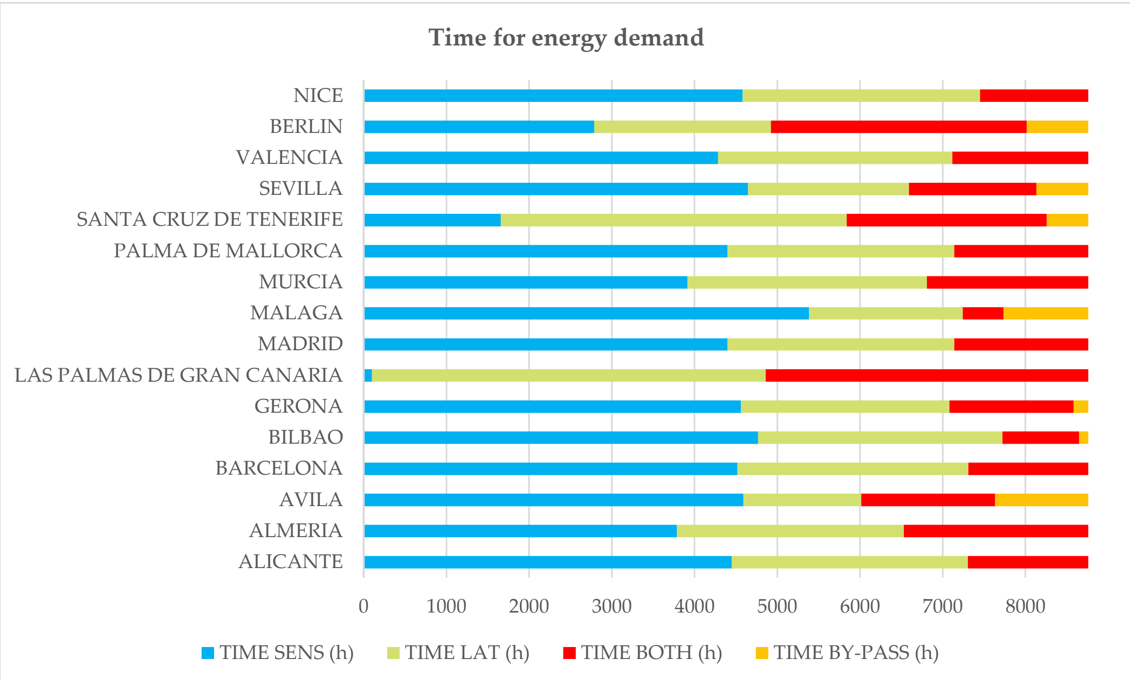


Figure 4.6. Frequency of the energy demand of the ventilation air.

Table 4.3. Ventilation air Energy demand (kWh/m²y) for a dwelling of 80m².

	ENERGY DEMAND DUE TO VENTILATION AIR (kWh/m2year)					
	Winter			Summer		
CITY	QHEAT (Sensible)	QHUM+QDEHUM (Latent)	QTOTAL	QCOOL (Sensible)	QDEHUM (Latent)	QTOTAL
ALICANTE	20.37	1.50	21.88	0.47	8.31	8.78
ALMERIA	14.00	1.90	15.90	1.22	9.38	10.60
AVILA	35.99	1.39	37.38	0.75	0.18	0.93
BARCELONA	20.29	2.15	22.45	0.43	5.34	5.77
BILBAO	25.23	1.11	26.34	0.17	2.91	3.08
GERONA	27.38	1.16	28.54	0.69	2.08	2.76
LAS PALMAS DE GRAN CANARIA	4.79	12.35	17.14	0.16	7.61	7.77
MADRID	21.86	2.17	24.04	0.95	4.13	5.08
MALAGA	15.61	0.35	15.97	1.16	0.81	1.97
MURCIA	18.59	4.29	22.88	0.55	9.15	9.70
PALMA DE MALLORCA	21.86	2.43	24.29	0.95	5.49	6.44
SANTA CRUZ DE TENERIFE	4.01	3.80	7.82	0.60	1.57	2.17
SEVILLA	17.28	0.54	17.82	3.25	1.95	5.19
VALENCIA	19.37	1.64	21.01	0.92	4.94	5.86
BERLIN	43.50	4.32	47.82	0.11	2.85	2.97
NICE	22.97	1.35	24.32	0.16	3.67	3.82

To be able to make a choice of the most appropriate energy recovery system for each city, frequencies of the energy demand should be analysed together with the potential energy to be recovered. Table 4.3 shows the ventilation air energy demand for an apartment of 80m². The energy has been calculated with a ventilation air flow of 30m³/h per person for 4 people living in the dwelling. The results can be compared to the Passivhauss standard where the heating demand should be lower than 15 kWh/m² a year and the cooling demand lower than 15 kWh/m² a year.

As previously mentioned, Roulet et al. [120] state that at least 50% of energy losses are due to ventilation, which means the values obtained should not exceed 7.5 kWh/m² a year to avoid energy recovery from the ventilation system. The grey cells in Table 4.3. Ventilation air Energy demand (kWh/m²y) for a dwelling of 80m².Table 4.3 indicate when the energy recovery will be mandatory for meeting the energy consumption for nZEB dwellings, and if the energy recovered should be latent or sensible.

4.5. Conclusions

Energy demand due to ventilation air in dwellings has become a very significant issue. It has already been demonstrated that heat recovery from ventilation air is a necessity in severe climatic conditions in order to meet the energy demand levels required for nZEB dwellings. Based on an in-depth analysis of the climatic data for several cities located in mild and warm climates in the south of Europe, this research proposes a methodology for evaluating the advisability of recovering the sensible, the latent or both energies from the ventilation air. The methodology calculates only real demands, identifying the season of the year for outside air conditions in order to make the appropriate decision as regards conditioning the ventilation air.

The south of Spain has a high energy demand due to the latent energy needed to condition the ventilation air in dwellings. More than 40% of the energy demand is due to the latent loads which represent a high potential for energy recovery systems instead of heat recovery systems. Cities located mid way down the Spanish Mediterranean coast have a latent energy demand due to ventilation air of between 20% and 40% of the total energy demand. However, the latent energy for cities located at the north of the Mediterranean sea represents less than 20% of the total energy. The latent energy for those cities is at the same level as that of continental cities such as Madrid or Berlin.

For the winter season, only the cities located in the Canary Islands have significant potential for latent energy recovery. Only in Santa Cruz de Tenerife is the use of a latent energy exchanger mandatory to reach nZEB energy demand levels. However, in this case a sensible heat exchanger does not seem to be necessary.

For the rest of the cities under study, the recovery of latent energy is very low compared to sensible heat. Nevertheless, in the summer dwellings in cities located at the south of the Mediterranean coast such as Alicante, Murcia or Almeria, should preferably use a latent recovery system rather than a sensible heat exchanger. The sensible recovery system should be mandatory for those cities to reach nZEB heating demand values during winter, while the latent heat exchanger is highly recommended but not a necessity during summer. It is concluded that a membrane-based recovery system seems not to be the best choice as both transfers occur at the same time. Besides, the thermal efficiency could be penalized compared with traditional heat exchangers.

Given the disparity of strategies needed depending on the climate data for Europe, energy maps need to be drawn showing the potential latent energy that could be recovered.

Moreover, the demands for latent and sensible energy do not arise at the same time, and this has an influence on the kind of recovery system appropriate for each climate condition. The choice of the recovery system is decisive. Most current research is focused on developing new materials with the capability of transferring both moisture and heat simultaneously. However, this solution may not be the most suitable for mild and warm climates where the need to recover heat or transfer moisture does not occur at the same time for most of the year.

Chapter 5

Control strategies for Energy Recovery Ventilators in the South of Europe for residential nZEB. Quantitative analysis of the air conditioning demand

5. Control strategies for Energy Recovery Ventilators in the South of Europe for residential nZEB. Quantitative analysis of the air conditioning demand

This chapter is based on the following published paper:

S. Guillén-Lambea, B. Rodríguez-Soria, J.M. Marín, *"Control strategies for Energy Recovery Ventilators in the South of Europe for residential nZEB. Quantitative analysis of the air conditioning demand"*, Energy Build. 146 (2017). 271-282.

doi.10.1016/j.enbuild.2017.04.058

Abstract

Mechanical ventilation systems are essential for ensuring the indoor quality of air in nZEB (nearly Zero Energy Buildings) with a high level of airtightness. In cold countries, it has already been demonstrated that Heat Recovery Ventilators (HRV) recovering the sensible energy from air ventilation are needed to achieve the energy demand goals for nZEB set by Passivhaus. In tropical areas with hot temperatures and high relative humidity in the ambient air, the necessity of recovering latent and sensible energy with Energy Recovery Ventilators (ERV) has also been demonstrated. However, in warm climates with medium relative humidity levels, for example in cities located on the Mediterranean coast, the evaluation of the effectiveness of an EVR for residential buildings has to be analyzed and optimized.

This research establishes the effectiveness of several control strategies for ventilation air systems including ERV with the aim of optimizing the air conditioning energy demand of dwellings located in several cities in the South of Europe. Possible control strategies have been analyzed to minimize the undesirable operation of ERVs which could otherwise increase the air conditioning energy demand for winter and summer seasons. The impact of the latent effectiveness and the effect of free-cooling on the air conditioning energy demand is also studied.

Keywords

Energy Recovery Ventilator; Residential dwellings; Mediterranean climate; nZEB;

5.1. Introduction

Guillén-Lambea et al.[121] show that ventilation thermal loads account for almost the total thermal loads for residential nZEB located in mild climates and conclude that only buildings located in the hottest cities (of which there are few in the Mediterranean area) are capable of fulfilling the air conditioning demand of nZEB without a Heat Recovery Ventilator (HRV).

Depending on the climate area, the latent load could represent a significant fraction of the total thermal load in air conditioning systems. The energy recovery ventilator (ERV) is an exchanger made of a permeable medium that transfers both moisture and heat from one air stream to another. Suitable permeable materials include cellulose, polymers, and other synthetic membranes [122]. Zhang [46] states that cooling and dehumidifying fresh ventilation air constitutes 20–40% of the total energy load for air conditioning in hot and humid regions. An enthalpy/membrane energy exchanger has been experimentally investigated [117] and the study shows that including an ERV in the mechanical ventilation system instead of a conventional HVAC system reduces the total energy consumption by 8% in tropical climates (Kuala Lumpur) and by 4% in a moderate climate (Sydney). Zhang et al. [123] developed a theoretical thermodynamic model that includes a membrane-based energy exchanger air dehumidification system. Their results show that using a membrane energy exchanger provides energy savings of up to 33% for a commercial building situated in a humid region in China.

Several researchers have looked at control strategies in order to achieve the highest possible performance of ERVs. Rasouli et al. [38,124] investigate the energy savings achieved with the use of an optimized control system for the ERV by performing simulations using TRNSYS of an office building in four North American cities. They find that an ERV not properly controlled may increase the cooling demand, but conclude that an ERV can save energy by up to 10% for an office building in Chicago and 15% in Miami using an optimal control strategy, compared with the use of an HRV only. Liu et al. [125] simulate an apartment in five cities in China demonstrating that the ERV is an effective energy saving method in some of them, but conclude that an ERV is better for non-residential buildings that need more fresh air.

Although membrane ERVs are available on the market, they continue to raise some unanswered questions. For example, what is the performance of these units working under real conditions in real houses, and how does this compare with the performance measured in the laboratory? More importantly, are these products suitable for recovering the humidity in residential buildings located in warm and medium humid climates in the south of Europe?

The present study is focused on the Mediterranean area, where warm climate conditions with medium humidity could justify the use of energy recovery systems as opposed to heat recovery systems alone. For this purpose, a dwelling for a family of four people (nZEB_RD) situated in a block of houses has been modeled in TRNSYS [43]. Simulations have been done for different control strategies of the energy recovery system in order to define the maximum recovery energy from ventilation air for each location. The research's aim is to propose an optimal control for the ERV to minimize the air conditioning energy demand for areas with mild winters and warm and medium-humid summers, characteristic of the Mediterranean area. Additionally, simulations have been performed to check the influence of the latent effectiveness of the ERV and the effect of the free-cooling on the total air conditioning energy demand.

5.2. Computational model.

The building model Type56 [61] for nZEB_RD is used and the heat exchanger is simulated using the Type667 [126].

In the TRNSYS model, the Engineering Equation Solver (EES) is called using Type 66 [60] in order to control the by-pass of the ERV depending on the temperature, humidity and enthalpy of the air streams. EES [63] is a non-linear equation solver that has been used to solve sets of equations to control the operating mode of the ERV, simulating several operating strategies.

The building area and enclosure technical parameters for nZEB_RD are indicated in Table 2.9. The envelope transmittance values are those recommended by Passivhaus [19] for Southern Europe (Table 3.3). The air ventilation flow will be constant throughout the year, 120m^3/h, except that an extra ventilation flow is added during five hours of high occupation assumed at the weekend when the air ventilation flow will be 240m^3/h.

The model includes sensible and latent loads due to occupation, for lighting and equipment a load of 2.5 W/m^2 and a computer with a monitor in the living room with a load of 230W, have been considered. The nominal latent and sensible loads are multiplied by a coefficient depending on the time of day, related to the occupancy indicated in Table 2.4. Coefficients of internal loads applied in the model depending on the time of day.Table 2.4.

The room temperature set is 20°C for heating and 26°C for cooling. As regards relative humidity, the simulations were performed with a relative humidity set at 30% for winter and 60% for summer.

The simulations provide the sensible energy demand for heating and cooling and the latent demand for dehumidification and humidification throughout one year on an hourly basis for several cities located in different countries.

5.2.1. Selection of climate data and cities.

The climate data files are taken from the Meteonorm meteorological database [118].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.

The climate considered in the study is common in Italy, Southern France, Spain and Greece, and representative cities from the Mediterranean area have been selected taking into account the different humidity levels found close to the Mediterranean area. These values are not so important as for cities located in tropical climates, cases which have already been studied by other authors whose results show the advantages of ERV systems in such locations. Zhang [127] found good results for ERV systems in the south of China, were the summer is long, hot and humid. The novelty of the present study is the evaluation of the effectiveness of an ERV in a climate where humidity levels are not as high as in tropical climates.

The locations of the selected cities are shown on the map in Figure 5.1. The mean season air temperatures and relative humidity (winter and summer) are given in Table 5.1. Table 5.1 also includes the percentage of the latent energy in the ambient air calculated on an hourly basis throughout the year [128].

Table 5.1. Mean season (winter and summer) air temperature and relative humidity. Meteonorm meteorological database.

Cities		Winter	Summer	Year	% of latent energy on ventilation air[128]
ALMERIA	T (ºC)	15.6	24.5	18.5	43%
	HR (%)	74.6	71.5	74.0	
ALICANTE	T (ºC)	14.8	24.0	17.9	32%
	HR (%)	68.5	70.0	69.0	
VALENCIA	T (ºC)	14.4	23.4	17.4	24%
	HR (%)	65.0	70.0	67.0	
PALMA DE MALLORCA	T (ºC)	12.7	22.7	16.0	26%
	HR (%)	78.4	74.3	77.0	
BARCELONA	T (ºC)	12.2	21.7	15.3	27%
	HR (%)	77.9	77.8	78.0	
MARSEILLE	T (ºC)	11.2	22.1	14.8	7%
	HR (%)	70.9	64.5	69.0	
ROME	T (ºC)	11.5	22.6	15.2	17%
	HR (%)	74.8	67.5	72.0	
PALERMO	T (ºC)	15.7	24.6	18.7	51%
	HR (%)	73.3	76.0	74.0	
NAPLES	T (ºC)	12.4	23.1	16.0	23%
	HR (%)	73.0	71.0	72.0	
MURCIA	T (ºC)	13.9	23.1	16.9	41%
	HR (%)	77.4	76.3	77.0	
CAGLIARI	T (ºC)	13.3	23.3	16.7	21%
	HR (%)	76.4	67.3	73.0	

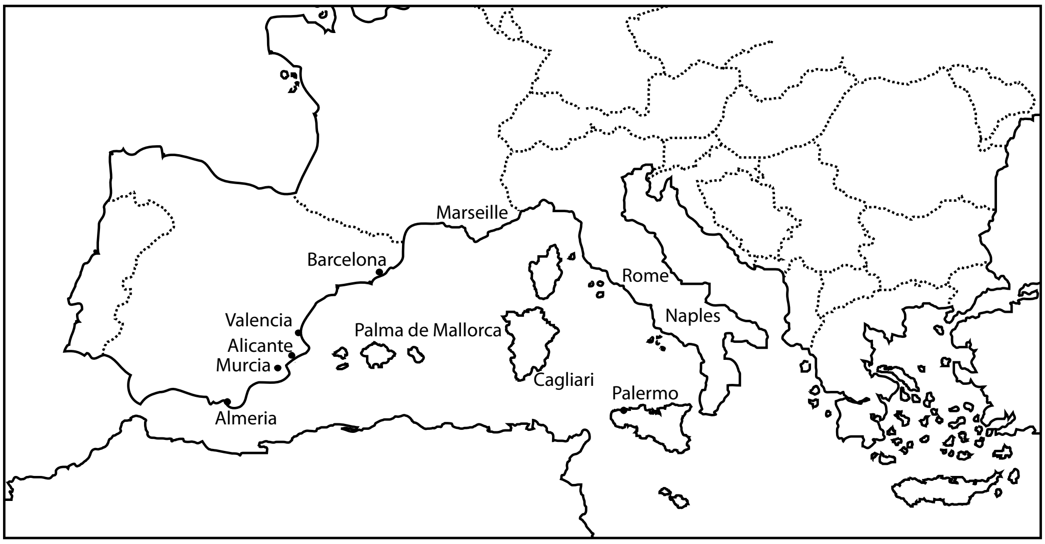


Figure 5.1. Mediterranean cities selected.

5.3. Control strategies for Energy Recovery Ventilators in the South of Europe.

The control strategies have been analysed separately for the winter season (from October to May) and the summer season (from June to September). Heating demand and cooling demand calculations have significant differences.

5.3.1. Control strategies during winter season.

Three winter strategies (WINTER 1, WINTER 2, WINTER 3) have been simulated in TRNSYS for each of the Mediterranean cities, modifying the EES type to control the by-pass in the recovery system. The strategies depend on the outdoor air temperature and humidity, as shown in Table 5.2.

WINTER 1 simulates a ventilation system with an ERV which has a control based only on the sensible energy. If the outdoor air temperature is lower than the indoor air temperature, the supply air will pass through the heat exchanger to recover energy (a situation occurring almost all of the time for all the studied cities), otherwise the by-pass will be open. This situation will reduce the maximum sensible heating demand. However, this is not the optimum condition for recovering the latent energy.

WINTER 2 simulates a ventilation system with an ERV which has a control based only on the latent energy. If the outdoor air absolute humidity is lower than the indoor air absolute humidity, the by-pass will be open and the supply air will not pass through the heat exchanger. Otherwise, the by-pass will be closed. This situation will reduce the maximum dehumidification demand but as sensible energy is not recovered the heating demand will increase.

A third simulation has been added, WINTER 3, which simulates a ventilation system with an HRV for the purposes of comparison. The control system will open the by-pass only if the outside temperature is higher than the indoor temperature (almost never).

Table 5.2. Strategies for energy recovery in the winter season.

WINTER	**Control Strategy**		
Outdoor air temperature vs Indoor air temperature (T_{out}, T_{in})	**Strategy for sensible energy demand**	**Strategy for latent energy demand**	**HRV for comparison**
$T_{out} < T_{in}$	ERV	If $w_{out} > w_{in}$ then ERV else By-pass open	HRV
$T_{out} > T_{in}$	By-pass open		By-pass open
	WINTER 1	WINTER 2	WINTER 3

T_{out}: outdoor air temperature; T_{in}: indoor air temperature;

w_{out}: outdoor air absolute humidity; w_{in}: indoor air absolute humidity

5.3.2. Control strategies during summer season.

Four summer strategies (SUMMER 1, SUMMER 2, SUMMER 3, SUMMER 4) have been simulated in TRNSYS, modifying the EES type to control the by-pass. These are shown in Table 5.3.

SUMMER 1 simulates a ventilation system with an ERV which has a control based on the sensible energy. If the outdoor air temperature is lower than the indoor air temperature, the by-pass will be open and the supply air will not pass through the heat exchanger to cool the dwelling (a situation occurring during nights). Otherwise, the by-pass will be closed. This situation will reduce the maximum sensible cooling demand but will be not the optimum for recovering the latent energy.

SUMMER 2 simulates a ventilation system with an ERV which has a control based on the latent energy. If the outdoor air absolute humidity is lower than the indoor absolute humidity, the by-pass will be open and the supply air will not pass through the heat exchanger. Otherwise, the by-pass will be closed. This situation will reduce the maximum dehumidification demand but the sensible cooling demand is expected to be higher than for the SUMMER 1 strategy.

SUMMER 3 simulates a ventilation system with an ERV. The control system will check firstly the outdoor and indoor air temperature to apply the appropriate control as follows:

1) If the outdoor air temperature is higher than the indoor temperature the supply air will pass through the ERV.

2) If the outdoor air temperature is lower than the indoor air temperature then:

a) If the outdoor air absolute humidity is higher than the indoor absolute humidity and the latent energy to be recovered is higher than the sensible energy to be added to the dwelling, the supply air will pass through the ERV.

b) Otherwise, the supply air will pass through the by-pass.

SUMMER 4 simulates a ventilation system with an HRV to recover only sensible energy, for the purposes of comparison. The air will pass through the heat exchanger if the outdoor air temperature is higher than the indoor air temperature to reduce the cooling sensible energy demand.

Table 5.3. Strategies for energy recovery in the summer season.

SUMMER	**Control Strategy**			
Outdoor air temperature vs Indoor air temperature (T_{out}, T_{in})	**Strategy for sensible energy demand**	**Strategy for latent energy demand**	**Optimal strategy**	**HRV for comparison**
$T_{out}< T_{in}$	By-pass open	If $w_{out} > w_{in}$ then ERV else By-pass open	If ($w_{out} > w_{in}$ and $Q_l>Q_s$) then ERV else By-pass open	By-pass open
$T_{out}> T_{in}$	ERV		ERV	HRV
	SUMMER 1	SUMMER 2	SUMMER 3	SUMMER 4

T_{out}: outdoor air temperature; T_{in}: indoor air temperature;

w_{out}: outdoor air absolute humidity; w_{in}: indoor air absolute humidity

Q_l: Latent energy to be recovered; Q_s: Sensible energy to be recovered;

5.4. Sensitivity of the latent effectiveness of the ERV.

The ERV recovers the sensible and the latent energy following Equation (5.1).

$$\dot{Q}_{TOT,rec} = \dot{Q}_{s,rec} + \dot{Q}_{l,rec} = \dot{m}_{exh} \cdot \left(h_{exh,in} - h_{exh,out}\right) = \dot{m}_{sup} \cdot \left(h_{sup,out} - h_{sup,in}\right) \quad (5.1)$$

Where

$\dot{m}_{exh} = \dot{m}_{sup} = \dot{m}_{vent}$ for a balanced system is the ventilation air mass flow (Kg/s).

$h_{exh,\ in}$ is the enthalpy of the exhaust air at the inlet of the energy exchanger (kJ/kg $_{dry\text{-}air}$)

$h_{exh,\ out}$ is the enthalpy of the exhaust air leaving the energy exchanger (kJ/kg $_{dry\text{-}air}$)

$h_{sup,\ in}$ is the enthalpy of the fresh air at the inlet of the energy exchanger (kJ/kg $_{dry\text{-}air}$)

$h_{sup,\ out}$ is the enthalpy of the fresh air leaving the energy exchanger (kJ/kg $_{dry\text{-}air}$)

The heat recovery $\dot{Q}_{s,rec}$ (kW) depends on the sensible effectiveness of the heat exchanger and can be calculated using Equation (5.2),

$$\dot{Q}_{s,rec} = \varepsilon_{sens} \cdot \dot{Q}_s \quad (5.2)$$

Where

$\dot{Q}_s$ is the sensible energy demand due to the air ventilation (kW)

ε_{sens}, the sensible effectiveness of the heat exchanger (-) for balanced systems, is defined by Equation (5.3).

$$\varepsilon_{sens} = \frac{(T_{exh,in} - T_{exh,out})}{(T_{exh,in} - T_{sup,in})} \quad (5.3)$$

$T_{sup,in}$ is the temperature of the supply air at the inlet of the heat exchanger (ºC)

$T_{sup,out}$ is the temperature of the supply air exiting the heat exchanger or of the supply air entering the dwelling (ºC)

$T_{exh,in}$ is the temperature of the exhaust air entering the heat exchanger (ºC) or the exhaust air temperature leaving the dwelling (ºC)

$T_{exh,out}$ is the temperature of the exhaust air exiting the heat exchanger (ºC)

While the moisture recovery $\dot{Q}_{l,rec}$ (kW) depends on the latent effectiveness which can be calculated using Equation (5.4).

$$\dot{Q}_{l,rec} = \varepsilon_{lat} \cdot \dot{Q}_l \tag{5.4}$$

Where

$\dot{Q}_l$ is the latent energy demand due to the air ventilation (kW)

ε_{lat} is the latent effectiveness of the heat exchanger (-) defined by Equation (5.5),

$$\varepsilon_{lat} = \frac{(w_{exh,in} - w_{exh,out})}{(w_{exh,in} - w_{sup,in})} \tag{5.5}$$

$W_{sup,in}$ is the supply air specific humidity at the inlet of the heat exchanger ($kg/kg_{dry\text{-}air}$)

$w_{sup,out}$ is the supply air specific humidity exiting the heat exchanger ($kg/kg_{dry\text{-}air}$)

$w_{exh,in}$ is the exhaust air specific humidity at the inlet of the heat exchanger ($kg/kg_{dry\text{-}air}$)

$w_{exh,out}$ is the exhaust air specific humidity at the outlet of the heat exchanger ($kg/kg_{dry\text{-}air}$)

Following the equations, the sensible and latent effectiveness of the energy recovery system determines the energy loads of the air conditioning system due to ventilation air. The energy savings from the ventilation air of an ERV should be directly proportional to the sensible and latent effectiveness.

Woods [45] published a large review of ERV technologies for air conditioning systems. The data provided in his research confirms that the latent effectiveness is generally less than the sensible effectiveness. Zhang et al.[129] showed that while the sensible effectiveness remains practically constant, the latent effectiveness depends on the material permeability and the operating conditions (the air temperature and humidity). Several research studies have examined this phenomena [130,131]. Mardiana-Idayu and Riffat [44] state that heat recovery systems typically recover about 60–95% of the heat. Mardiana et al. [51] discuss the physical and performance parameters of a heat recovery unit and the significance of these parameters for the operation and efficiency of the system.

For the first set of simulations, the sensible effectiveness and latent effectiveness of the ERV remain invariable; their values are 0.9 and 0.6, respectively (results in Section 5.6.2 below). The effectiveness values have been selected taking into consideration the higher performances of ERVs currently available on the market as a first approach.

For the second set of simulations, the sensible effectiveness remains at 0.9 while the latent effectiveness varies in steps of 0.1 in order to find the optimum value for the selected cities (results in Section 5.6.3 below).

5.5. Natural ventilation and free-cooling.

Other 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. Additional specific actions and design modifications could be implemented to reach the required level of cooling demand, such as high performance shading devices or an optimal orientation as well as extending the time during which windows are open.

In summer, when the outdoor temperature is lower than the indoor temperature, the outside air could be used to reduce the cooling energy. In order to reduce the cooling demand, natural ventilation or free cooling are essential.

Natural ventilation is a technique whereby the entry of outside air into a building by natural means (not mechanical) is allowed. The outside air should enter the dwelling by opening the windows. The action thus depends on human factors, which is a drawback for calculating the energy efficiency of a dwelling. The infiltration due to opening windows is as required by Spanish law [14].

In a third step, simulations have been performed opening the windows during summer months between 01h am and 08h am, inclusive. During this time interval, it is assumed that the external living spaces have air infiltration caused by opening windows of 4 air changes per hour.

Free-cooling is a technique whereby the entry of outside air is allowed inside a building controlled by mechanical means. In fact it is controlled mechanical ventilation and takes advantage of many benefits of natural ventilation and eliminates much of its drawbacks, such as the human factor. Additional simulations have been carried out for a doubled ventilation air flow (240 m^3/h) during summer nights. Section 5.6.4 shows the results for simulations performed applying natural ventilation and free cooling.

5.6. Results and discussion.

Firstly, as a base case, the results obtained without energy recovery in the ventilation system are presented to evaluate the benefits reported by the use of recovery systems for the cities under study (Section 5.6.1).

In the first step (Section 5.6.2), the control strategies are evaluated. The sensible effectiveness remained at 0.9 and the latent at 0.6. In the second step (Section 5.6.3), the sensible effectiveness remained at 0.9 while the latent varied in steps of 0.1 (from 0.4 to 0.9). In the third step (Section 5.6.4), simulations have been performed with the best control strategy and applying natural ventilation and free cooling strategies.

5.6.1. Base case: without energy recovery system.

Figure 5.2 shows the sensible and latent air conditioning demands for the simulated dwelling (in summer and in winter) without any energy recovery system for the ventilation air for each city under study. Simulations without an energy recovery system have been done in order to ascertain by comparison the benefits of the different recovery strategies proposed.

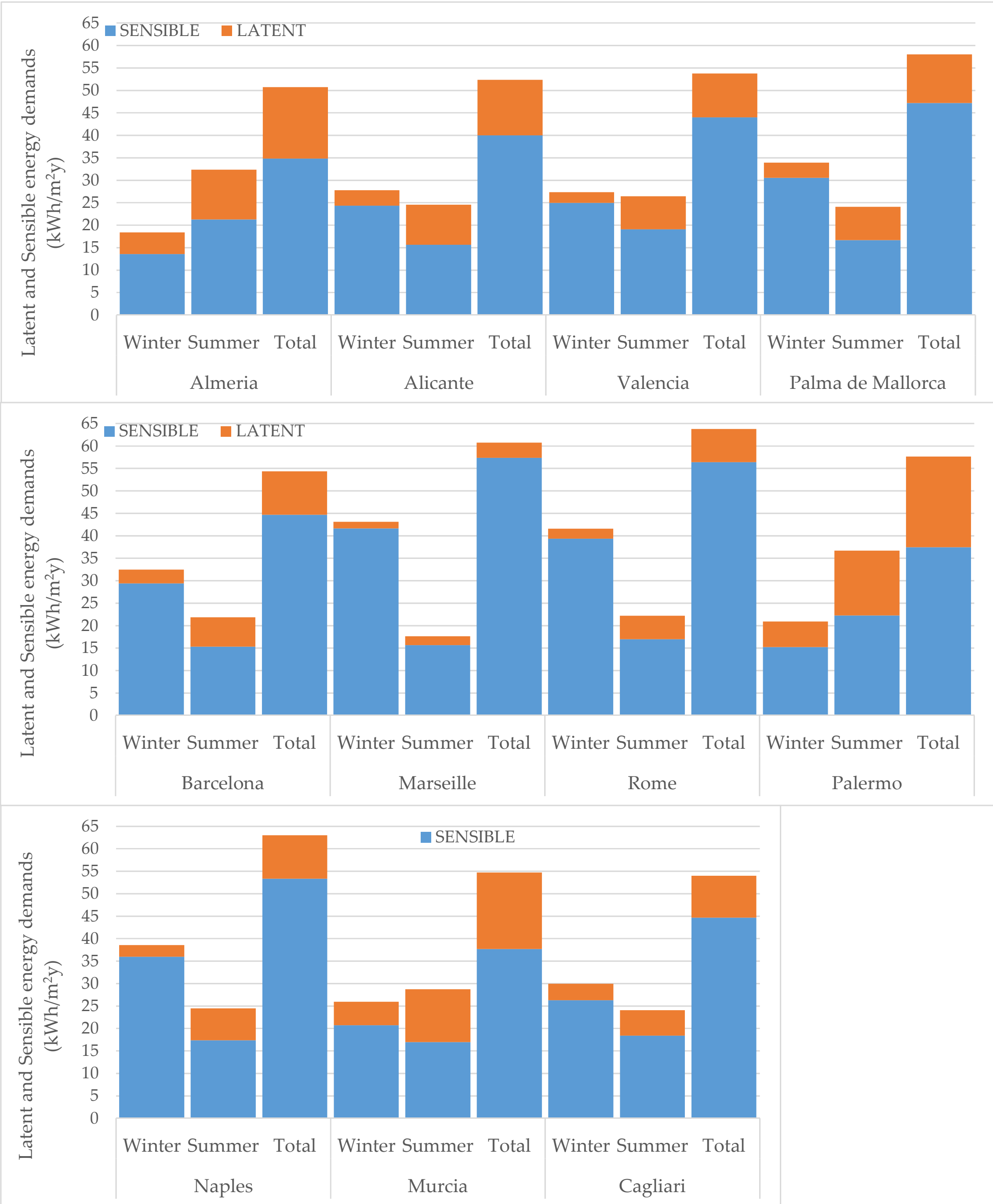


Figure 5.2. Air conditioning energy demand in the selected cities without energy recovery in the ventilation air system.

All the cities have higher latent energy demand for summer than for winter. Almeria, Palermo and Murcia have greater cooling demand than heating demand. Palermo has the highest dehumidification energy demand with 35% of the total air conditioning energy.

The Table 5.4 shows the percentage of the latent energy demand for the selected cities, those values can be compared with the percentage of the latent energy in the ambient air showed in Table 5.1.

Table 5.4. Percentage of the latent energy demand.

CITIES	% Latent energy
Almería	31%
Alicante	24%
Valencia	18%
Palma de Mallorca	19%
Barcelona	18%
Marseille	6%
Rome	12%
Palermo	35%
Naples	15%
Murcia	31%
Cagliari	17%

5.6.2. Control strategies for the ERV.

The sensible effectiveness and latent effectiveness of the ERV remain invariable, their values being 0.9 and 0.6, respectively.

Murcia (41%), Palermo (51%) and Almeria (43%) are the cities with the highest percentage of latent energy in the ambient air (see percentages in Table 4). The results for Murcia, as an example of a city with high potential for latent energy recovery, are shown in Table 5.5. The calculated sensible and latent energy demand without any recovery system (base case) are also reflected in Table 5.5 for comparison.

For the winter season, the sensible demand is much more important than the latent demand and therefore a control strategy based on temperature is the most suitable. The results confirm that the control strategy based on temperature (WINTER 1) is the most appropriate since it can reduce sensible heating demand by 73% and only slightly increase the dehumidification demand by 3%. The total energy demand during winter is reduced by 58% compared with an air ventilation system without energy recovery.

The control strategy based on latent demand (WINTER 2) reduces the sensible demand insignificantly, by a mere 6%, and the latent demand is reduced by just16%. This slight reduction is due to the fact that most of the time the humidity in the indoor air is higher than outdoors because of internal gains, hence the supply air does not pass through the ERV.

Table 5.5. Energy demands for Murcia depending on the control strategy of the ERV.

	Energy demand (kWh/m²y)		
Winter strategies	**Sensible Heating demand (kWh/m²y)**	**Dehumidification demand (kWh/m²y)**	**Total Winter demand (kWh/m²y)**
WITHOUT RECOVERY	20.7	5.2	26.0
WINTER 1	5.6	5.4	11.0
WINTER 2	19.4	4.4	23.8
WINTER 3 (HRV)	5.6	3.9	9.6
Summer strategies	**Sensible Cooling demand (kWh/m²y)**	**Dehumidification demand (kWh/m²y)**	**Total Summer demand (kWh/m²y)**
WITHOUT RECOVERY	17.0	11.8	28.7
SUMMER 1	16.5	10.1	26.6
SUMMER 2	18.8	9.7	28.5
SUMMER 3	17.0	8.7	25.6
SUMMER 4 (HRV)	16.5	11.7	28.3

Finally, the values obtained for a HRV (WINTER 3) are the best for the winter season. This is due to the fact that using an ERV the moisture transfer occurs from the dwelling to the incoming air and the humidity is returned to the house. Hence, at this time operating an ERV increases the latent energy as it is added to the supply air.

For the summer season, the results indicate than the use of an ERV slightly reduces the cooling demand as a non-significant energy load is added by the air ventilation. The cooling demand is more influenced by other parameters such as internal loads and solar radiation. Besides, the use of a HRV (SUMMER 4) does not significantly reduce the energy demand of the dwelling, and its inclusion in the air ventilation system does not seem to be profitable.

The reduction obtained by the temperature control strategy (SUMMER 1) is not so significant as to justify the use of an ERV: 3% for sensible demand and 14% for latent demand resulting in 7% of the total energy demand. Accordingly, temperature control during summer is not appropriate.

Otherwise, a control strategy based on the humidity control (SUMMER 2) significantly reduces the latent demand by 18% but increases the sensible cooling demand by 11% because the outdoor fresh air is heated by the indoor air before entering the dwelling, worsening the sensible demand. In consequence, the reduction is less than 1% of the total energy demand during summer.

The enthalpy control system checks every hour the potential sensible and latent energy demands to be recovered (SUMMER 3) in order to control the by-pass. The sensible cooling demand is not affected, but the latent demand is reduced by 27% and the total energy demand by 11% during summer.

The results obtained for all the cities indicate that the ERV optimal control is WINTER 1 + SUMMER 3.

Figure 5.3 shows the results in all the selected cities applying this optimal control.

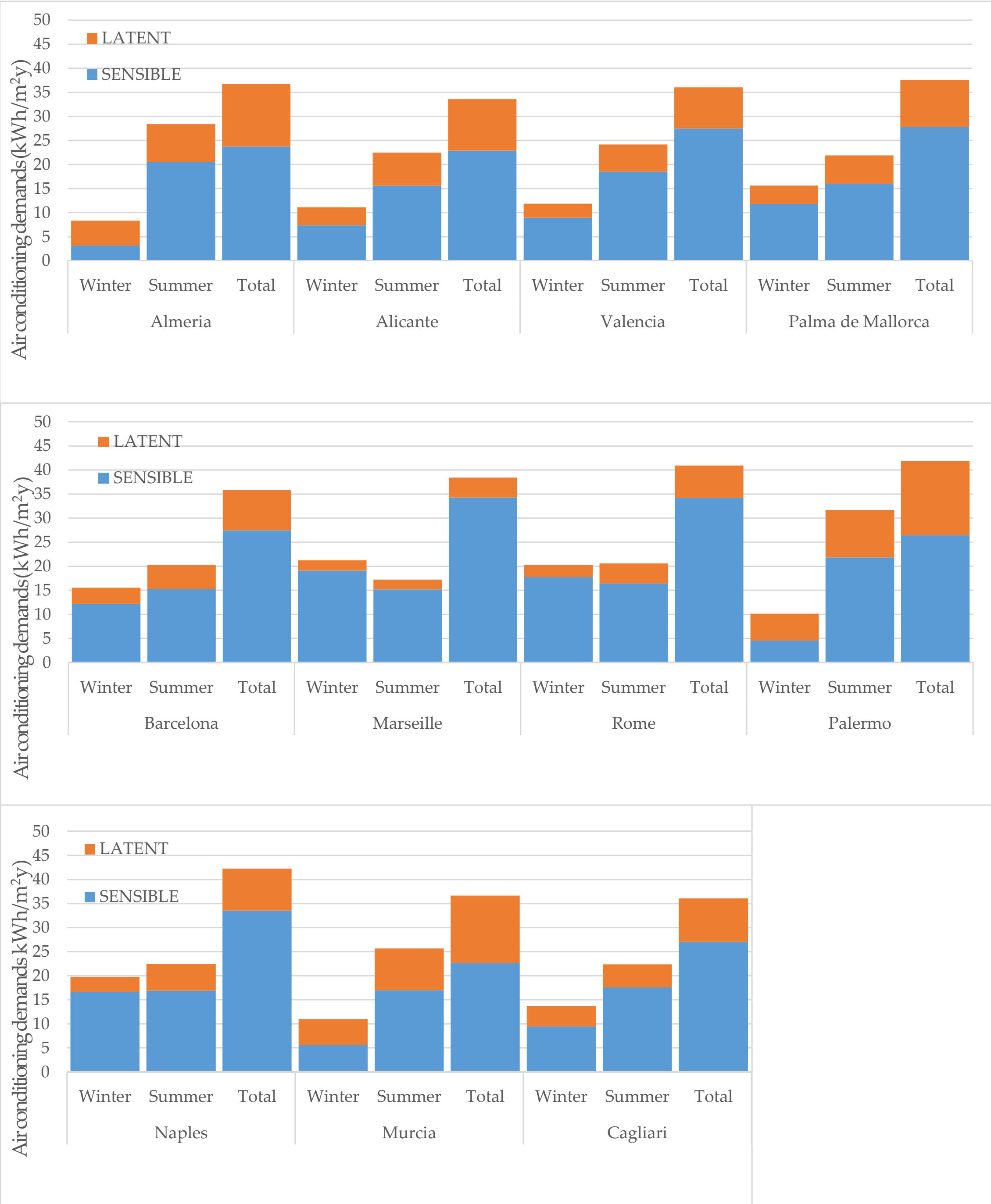


Figure 5.3. Energy demand in the selected cities with the optimal control strategy of the ERV (WINTER 1+ SUMMER 3).

Comparing Figure 5.3 with Figure 5.2, the sensible heating demand due to air ventilation has been almost eliminated. The sensible cooling demand remains almost invariable, the reductions being between 4 % and 0%. The greatest reduction is for Palma de Mallorca and Cagliari with 4%, followed by Naples, Rome, Marseille, Valencia and Almeria with 3%. The lowest is for Murcia and Alicante with 0%. This is due to the fact that the cooling demand is principally affected by internal gains and radiation heat much more than by the ventilation air. The cooling load due to the ventilation air is almost unappreciable.

The results show that in summer the difference in sensible cooling demand without and with energy recovery applying SUMMER 1 or HRV (controlled by temperatures) for Murcia is just 0.5 kWh/m²y (see Table 5.5).

The latent demand is slightly increased in the winter season for all the cities except for Palermo. However, in summer the dehumidification energy demand is reduced in all the cities by more than 17%, except for Marseille where the latent energy demand increases by 4%. The largest reduction is obtained in Palermo with 32%.

Cooling demand is higher than the heating demand using the ERV in all the cities except Marseille.

Looking at the total demands, the reductions in sensible and latent demand throughout the year with an optimized control for the ERV compared with a ventilation system without an energy recovery ventilator are shown in Figure 5.4. The reduction in the total air conditioning energy demand when including an HRV in the air ventilation system has also been included in order to show the extra reduction provided by the ERV.

Marseille and Cagliari show an increase in the total energy demand when including an ERV instead of an HRV. The extra reduction in the air conditioning energy demand when installing an ERV instead of a HRV is the greatest for Palermo (5.1%). For Almeria and Murcia the extra reduction is 2.4 % and 2.2 %, respectively. For the rest of the cities the reduction is almost negligible.

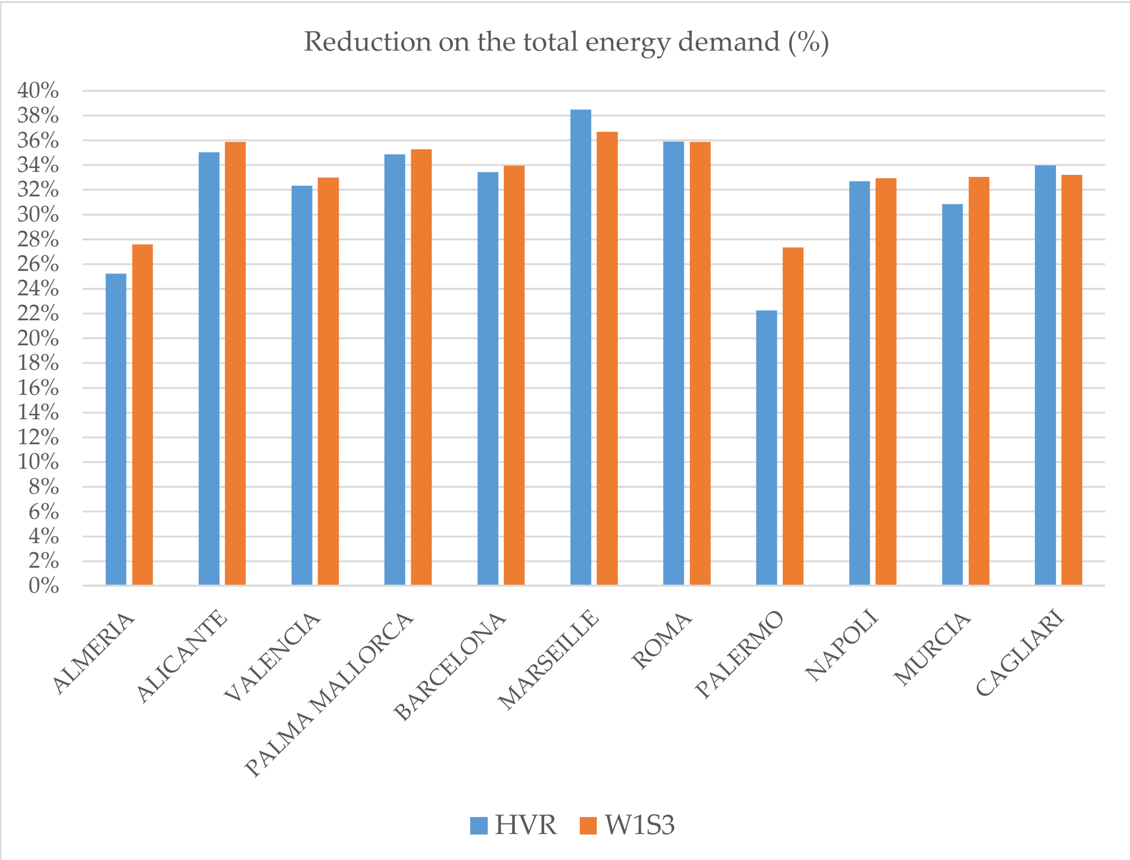


Figure 5.4. Reduction in air conditioning energy demand (%).

5.6.3. Latent effectiveness of the ERV.

A more complete analysis has been carried out on the latent effectiveness. In a second step, additional simulations have been performed to check the impact of the latent recovery effectiveness on the air-conditioning energy demand. The sensible effectiveness remained invariable while the latent effectiveness varied in steps of 0.1. The control strategy was WINTER 1 and SUMMER 3 (W1_S3) as these provide the best results.

The simulations were performed for Valencia and Palma de Mallorca as cities with moderate latent energy demand, for Murcia and Almeria as cities with medium latent energy demand, and for Palermo as the city with highest latent energy demand. The results are shown in Figure 5.5.

For all the cities, the winter dehumidification demand increases when the latent ERV efficiency is increased. This is because the control strategy is based on winter temperatures, and the exchange of sensible energy prevails over latent energy as it is much more important. However, to avoid an increase in the latent demand, outdoor air should not pass through the ERV if its absolute humidity is less than that of the housing. In such a case, by passing through the ERV, the outdoor air absorbs moisture from the housing which is reintroduced. Thus, increasing the latent efficiency leads to greater demand for dehumidification in winter. In contrast, in the summer season increasing the efficiency decreases the latent demand because the outdoor humidity is almost always higher than that of the dwelling and therefore the air is dried before entering. In order to obtain the optimal latent effectiveness, the addition of winter and summer latent demands should be analyzed.

For Valencia and Palma de Mallorca, the total latent energy demand rises when the latent effectiveness increases. This is because the latent energy demand increases more in winter than it decreases in summer and therefore the total balance, contrary to expectations, is worse. There is an optimum value for latent effectiveness on these cities: 0.5. If the effectiveness is further reduced to 0.4, then the total latent demand increases again.

For Murcia the optimum value is between 0.6 and 0.7 at which the total latent energy demand remains constant at the minimum value. For Almeria the optimum value is 0.6. For Palermo, the city with the greatest latent energy, the optimum value for latent energy demand is 0.8.

An increase in the sensible effectiveness (ε_s) leads directly to a reduction in the sensible demand. This obvious fact cannot be applied to the latent effectiveness for Mediterranean cities were an increase in the latent effectiveness (ε_l) does not lead directly to a reduction in the latent demand as, in some conditions, the humidity will be transferred in the wrong direction for energy savings.

Figure 5.5. Latent energy demand for ε_s=0.9.

5.6.4. Natural Ventilation and Free cooling.

Simulations applying free cooling and natural ventilation have been performed in order to check their impact on a dwelling with a mechanical ventilation system. The simulations were carried out using the control strategy SUMMER 3, as this was revealed to be the best in terms of energy demand during summer.

The results for Murcia are shown in Table 5.6 for natural ventilation SUMMER 3 OW (Open Windows) and for Free Cooling SUMMER 3 FC.

Table 5.6. Energy demands for Murcia depending on the control strategy of the ERV.

Summer strategies	Sensible Cooling demand (kWh/m²y)	Dehumidification demand (kWh/m²y)	Total Summer demand (kWh/m²y)
SUMMER 3	17.0	8.7	25.6
SUMMER 3 OW	11.0	20.0	31.0
SUMMER 3 FC	15.7	9.6	25.3

OW: Open Window; FC: Free Cooling

The natural ventilation reduces the sensible cooling demand by 35%, which is very effective. However, it is not appropriate for latent energy which is increased by 131%. The total energy demand during summer is increased by 21% compared with the result with closed windows (SUMMER 3).

For Free Cooling, the sensible cooling demand is reduced by 8% but the latent demand is increased by 11% and the total energy is reduced only by 1.5% during summer compared with SUMMER 3.

5.7. Conclusions.

Eleven cities located on the Mediterranean coast in Southern Europe have been selected for this study. The Mediterranean climate is warm with medium relative humidity levels.

Simulations were performed to check the suitability of including ERVs instead of HRVs in air ventilation systems. Possible ERV control strategies have been analyzed separately for the winter and summer seasons.

The optimum strategy during winter is a control based only on the sensible energy. When the outdoor air temperature is lower than the indoor temperature, the supply air passes through the ERV. Otherwise, it passes through the by-pass. This situation reduces the maximum sensible heating demand. However, does not represent the optimum for the recovery of the latent energy.

For all the cities except Palermo (the most humid city studied), the use of an HRV instead of an ERV results in lower values for the air conditioning demand in the winter season.

The optimal strategy found for the summer season is based on the enthalpy control. If the outdoor air temperature is higher than the indoor temperature, the supply air will pass through the ERV. If not, the air humidity and the potential latent and sensible energy demands should be calculated. If the outdoor air absolute humidity is higher than the indoor humidity and the potential latent energy demand to be recovered is higher than the sensible energy demand added to the dwelling, the supply air will pass through the ERV. If not, the supply air will pass through the by-pass.

The reduction in energy demand resulting from installing an ERV and applying the control strategy proposed in this article (for sensible effectiveness of 0.9 and latent effectiveness of 0.6) is very significant compared to the absence of a recovery system. Nevertheless, it is not very notable when compared to the use of an HRV.

Palermo achieves a reduction in the air conditioning energy demand of 27.3% with an ERV, 5.1% more than installing an HRV. For Palermo, Murcia and Almeria, the cities with percentages of latent energy in the ventilation air higher than 40%, the use of an ERV instead of an HRV could be recommended as effective for the reduction of air conditioning energy demand (5.1%, 2.4% and 2.2% respectively).

For three cities, Rome, Marseille and Cagliari, with percentages of latent energy in the ventilation air lower than 21%, the installation of an ERV instead of an HRV is not recommendable. For Marseille and Cagliari the air conditioning energy demand is increased. For Rome (17% of latent energy in the ventilation air) the energy demand remains unchanged.

For the rest of the cities, where the percentage of the latent energy in the ventilation air is between 23% and 27%, the use of an ERV instead of an HRV is not justified by the results obtained. A more in-depth and specific analysis is recommended for the cities with a percentage between 30% and 40% (Alicante 32%).

The results demonstrate that the cooling demand is slightly affected whereas heating is heavily impacted by the air ventilation flow. Analyzing the values obtained for the cooling demand in the Southern Europe cities when ERVs are installed, it is worth noting that the cooling demand is higher than the heating demand in all cities except Marseille.

Simulations for different levels of latent effectiveness while maintaining the sensible effectiveness invariable have been performed. An increase in latent effectiveness could increase the latent energy demand, as the optimum value should be calculated taking into account the dehumidification energy demand in both the summer and winter seasons.

In summer, the latent energy demand decreases when the latent effectiveness of the ERV increases. However, unexpectedly the opposite occurs in winter. The result is that in some cities, such as Valencia and Palma de Mallorca, increasing the latent effectiveness, contrary to expectations, increases the total latent energy demand.

The greater the latent potential energy that may be recovered, the higher is the optimum value of the latent efficiency. This is the case of Palermo, where the optimum value for latent effectiveness is 0.8 (for 0.9 sensible efficiency), but the reductions obtained in the total energy demand are not significant.

For Murcia and Almeria, the optimum value for latent effectiveness is 0.6.

Simulations applying natural ventilation and free cooling have been performed. Opening windows during summer nights is a very effective way of reducing the sensible demand under nZEB requirements, but it is not appropriate for latent energy which substantially increases.

Furthermore, simulations have been performed for a double ventilation air flow during summer nights (Free Cooling). The sensible cooling demand is reduced, but latent demand is increased and the total energy is reduced by only 1.5% during summer for Murcia, compared with the absence of free-cooling.

Chapter 6

Infiltration effect on air conditioning demand. Computational simulations to set airtightness parameters for residential nZEB in the south of Europe

6. Infiltration effect on air conditioning demand. Computational simulations to set airtightness parameters for residential nZEB in the south of Europe

Some of the results presented in this chapter are included in the following publication:

S. Guillén-Lambea, B. Rodríguez-Soria, J.M. Marín, J. Sierra-Pérez, *"Impact of infiltrations in energy demand of a dwelling. Sensitivity to infiltrations for Mediterranean climate"*. 10th International Conference on Advanced Building Skins, November 3-4 2015, (Bern, Switzerland). ISBN 978-3-98120538-1.

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

6.1. Introduction

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 [132], the UK [133], the north of China [134], and Spain [135,136]. A recent research study [135] 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. [137] 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_{50} (Air Changes per Hour at 50Pa) to 13.1 ACH_{50}.

However, the influence of airtightness in dwellings located in mild climates has not been sufficiently investigated. Sherman et al. [138] 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 buildings. For this purpose, simulations have been performed in TRNSYS [43] for several levels of infiltration in the selected dwelling (nZEB_RD) in numerous European cities, in order to ascertain the influence of airtightness on the heating and cooling demands. The parameters to convert n50 to the real infiltration level ($n_{average}$ to be used by the model) for nZEB have been proposed.

6.2. 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.

6.2.1. 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 (Figure 6.1).

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.

Figure 6.1. Blower door test (nZEB2).

Most countries express their airtightness requirements as n_{50} (ACH). However, 50Pa is not the real pressure difference throughout the building envelope. Real pressures would be in the 1-4 Pa range for houses, 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 with mechanical ventilation systems and 3 ACH without [101].

6.2.2. Airtightness definitions

Air change is the rate at which outside air replaces indoor air in a space at the reference pressure. It is normally expressed as the number of changes of outside air per hour (ACH). n_{50} is calculated by dividing the mean air leakage at 50 Pa ($\dot{V}_{50}$) by the internal volume (V) (Equation (6.1)):

$$n_{50} = \dot{V}_{50}/V \tag{6.1}$$

To define the infiltrations in a building, the air permeability is widely used, Q_{50} ($m^3/h.m^2$) at 50 Pa pressure difference. The air permeability is the capability of a surface (or envelope) to let air pass through. Normalization using the envelope area is particularly useful to define the quality of the envelope. This is calculated by dividing the mean air leakage rate at 50 Pa by the envelope area (A_e).

$$Q_{50} = \frac{v_{50}}{A_e} \tag{6.2}$$

Normalization using the floor area, w_{50} ($m^3/h.m^2$), is expressed as the specific leakage rate at the reference pressure difference. It is calculated by dividing the mean air leakage rate at 50 Pa by the floor area (A_f).

$$w_{50} = \frac{v_{50}}{A_f} \tag{6.3}$$

6.2.3. 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 (6.4):

$$n_{average} = n_{50}/N \tag{6.4}$$

The N factor varies from 10 to 30. Kronvall and Persily [139] 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 [140] used the data to correlate the infiltration against the leakage for more than 40 houses and achieved the following result (Equation 6.5):

$$n_{average}=n_{50}/18-0.08 \quad (6.5)$$

Sherman [141,142] 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 6.2). 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 6.1. N-factor table , 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 6.2. USA Climate zone for LBL infiltration model [141,142]**.**

Table 6.1. N-factor table [141,142]**.**

Climate zone	House stories	1	1.5	2	3
	Well-shielded	18.6	16.7	14.9	13.0
1	Normal	15.5	14.0	12.4	10.9
	Exposed	14.0	12.6	11.2	9.8
	Well-shielded	22.2	20.0	17.8	15.5
2	Normal	18.5	16.7	14.8	13.0
	Exposed	16.7	15.0	13.3	11.7
	Well-shielded	25.8	23.2	20.6	18.1
3	Normal	21.5	19.4	17.2	15.1
	Exposed	19.4	17.4	15.5	13.5
	Well-shielded	29.4	26.5	23.5	20.6
4	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 [143]. Jokisalo et al. [132] 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 [144] 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 [145] 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[146].

6.2.4. Power law

The air infiltration measurements fit a power law which has the form shown in Equation (6.6). The subscript f is related to the fan induced pressure or flow:

$$\dot{V}_f = \kappa \cdot \Delta P^n{}_f \tag{6.6}$$

Where

$\dot{V}_f$ is the air flow rate (m³/s) passing through the building envelope,

κ is the leakage coefficient that is related to the size of the opening (m³/sPaⁿ),

ΔP_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 [147]. 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 [132] 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 [148].

The EN 15242:2007 standard [149] 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 (6.6), assuming that the leakage coefficient remains constant, giving Equation (6.7).

$$\frac{n_{\Delta P1}}{\Delta P1^n} = \frac{n_{\Delta P2}}{\Delta P2^n} \tag{6.7}$$

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.

6.2.5. Effective leakage area (ELA) and normalized leakage

Leakage is described as a power law Equation (6.8). The ELA (effective leakage area) 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:

$$ELA = \dot{V}_f. \cdot \frac{\sqrt{\rho/2\Delta p_r}}{C_D} \tag{6.8}$$

Assuming that Equation (6.6) and Equation (6.8) characterize the flow at some reference pressure difference Δp_r and the discharge coefficient C_D=1, the ELA can be calculated from the blower door data:

$$ELA = \kappa \cdot \Delta P_r^{n-1/2} \sqrt{\frac{\rho}{2}} \tag{6.9}$$

Which leads to:

$$Q_f = ELA \cdot \left(\frac{\Delta P_f}{\Delta P_r}\right)^n \cdot \sqrt{\frac{2P_r}{\rho}} \tag{6.10}$$

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.

Air leakage areas at one reference pressure difference can be converted to air leakage areas at another reference pressure difference according to:

$$A_{r2} = A_{r1} \cdot \left(\frac{C_{D1}}{C_{D2}}\right) \cdot \left(\frac{\Delta P_{r2}}{\Delta P_{r1}}\right)^{n-0.5} \tag{6.11}$$

The normalized leakage is a useful metric for comparing a range of buildings.

The NL is defined in ASHRAE standard 119 [150] , assuming n=0.65, with H the building height (m), C_D= 1, as follows:

$$NL = 1000 \cdot \left(\frac{ELA_{4\,Pa}}{A_f}\right)\left(\frac{H}{2.5\,m}\right)^{0.3} \tag{6.12}$$

6.2.6. Sherman Grimsrud and LBL infiltration models.

The Sherman Grimsrud model developed by Sherman in 1980 [151] and the LBL (Lawrence Berkeley Laboratory) infiltration model developed by Sherman in 1986 [152] 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 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 at 4 Pa, as the area of a perfect nozzle (discharge coefficient of unity). The LBL model is incorporated into the ASHRAE Standard 119 [150].

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

$$Q = ELA \cdot s \tag{6.13}$$

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

$$s = \sqrt{f_s^2 \cdot |\Delta T| \cdot f_w^2 \cdot V^2} \tag{6.14}$$

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. 6.15

$$f_s = \left(\frac{1+R/2}{3}\right) \cdot \left(1 - \frac{X^2}{(2-R)^2}\right)^{3/2} \cdot \left(\frac{g \cdot H}{T_0}\right) \tag{6.15}$$

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:

$$f_w = C \cdot (1-R)^{1/3} \cdot A \cdot \left(\frac{H}{10m}\right)^B \tag{6.16}$$

C is an empirical shielding parameter whose values are given in Table 6.2. The second term corrects the wind speed. A and B are terrain parameters whose values are indicated in Table 6.3.

Table 6.2. Local shielding classes [142].

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 6.3. Terrain parameters values [142].

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 ((m³/s)²/(m⁴ºK)) and a wind coefficient (C_w) ((m³/s)²/(m⁴ (m/s)). These coefficients are functions of a factor that it calls the shelter class together with the height of the building (in stories).

$$s = \sqrt{C_s \cdot \Delta T + C_w \cdot V^2} \quad (6.17)$$

Table 6.4. Stack coefficient Cs [151].

House stories	1	2	3
C_s	0.000145	0.00029	0.000435

Table 6.5. Wind coefficient Cw [151].

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

6.2.7. Infiltrations according to the Passivhaus standard

The infiltration air change rate as a result of leaks is determined by the PHPP tool on the basis of a simple approximation equation found also in the EN ISO 13790 until 2008 [80] (Equation 2.3). The rate of air leakage depends on the fan pressurization test result (n_{50}) and the wind screening coefficient according to EN 832 [82]. The values are listed in Table 2.13. Also, a correction factor is applied, the relation between V_{n50} (air volume during blower door test) and V_v (real volume).

The default value for infiltration for PHPP 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.

6.3. Computational model

The dwelling model nZEB_RD in TRNSYS incorporates all the requirements set by the Passivhaus standard as an example of a nZEB dwelling. 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.

6.3.1. Dwelling model parameters

The dwelling nZEB_RD is described in Chapter 2 (2.3.3.1.). The recommended envelope transmittance limit values for central and northern European countries are different from those for Mediterranean countries. These values can be found in Table 3.3.

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 heat exchanger efficiency in the model is 85%, representative of the efficiency currently available on 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. 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 [29] regarding the indoor environmental input parameters for the design and assessment of energy performance of buildings. This interval is wider than that of most European standards (See Table 7.1).

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 [9] 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, lighting and equipment depending on the time of the day and the day of the week, as set out in Table 2.4.

6.3.2. 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.[153] 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 6.6, four of them located in northern Europe for the purposes of comparison. The southern and northern cities are indicated in Figure 6.3.

Table 6.6. Selected cities.

COUNTRY	CITY	CLIMATIC ZONE
SPAIN	Almeria	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

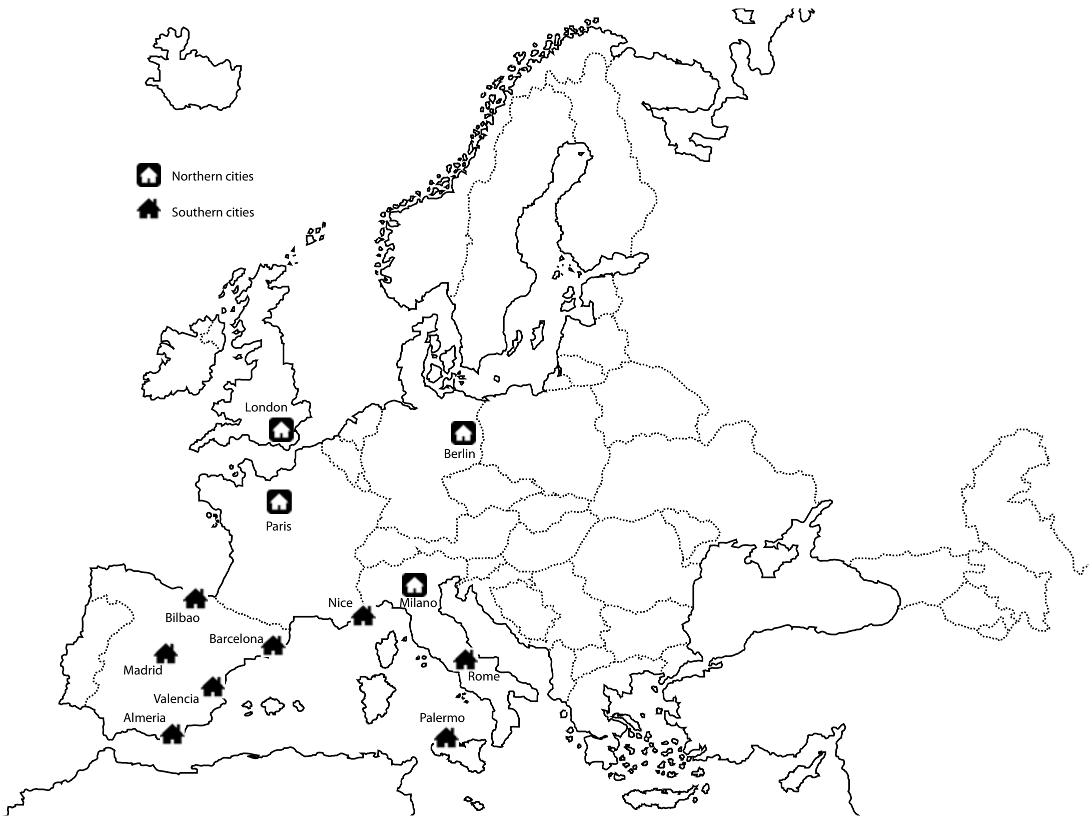


Figure 6.3. Cities location.

The climate data files are taken from the Meteonorm meteorological database [118]. 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.

6.4. 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 0.6ACH 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 1 , 2.5 Pa or 4 Pa [147] than to 50 Pa. 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 (6.4) for houses with heat recovery ventilation. The reverse conversion can also be carried out by applying the Power Law (6.6), 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 Table 6.8.

Table 6.7 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. Taking into account the most recent correlation, and supposing that the dwelling has a ΔP=2.5 Pa which is a suitable value for mechanical ventilation systems, it seems that the n value given by EN 15242 is the most appropriate. Applying this conversion, the value of $n_{average}$= 0.08 ACH (ΔP =2.5 Pa) for the simulation model corresponds to n_{50}=0.6 ACH

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 [138]. Zendher, as a developer and manufacturer of air ventilation systems including HRV/ERV, has confirmed that a n_{50}= 2ACH will not affect the air system performance.

For all the cities under study a reverse conversion can be done to obtain the corresponding n_{50}.

Table 6.7. $n_{average}$ 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 factor N	Kronvall and Persily and ISO 13789; N=20	0.80	1.60	2.40	3.20	4.00	4.80
	Persily (6.2)	0.80	1.52	2.24	2.96	3.68	4.40
	Sherman LBL (4- well-shielded*) N=20.6	0.82	1.65	2.47	3.30	4.12	4.94
	Sherman LBL (2- well-shielded*) N=15.5	0.62	1.24	1.86	2.48	3.10	3.72
	Sherman LBL (4- exposed*) N=15.4	0.62	1.23	1.85	2.46	3.08	3.70
	Sherman LBL (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 6.2.6, 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) [126]. 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_{50} for the selected dwelling is 37.1 cm^2 and ELA_4 is 25.4 cm^2.

Some simulations have also been performed with Type 960 which contains the LBL model for the purposes of comparison. The values obtained for the energy demand are the same as for the cooling demand and very similar (< 1%) for the heating demand as those obtained with Type932.

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. [154] 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.

6.5. Results and discussion.

Figure 6.4 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:

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

- Red 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.

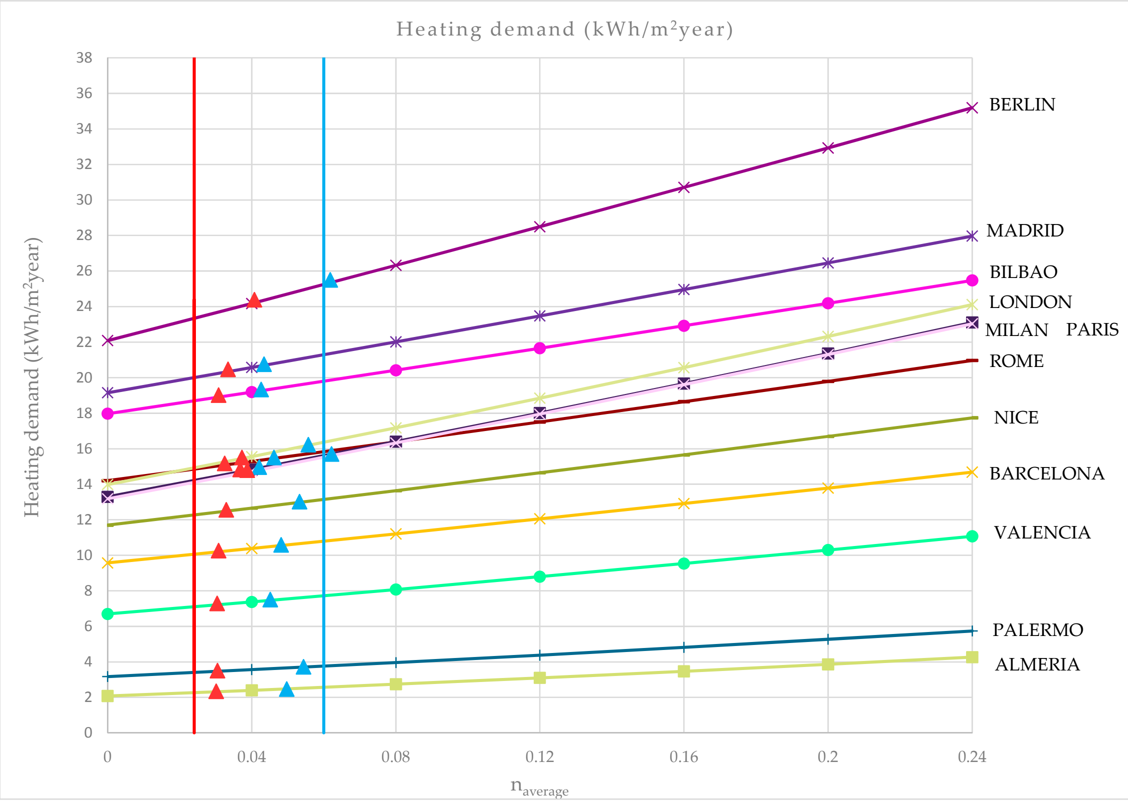


Figure 6.4. $n_{average}$ and heating energy demand depending on the air infiltration.

The vertical red and blue lines represent the $n_{average}$ value for the Passivhaus standard. For e= 0.1 (no screening), the $n_{average}$ is 0.06 (blue line) while for e= 0.04 (high screening) the $n_{average}$ is 0.024 (red line). 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 (15kWh/m^2 year), 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^{2}year 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^{2}year. 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/m²year 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 0.042ACH (lowest value for Milan) to 0.062ACH (highest value for Berlin and Paris) for class 1, and from 0.030ACH (lowest value for Almeria and Valencia) to 0.041ACH (highest value for Berlin) for class 5.

The cooling demand depending on the $n_{average}$ for each city is shown in Figure 6.5. 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:

- Blue triangles: Sherman Grimsrud infiltration model for wind coefficient C_w= 0.000494 for no wind obstructions, class 1.
- Red triangles: Sherman Grimsrud infiltration model for wind coefficient C_w= 0.000049 for local shielding, class 5: shelter produced by buildings or other structures that are immediately adjacent.

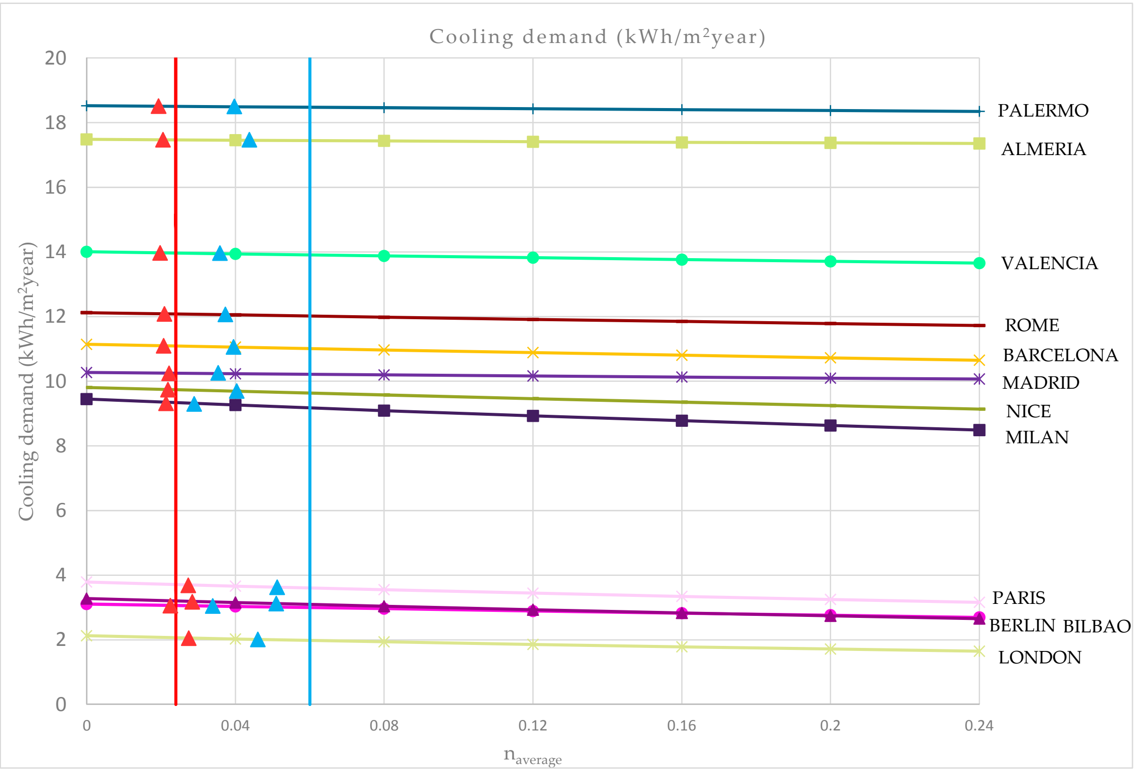


Figure 6.5. $n_{average}$ and cooling energy demand depending on the air infiltration.

The vertical red and blue lines represent the $n_{average}$ value for the Passivhaus standard, as in Figure 6.4. 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 (15kWh/m² year), 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.

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 0.029ACH (lowest value for Milan) to 0.051ACH (highest value for Berlin and Paris) for class 1, and from 0.019ACH (lowest value for Palermo) to 0.028ACH (highest value for Berlin) for class 5.

Figure 6.6represents the increase in the total air conditioning energy demand (heating plus cooling) throughout the year.

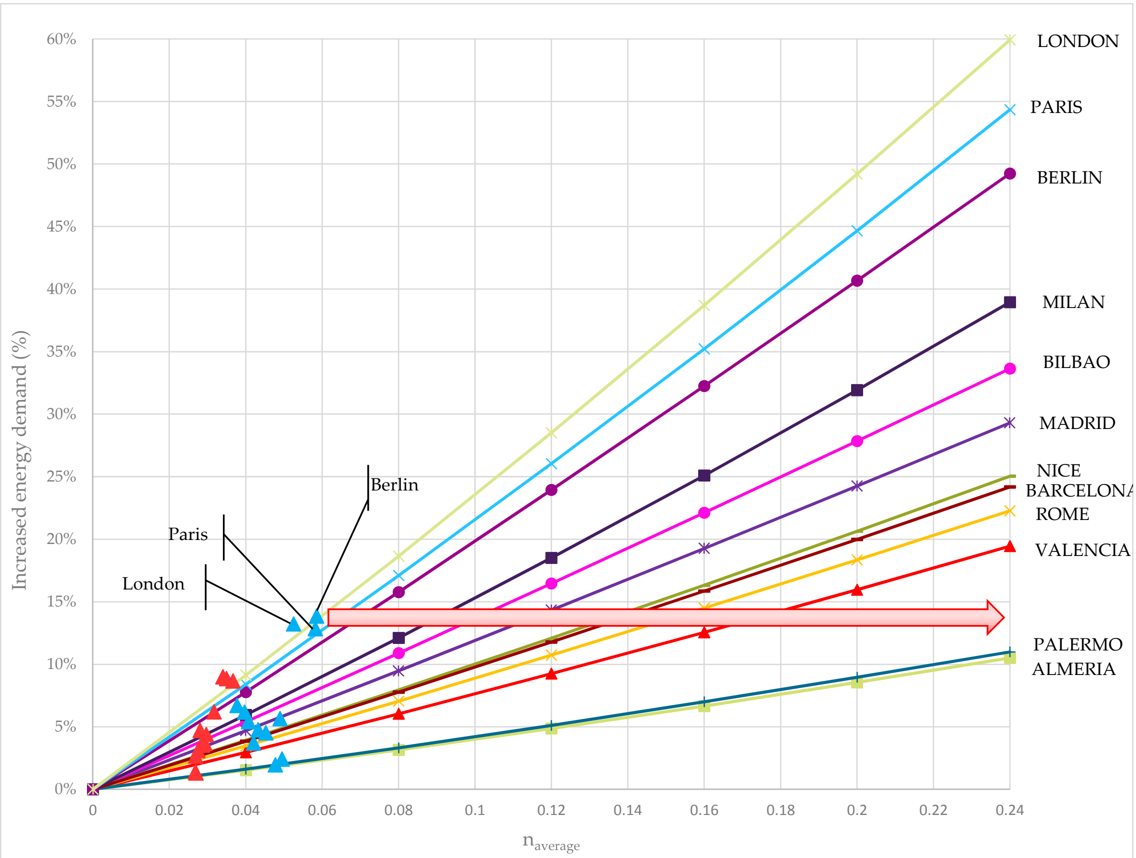


Figure 6.6. Increased energy demand (%) depending on the air infiltration $n_{average}$.

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 0.08ACH, 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 0.08ACH.

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

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 0.09ACH and 0.12ACH; for Nice, Barcelona, Rome and Valencia between 0.13ACH and 0.17ACH; and even more than 0.24ACH for Palermo and Almeria.

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

The mean infiltration values (n_{avSG}) obtained applying the Sherman Grimsrud infiltration model throughout the year range from 0.038ACH (lowest value for Milan) to 0.059ACH (highest value for Paris) for class 1, and from 0.027ACH (lowest value for Almeria, Valencia, Barcelona and Palermo) to 0.037ACH (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 6.7 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.

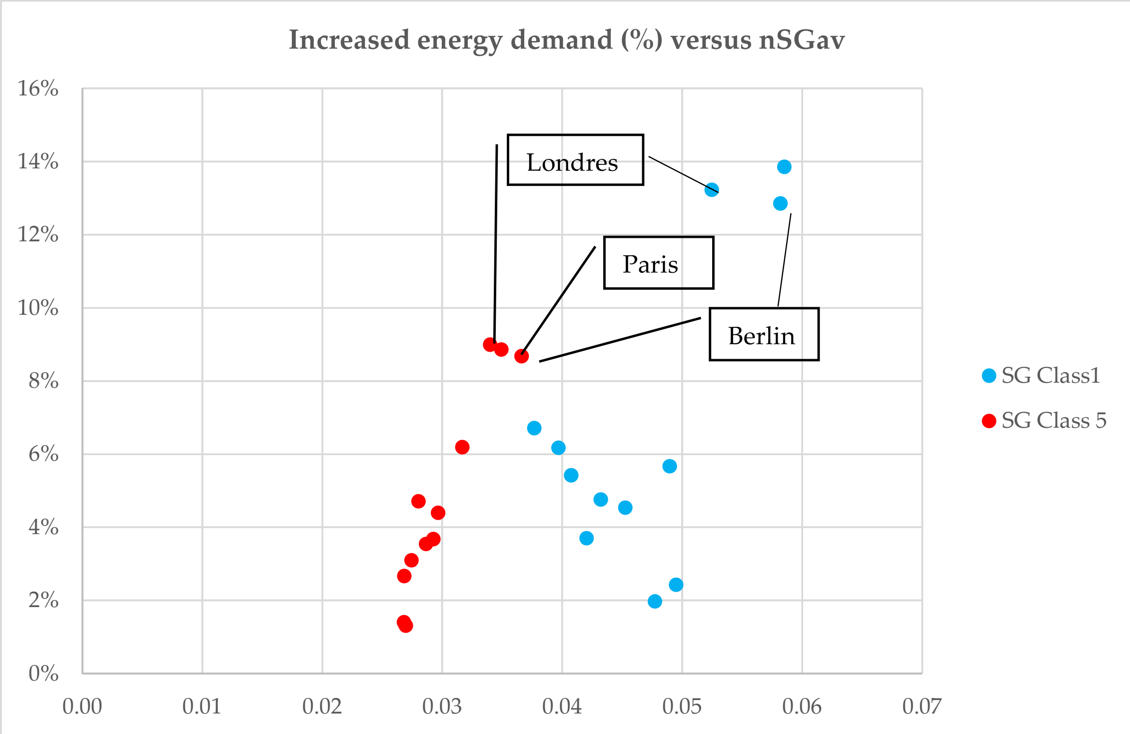


Figure 6.7. Increased energy demand (%) depending on the air infiltration $n_{average}$.

The variation of the air infiltration rate during different months of the year can be seen in Figure 6.8 for class 1 and in Figure 6.9 for class 5.

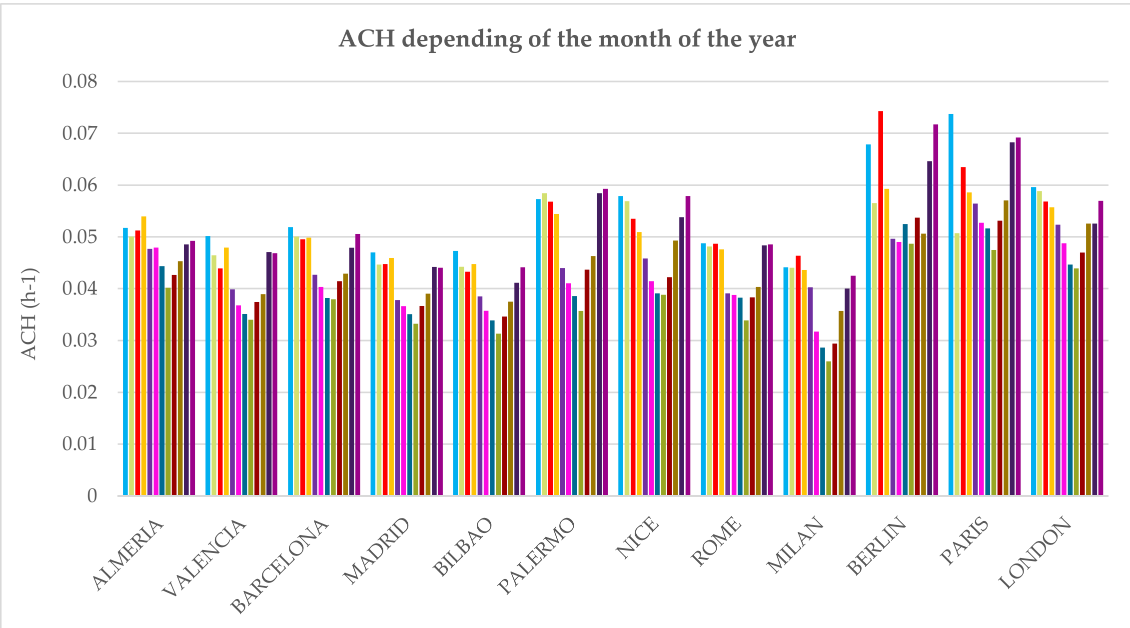


Figure 6.8. ACH depending of the month of the year. Sherman Grimsrud model Class 1.

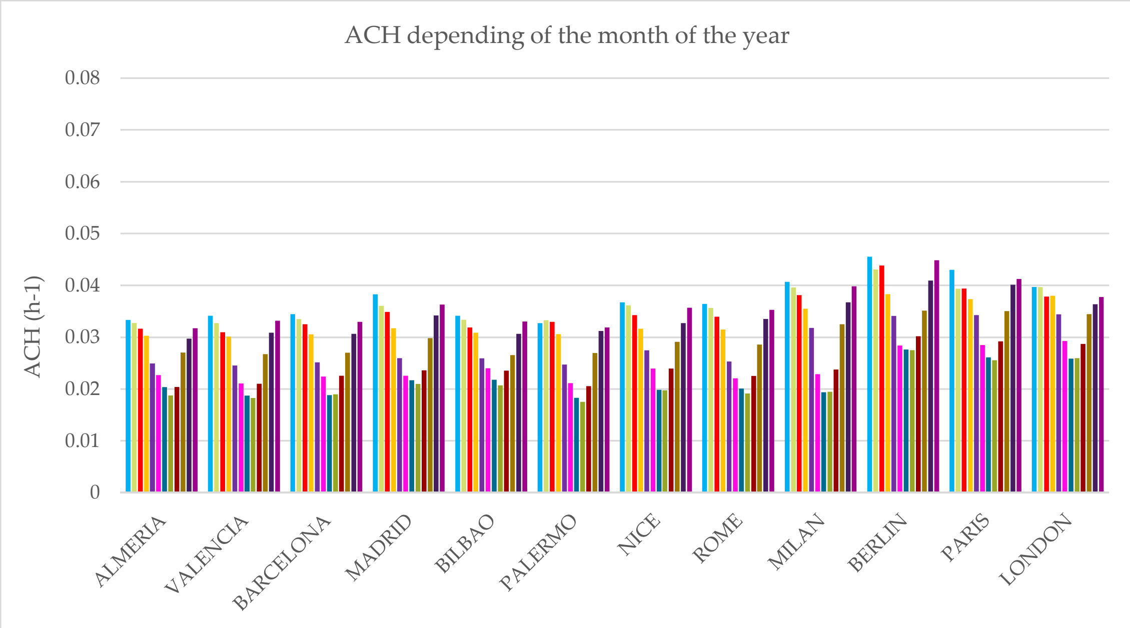


Figure 6.9. ACH depending of the month of the year. Sherman Grimsrud model Class 5.

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 0.026ACH but minor in Almeria with a difference of 0.012ACH 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 0.013ACH.

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 6.4) with the n_{avSG} obtained for nZEB dwellings located in areas without wind obstructions (class 1) and in city centres (well-shielded, class 5). The values are shown in Table 6.8.

For class 1, the correlation factor value is between 12 and 14 for all the Mediterranean cities and approximately 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 approximately 17 for cities located in northern Europe.

Table 6.8. N correlation factor obtained from Sherman Grimsrud model.

	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

6.6. 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 0.6ACH (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 0.6ACH 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.

Chapter 7

Comfort settings and energy demand for residential nZEB in warm climates.

7. Comfort settings and energy demand for residential nZEB in warm climates.

Abstract

Building policies worldwide are becoming more demanding in terms of improving the energy performance of buildings to ensure that the target for nearly zero-energy buildings (nZEB) will be reached.

Setting the thermal comfort parameters for a nZEB is a big challenge because the parameters must provide adequate indoor thermal conditions while at the same time guaranteeing the sustainability of buildings. Thermal comfort parameters for residential buildings have a strong impact on air conditioning demand.

In this study, simulations have been performed to check the impact of comfort parameters on the air conditioning energy demand for residential nZEBs following the Passivhaus standard. Fifteen cities located in the south of Europe were selected for this study: twelve cities located in Spain, two in Italy and one in France as examples of a warm climate. Energy demand simulations have been carried out for a range of temperatures and different degrees of air humidity in order to calculate their impact depending on the climate data. The results obtained for a nZEB dwelling were compared with those obtained for a traditional dwelling to provide information for the development of further standards and norms concerning indoor climate and energy calculations.

Moreover, simulations have been performed following adaptive models where the comfort temperature depends on the outdoor conditions. These results will help countries with warm climates, like those in southern Europe, to define their thermal comfort parameters for nZEB.

Keywords

Residential nZEB, Thermal comfort, Building Energy demand, Mediterranean climate

7.1. Introduction

Thermal comfort parameters in residential buildings have a strong impact on the energy demand [155] and must therefore be selected with extreme caution [95]. In order to obtain maximum optimization, their values should be personalized depending on the climate area given that it has been demonstrated that indoor thermal comfort parameters depend on the outdoor conditions [156,157] and, more specifically, the thermal comfort in residential buildings shows a strong dependency on recent outdoor temperatures [158].

In Europe, the EN 15251 standard [29] set limits for indoor conditions to ensure the comfort of occupants when making energy performance calculations. The latest version of the norm is dated 2008 and it has not been reviewed since to include the new nZEB requirements.

Nowadays, northern European countries have already adapted their regulations to nZEB requirements. Conversely, some southern countries have yet to adapt their regulations to the new energy demand objectives. Therefore, new research into the influence of comfort parameters on energy demand is needed since their impact is expected to be more important for warmer climates (in percentage if not in absolute values), but this has yet to be proven.

It has been shown that adaptive comfort models yield energy savings for natural ventilated buildings and ventilated systems without energy recovery. However, the Passivhaus standard, as a reference implementing nZEB requirements in Europe [18], imposes mechanical ventilation systems with energy recovery. Therefore, t further research is required to find out whether these comfort models offer the same advantages for constructions built under this standard.

Fifteen southern European cities were selected for this research. Their climate is defined by the Köppen-Geiger climate worldwide classification as a temperate climate [159,160], which is found in the Mediterranean area (the Spanish coast, Italy, France, Greece, Turkey, Lebanon, Israel, and north African countries such as Morocco and Tunisia) and in parts of southern Australia and the southern USA. The Passivhaus standard has its own climate classification [161], divided worldwide into 7 climate areas. Europe has 5 climate areas (arctic, cold, cold temperate, warm temperate and warm) while the Mediterranean area is divided into two areas (warm and warm temperate).

In this work, energy simulations were performed for a dwelling built under the Passivhaus standard (nZEB) and for a dwelling with the same layout but built with the constructive and functional characteristics of a traditional dwelling (not nZEB).

TRNSYS [55] was used as a simulation tool and the model was validated with experimental data. The simulations were done for a range of temperatures and air humidity set points in order to calculate their impact for each of the cities selected, providing sensible and latent energy demand throughout one year on an hourly basis.

Additionally, the effect of using an ERV instead an HRV, when varying the relative humidity set for air conditioning, was calculated for the cities with the most humid climate.

Moreover, simulations were performed following adaptive models where the comfort temperature depends on the outdoor conditions. Temperature ranges based on adaptive models, usually wider than those required by the current standards, have been evaluated for their possible inclusion in the nZEB requirements for warm climates.

7.2. Literature review

This section presents the state-of-the-art with respect to the influence of comfort set values on the building air conditioning demand for residential nZEB, more specifically for warm and temperate climates. The aim is to provide the reader with a better understanding of areas of active research in building energy demand optimization.

Kwong et al. [35] provide a review of the energy efficiency in air conditioned tropical buildings by considering the thermal comfort of occupants. They state that the assessment of human thermal comfort conditions should be incorporated into the building energy audit for enhancing energy efficiency. Several studies have shown that substantial energy reductions can be made by modifying the summer set point temperature (SST) [162,163]. Al Sanea [164] found a net saving in yearly energy-cost of about 4% per 1 ºC increase in the thermostat setting in summer within the thermal comfort zone in the hot desert area in Riyadh.

Cetin et al. [165] investigated the effect of smart thermostats on thermal comfort and energy savings for representative single family residential buildings located in 3 climate zones with dominant cooling loads. They state than a one degree increase in the set point temperature is an important influencing factor in all climate zones.

Rohdin et al. [166] report the performance of nine passive houses built in Sweden. The energy use in these buildings is highly dependent on the set point temperature. For a 20ºC set point the specific annual energy use for heating is around 21kWh/m^{2}y, while it is about 35kWh/m^{2}y for a 24ºC set point.

A study carried out with TRNSYS for a detached single family home (energy plus house) in Copenhagen and Madrid [167] showed that moving the indoor temperature set point from 23ºC to 25ºC in Madrid can decrease the cooling need by 23%. The study also demonstrated the advantages of quantifying the energy saving potential with respect to different temperature set points. The same authors published a more recent study [168] presenting the results of thermal environment measurements and energy use in the single family house during a one year period. The operative temperature set-points were varied during the heating and cooling seasons, and it was concluded that the adaptive actions of the occupants play a crucial role in the thermal comfort and the annual energy performance of the building.

Ghahramani et al. [169] concluded that daily optimal set points based on the outside temperature improve the energy efficiency of office buildings. After simulating the DOE reference office building types in all the United States climate zones, they showed that the choice of set points is a very influential factor (up to 30%) on energy savings.

In their review of thermal comfort models, Yang et al. [155] state that the static Predicted Mean Vote (PMV) model works effectively in air-conditioned buildings but does not work well in naturally ventilated buildings. They conclude that adaptive comfort models have a wider range of comfort temperature and provide significant energy savings.

Denmark was one of the first countries to include the adaptive thermal comfort approach in its building code in 2015 [170]. This reflects the effectiveness of controlling the comfort set points from the energy savings point of view in cold climates. It remains an open question whether such an action will be so effective and interesting for countries with warmer climates.

There are numerous publications investigating the effect of relative humidity on human thermal comfort in hot and humid climates [31,39,171]. However, the relation between the humidity control and the energy demand has not been studied in depth, and much less for temperate climates with medium moisture loads such as that found in the area of the Mediterranean area.

Wan et al.[172] investigate the effect of indoor temperature and relative humidity on human thermal comfort and energy consumption in a central air conditioning system in the south of China, concluding that the influence of indoor relative humidity on energy consumption is greater than the indoor temperature. Some research has been carried out on the use of energy recovery devices to optimize the energy performance of buildings [127,173–175] but the suitability of the use of ERV in warm climates is still an open question.

In summary, previous research does not appear to have analyzed the savings resulting from adjusting the set points with respect to other factors such as the climate and construction type (nZEB versus traditional buildings). There is a lack of research examining the impact of comfort settings on energy demand in warm climates and, specifically, this impact has not been studied for nZEB. It is hoped that the findings of the present study can help to establish procedures to achieve optimal thermal comfort and energy demand optimization in nZEB residential buildings in warm regions.

Section 7.3 includes a brief review of the thermal comfort concept and comfort models and Section 7.4 reviews the current European comfort standards which should be considered in order to provide thermal satisfaction to the occupants when optimizing the air conditioning energy demand.

7.3. Thermal comfort in buildings. Theoretical background

The EN ISO 7730 standard [111] defines thermal comfort as 'that condition of mind which expresses satisfaction with the thermal environment'. It can thus be said that thermal comfort results from a combination of environmental factors and personal factors. The environmental factors are the air temperature (dry bulb temperature (DBT)), the air velocity (m/s), the radiant temperature of the surroundings (including surfaces, heat generating equipment, the sun and the sky, usually expressed as mean radiant temperature (MRT)) and the relative humidity (RH, expressed as a percentage).

The personal factors are clothing and metabolic heat (the heat produced through physical activity).

The norms and standards regulate the operative temperature (T_o) which depends on the indoor air temperature (T_a) and the mean radiant temperature (T_{rm}). The T_{rm} is the mean radiant temperature of the inner surface of the envelope that delimits the enclosure and 'a' is a factor which depends on the air velocity. The operative temperature is calculated as follows [176]:

$$T_O = aT_a + (1 - a)T_{rm} \quad (7.1)$$

For an air velocity lower than 0.2 m/s, as recommended by Passivhaus for nZEB, the 'a' factor is 0.5.

T_{rm} is very similar to the temperature of the indoor air for nZEB due to the low U-values required for the envelope.

Although human tolerance to humidity variations is much greater than tolerance to temperature variations, humidity control is also important. High humidity can cause condensation problems on cold surfaces and retards human heat loss by evaporative cooling, while low humidity tends to lead to dry throat and nasal passages.

Nowadays, there are two different approaches defining thermal comfort, the heat balance or steady state model and the adaptive thermal comfort model.

7.3.1. Steady-state comfort model.

The steady-state comfort model is based on the work of Fanger who used data from climate chambers to construct his theory [177]. The model uses the four factors related to the environment and the two personal factors: the Predicted Mean Vote index (PMV) and the Predicted Percentage of Dissatisfied index (PPD). The PMV predicts the mean value of thermal votes for a large group of people under the same environmental conditions and the PPD defines how many people will fall outside the comfort limits determining how many are thermally dissatisfied. Depending on the ranges PPD and PMV, three kinds of comfort zones are defined. This empirical approach has been further developed over the years. Fanger's equation subsequently became the basis for ISO 7730-

1984 [178] and ASHRAE 55- 1992 [179] in which the temperature ranges are based on steady-state studies.

7.3.2. Adaptive thermal comfort model.

The adaptive model, incorporated in ASHRAE standard 55 [176], is based upon field surveys of people in their normal surroundings and assumes that the thermal sense is an important element of thermoregulatory behavior. The adaptive thermal comfort model considers that people having some control over their personal thermal environment are more likely to adjust their expectations leading to a wider comfort temperature range or humidity level and increased tolerance conditions. This tolerance extends to season and climate. This would lead to potential energy savings. The energy savings potential stated in the literature [180] ranges from 4 % to 60% using personalized ventilation with a lowered cooling set point. Besides, extending the temperature range to 18-30ºC with personalized control can save 40% of the annual energy consumption. Regarding the control of indoor relative humidity, increasing the relative humidity set-point in humid climates is the most effective strategy and thermal comfort can still be acceptable up to 30 ºC and 80% RH, without discomfort from the humidity [37].

The adaptive thermal comfort model defines the indoor thermal comfort as a function of the outdoor conditions. In the 1970s, Humphreys [181] represented the comfort temperature depending on the monthly mean outdoor temperature. He shows a clear difference between people in free running or heated and cooled buildings. The relationship for free-running buildings is closely linear. However, for air conditioned buildings the relationship is more complex.

McCartney et al. [156] subsequently collected and analyzed extensive data from five countries across Europe (France, Greece, Portugal, Sweden and the UK) creating adaptive relations between climate and comfort indoors. Five buildings were studied in each country for two types, naturally ventilated (NV) and air conditioned buildings (AC). These authors obtained equations for calculating the comfort temperature (Tc) depending the running mean outdoor temperature (T_{RM80}) for index 0.8 (see Equation (7.2)) for each country and a general equation recommended for use in Europe ((7.3) and (7.4)):

$$T_{RM80} = 0.8T_{RMn-1} + 0.2T_{DMn-1} \qquad (7.2)$$

Where T_{DMn-1} is the daily mean outdoor temperature on day n-1 (ºC)

$$Tc = 0.302T_{RM80} + 19.39^{\circ} \qquad T_{RM80} > 10^{\circ}C \qquad (7.3)$$

$$Tc = 22.88^{\circ}C; \qquad T_{RM80} > 10^{\circ}C \qquad (7.4)$$

Of the countries studied, Portugal and Greece have the most similar climate to that of Spain as they are located at similar latitudes. The equation obtained for Portugal (Equation (7.5)) is the following:

$$Tc = 0.381T_{RM80} + 18.12 \qquad (7.5)$$

For Greece, no equation has been defined for the winter period but for the summer season (T_{RM80} >10ºC) the equation obtained is the following (Equation (7.6)):

$$T_C = 0.205T_{RM80} + 21.69 \quad (7.6)$$

7.4. Comfort standards

The requirements for thermal comfort are prescribed in standards which establish variances in the comfort parameters between naturally ventilated, mechanically ventilated and mixed-mode buildings.

Differences are found in the response of people in buildings with no heating or cooling and those with mechanical control. This paper is focused on mechanically ventilated buildings and has taken a Passivhaus dwelling as an example of a nZEB dwelling. A mechanical ventilation system including a heat recovery ventilator (HRV) or an energy recovery ventilator (ERV) is a requirement of the Passivhaus standard to achieve the energy demand objectives for nZEB [27]. The most relevant international standards that should be considered for thermal comfort are ISO 7730:2005 [111], ASHRAE Standard 55: 2013 [182], and EN 15251:2008 [29].

7.4.1. ISO 7730:2005.

The international standard ISO 7730:2005 [111] provides methods to predict the thermal sensation and degree of discomfort of people by using the PMV and the PPD. Humphreys [183] concludes that the ISO PMV could lead to excessive cooling in warmer climates and unnecessary heating in cooler regions. The parameter limits to guarantee the comfort set by ISO 7730 are shown in Table 7.1.

7.4.2. ASHRAE Standard 55.

The first ASHRAE standard, 55 -1992 [179], which was not adaptive, followed the ISO 7730 by differentiating two temperature comfort ranges, one for summer and the other for winter.

The ASHRAE 55-2004 standard [184] introduced the differences in the comfort ranges for naturally ventilated (NV) and for air conditioned buildings (AC) or mechanical ventilated buildings (MV)).The standard proposed a method for determining acceptable thermal conditions for NV spaces, the comfort bandwidths being dependent on the Prevailing Mean Outdoor Air Temperature. Figure 7.1 shows the comfort range for MV buildings.

The maximum accepted humidity ratio was 0.012 kg/kg dry air, independent of the temperature and the season.

The ASHRAE 55-2010 standard [176] specifies the relation between the environmental parameters and personal parameters to provide thermal conditions acceptable to a majority of the building occupants.

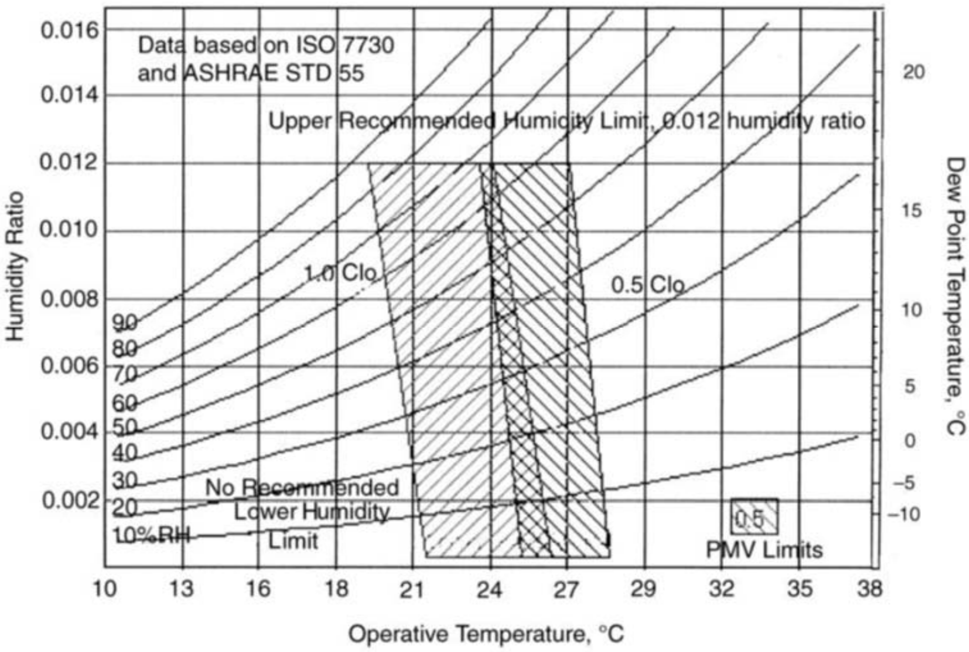


Figure 7.1. Comfort range for MV buildings. ASHRAE 55-2004 [184].

7.4.3. EN 15251:2008.

The EN 15251 standard [29] was designed to set limits for indoor conditions to ensure that the EPBD [6] did not compromise the comfort of occupants in the pursuit of energy reduction. The indoor parameters for dimensioning the heating, cooling and ventilation systems for European buildings are defined in the norm for design and energy performance calculations. Those values are different if the building is NV or AC. The standard gives an equation to calculate the comfort temperature for naturally ventilated buildings depending on the mean of the daily outdoor temperature.

For buildings with mechanical ventilation, the comfort limits are set using Fanger's Predicted Mean Vote (PMV). The minimum temperature for winter and the maximum for summer are defined depending on the clothing worn and the ambient categories, of which there are four depending on the expected level of comfort. Category II (Normal) is suggested for new buildings. The recommended design temperature for the air conditioning and values for relative humidity are shown in Table 7.1.

7.4.4. Spanish norms and other European standards.

Based on the requirements set by the European norm, European countries include in their national standards the requirements or recommendations for lower and upper limits for indoor air temperature. Some of the reviewed European standards do not include values for relative humidity. The current values for residential buildings in Spain and other nearby countries are shown in Table 7.1 for comparison.

Table 7.1. Max. and Min. Operative temp. and RH range required or recommended by the standards for residential buildings.

Standard/ Norm	EN15251 [a] [29]	ISO7730 [111]	ASHRAE 55 [176]	Germany [101]	France [c] [185]	Italy[d] [186]	Spain [187]	Passivhaus [27]
Min. Temp winter	20ºC[g]	20ºC[i]	20ºC[i]	20ºC	18ºC	20ºC	21ºC	20ºC
Max. Temp. summer	26ºC[h]	26ºC[h]	26ºC[h]	25ºC- 27ºC[b]	28ºC	26ºC	25ºC	26ºC
RH range	25 -60%	30-70 %	0.012[j]	--[f]	--[f]	--[f]	40-60 %	30-60 %

[a] *Recommended design values.*

[b] *Germany is limited at 25ºC, 26ºC and up to 27ºC in summer for climatic regions A, B and C respectively.*

[c] *France: the max. temp. when Mechanical Ventilated building is 28ºC, different limit value according to building type and external temp. in the case of Natural Ventilated building*

[d] *Italy set the max. Temp. for heating system (with +2ºC of tolerance) and the min. Temp. for cooling system (with -2ºC of tolerance)*

[e] *Category II (Normal level of expectation)*

[f] *No values in standards*

[g] *For 1 clo and 1.2 met*

[h] *For 0.5 clo and 1.2 met*

[i] *For 0.9 clo and 1.2 met*

[j] *Max. Specific Humidity kg/kg dry air*

7.5. Model description.

7.5.1. Climate data and selection of cities.

Fifteen cities located in southern Europe, an area which can be categorized as a warm climate region, were selected for this study.

The Basic Document HE1 of the Spanish Technical Building Code (CTE) [187,188] distinguishes five geographical areas depending on the severity of the climate in winter (a letter indicates the severity from lowest to highest: A, B, C, D and E) and four geographical areas depending on the climate severity in summer (a number indicates the severity from lowest to highest: 1, 2, 3 and 4). A total of 12 climatic zones are distinguished in the Spanish mainland (the climatic zones of the Canary Islands have not been included in the study). A city from each Spanish climatic zone, one from the south of France, and two cities from Italy were selected (Figure 7.2). Marseille (France) is located on the north coast of the Mediterranean, Rome (Italy) on the east and Palermo on the south-east where the climate is hotter and more humid than Rome.

The climate data files are taken from the Meteonorm meteorological database [118].

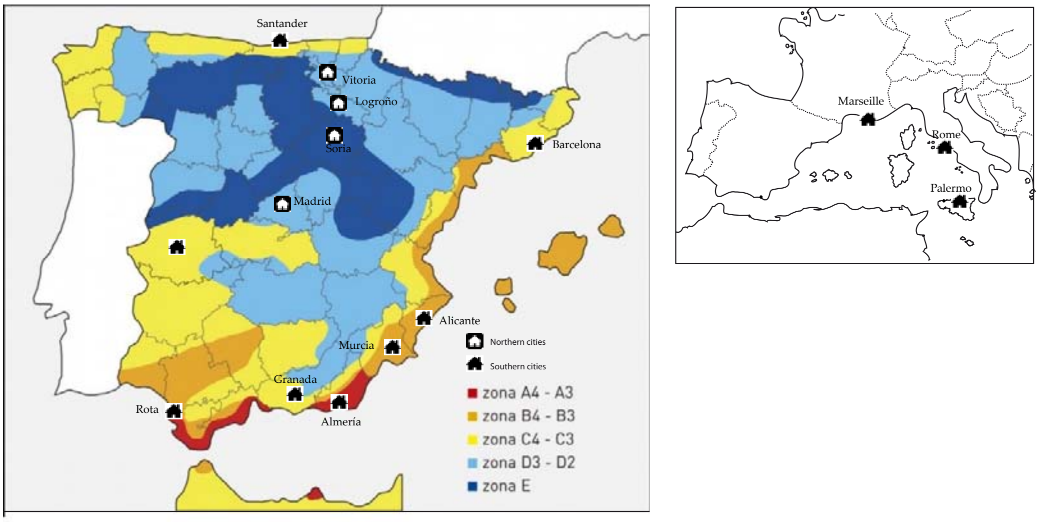


Figure 7.2. Selected cities and winter climatic zones described in the Spanish legislation.

7.5.2. Dwelling models: nZEB_RD and traditional dwelling model.

Two models were developed for the same dwelling layout: a nZEB dwelling model following the Passivhaus standard requirements and a second traditional dwelling model. The traditional dwelling model contains the parameters of a standard dwelling built in the south of Europe during the years before the requirements for nZEB dwellings appeared in the standards and new constructions began to spread throughout Europe.

The objective is to check the impact of comfort parameters on the air conditioning demand in both types of construction (nZEB and traditional). Only the parameters which have the greatest impact on the air conditioning demand of the dwelling are different in both models: the envelope transmittances, the air tightness and the air ventilation system.

1) For the nZEB model, the envelope transmittance U-values are those recommended by Passivhaus for Mediterranean countries. These are applied to the cities located in the Spanish winter climatic zones A, B and C, to Marseille and to the Italian cities. The U-values recommended by Passivhaus for central and northern Europe are applied to the Spanish cities located in winter climatic zones D and E (values in Table 7.2).

For the traditional dwelling model, the envelope transmittance U-values are those recommended by current Spanish regulations depending on the climatic zone (Table 7.2). France [189] and Italy [190] regulate the thermal transmittances of the building enclosure, and the values given in their current regulations are more demanding than the Spanish ones. In order to compare the results and to maintain the traditional dwelling performance as a typical construction before the EPDM, the transmittance values for the building enclosure assigned to Marseille and Rome are the values of

Spanish climatic area C and to Palermo the values of Spanish climatic area A (similar climates).

Table 7.2. Average transmittance limit depending on the location of the building enclosure (W/(m²K).

Average transmittance limit depending on the location of the building enclosure (W/(m²K))							
TNRSYS Model	**nZEB dwelling model**		**Traditional dwelling model**				
Norm/Standard	*Passivhaus: Provides different values for Central & North of Europe and Mediterranean countries.*		*DBHE1 (Spain)*				
Climatic zone	CENTRAL&NORTH	MEDIT.	A	B	C	D	E
External Walls	0.15	0.34	0.94	0.82	0.73	0.66	0.57
Floors	0.15	0.26	0.53	0.52	0.50	0.49	0.48
Roofs	0.15	0.26	0.50	0.45	0.41	0.38	0.35
Windows/ doors	0.80	1.40	4.10	3.25	2.48	2.48	2.48

2) The air infiltration flow for the nZEB model corresponds to the maximum value set by the Passivhaus standard, n_{50}=0.6 ACH (air changes by the hour), and for the traditional model n_{50}=1.8 ACH, which is a conservative value according to the study done by Montoya el al. [136] for air leakage in existing Catalan dwellings (in northern Spain).

3) The nZEB model includes a mechanical ventilation system with a Heat Recovery Ventilator (or Energy Recovery Ventilator), an essential component for Passivhaus. The traditional dwelling model does not have a recovery device.

The total air ventilation rate considered in the models is 120m³/h. The air ventilation flow is considered constant throughout the year, except that an extra ventilation flow is added for high occupation during three hours at the weekend (8 people at home) when the air ventilation flow is 240m³/h. The values for each room are shown in Figure 2.18.

The rest of the models parameters, such as the internal loads, are the same of those presented for nZEB_RD in chapter 2.

7.6. Methodology.

The simulations were performed changing the temperature and humidity settings for the two models, as shown in Table 7.3. The heating demand was obtained from October to May and the cooling demand from June to September [9].

It is considered that the operative temperature for nZEB buildings is practically equal to the indoor air temperature and equal to the temperature set for air conditioning systems, as is explained in 7.3. The hypothesis has been verified on the nZEB model.

However, this hypothesis cannot be applied to the traditional model where the operative temperature is lower than the room temperature (the temperature set point for the air conditioning demand) due to the inferior thermal insulation of the envelope in the traditional model. The mean radiant temperature has been calculated with TRNSYS by obtaining the inside wall temperature in the living room and then applying equation (7.1) for a=0.5. The air temperature set for the traditional model is finally one degree higher in winter to obtain the equivalent operative temperature. No adjustment is needed during summer due to the lower air temperature difference between indoors and outdoors.

Table 7.3 Temperature and humidity settings for the simulations performed.

		Toperative (ºC)	**Humidity**	**nZEB dwelling model**	**Traditional dwelling model**
First set of simulations	Simulations performed at constant set temperature and constant set humidity WINTER: Heating energy demand	19	RH 30-60%	All cities: HRV	All cities
		20			
		21			
Second set of simulations	Simulations performed at constant set temperature and constant set humidity SUMMER: Cooling energy demand	25	RH 60%	All cities: HRV and Mediterranean cities: ERV	All cities
		26			
		27			
Third set of simulations	Simulations performed at constant set temperature and constant set humidity WINTER AND SUMMER: Latent energy demand	20-26	RH 30-60%	Mediterranean cities HRV and ERV	------
			RH 30-65%		
			RH 30-70%		
			Max. 0.012 kg/kg dry air		
Fourth set of simulations	Simulations performed at variable set temperature [156] and constant set humidity: heating and cooling demand	Portuguese model [156]	RH 30-60%	Spanish cities: HRV	---------

When installing a HRV in the ventilation system, 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.

An ERV has been included (instead of an HRV) in the simulations for some cities located on the Mediterranean coast where the latent energy in the ventilation air can be significant. The Mediterranean cities selected are: Almería, Alicante, Rota, Murcia and Barcelona. Palermo was not selected because it has similar climate data to that of Almeria. In those cities, the effect of the ERV when varying the relative humidity set for air conditioning is obtained.

As regards the control strategy for the ERV, during winter this is based only on the sensible energy which is more important than the latent energy. During summer, the air supply will pass through the ERV when the outdoor air temperature is higher than the indoor temperature. If not, the possible latent and sensible demands that could be recovered from ventilation air by the ERV are calculated by Type 66 in the TRNSYS model. If the humidity ratio of the outdoor air is higher than that in the dwelling and the latent demand to be recovered is higher than the sensible demand to be added to the dwelling, the outside air will cross the ERV or else the air will pass through the by-pass. The effectiveness of the ERV is 90% for sensible energy and 60 % for latent energy, these being typical values provided by products currently available on the market.

For the fourth set of simulations, the energy savings are calculated with the set point temperature proposed by adaptive models, which depends on the outdoor climate. The simulations have been performed using the adaptive control algorithm developed by McCartney et al. [156]. As Spain was not included in their study, a comparison of the comfort temperatures obtained from the Portuguese model (Eq. 7.5), from the Greek model (only existing for summer, Eq. 7.6) and from the general equations (Eq. 7.3 and 7.4) defined for Europe has been carried out for five cities (one for each Spanish climate area in winter). Finally, the equation defined for Portugal (Eq. 7.4) has been used to calculate the air conditioning energy demand.

7.7. Results and discussion

7.7.1. Heating demand depending on a constant set temperature

Simulations have been performed for operative temperatures of 21ºC (as required by the Spanish norm), 20ºC (as required by most current international standards) and 19ºC (as recommended by the Passivhaus standard). The minimum RH setting is 30% (the humidification load for the selected cities is negligible) and the maximum is 60%.

For the nZEB dwelling, the heating demand obtained for each city is shown in Figure 7.3.

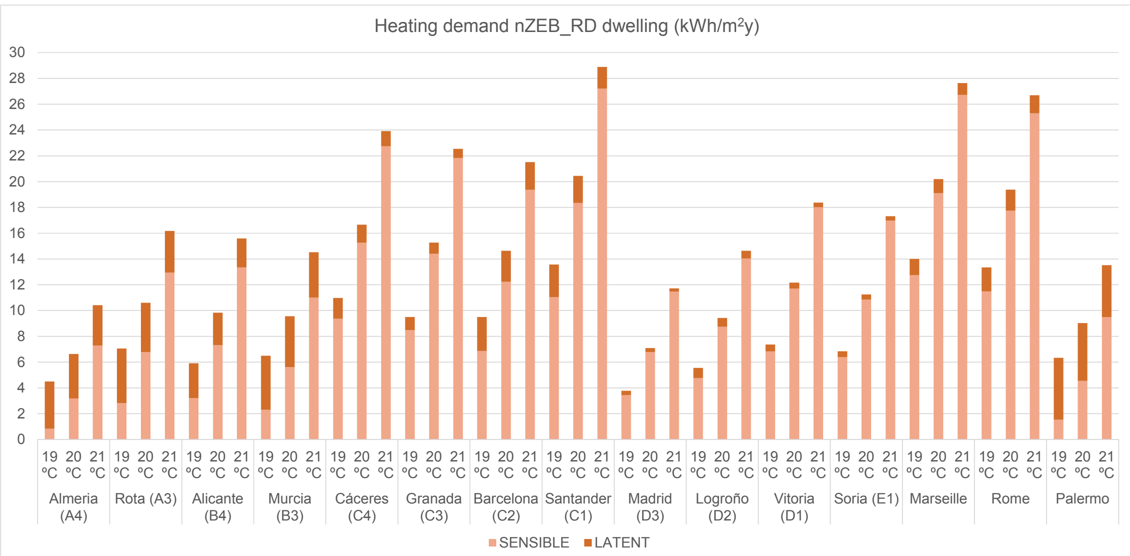


Figure 7.3. Heating energy demand (kWh/m²year). HRV system (nZEB_RD).

The Spanish cities located in climatic zone C, Marseille and Rome have the highest heating demand because the adjustment between the external wall transmittances and the climate conditions is worse than in the other cities. As expected, in all cases the variation in sensible energy is greater when the set temperature is increased from 20ºC to 21ºC than when it is lowered from 20ºC to 19ºC. However, this variation is more marked in the warmest cities.

When the set temperature was reduced from 20ºC to 19ºC, the smallest savings were for one of the hottest city, Almería, with an absolute reduction of 2.3 kWh/m^{2}y (where the heating sensible energy was less than 1 kWh/m^{2}y). The greatest savings were for Santander, where the sensible energy demand decreased by 7.3 kWh/m^{2}y.

When the set temperature was increased from 20ºC to 21ºC, the greatest increment in the sensible energy demand was also for the cities located in winter climatic zone C; for Santander the increment was 8.8 kWh/m^{2}y. The smallest increase was for Almería, where the sensible energy demand increased by 4.1 kWh/m^{2}y.

The impact of the latent energy was obviously smaller because the relative humidity setting was kept invariable at 60%. However, a reduction in the set temperature resulted in an increase in the latent energy demand while, in contrast, an increase in the set temperature from 20ºC to 21ºC had a saving effect on the latent energy demand during winter. This is due to the fact that when reducing the set temperature while maintaining constant RH, the air humidity ratio required is reduced and the latent energy demand is thus increased and vice versa. Table 7.4 shows the impact (%) on heating energy demand when moving the thermostat from 20ºC to 19ºC and to 21ºC.

Table 7.4. Impact on heating energy demand depending on thermostat setting (moving from 20ºC). HRV system (nZEB_RD).

	Sensible		Latent		Total heating	
Temp (ºC)	**19ºC**	**21ºC**	**19ºC**	**21ºC**	**19ºC**	**21ºC**
Almeria (A4)	-73.3%	129.1%	5.9%	-9.3%	-32.1%	57.1%
Rota (A3)	-58.2%	90.9%	10.4%	-15.4%	-33.5%	52.6%
Alicante (B4)	-56.2%	82.3%	7.7%	-10.8%	-39.8%	58.5%
Murcia (B3)	-58.8%	96.1%	6.3%	-11.2%	-32.0%	51.8%
Cáceres (C4)	-38.7%	49.1%	15.7%	-16.1%	-34.1%	43.6%
Granada (C3)	-41.1%	51.7%	18.0%	-18.8%	-37.7%	47.7%
Barcelona (C2)	-43.7%	58.4%	8.9%	-11.2%	-35.1%	46.9%
Santander (C1)	-39.8%	48.4%	20.1%	-20.8%	-33.7%	41.3%
Madrid (D3)	-49.3%	69.2%	12.9%	-16.1%	-46.5%	65.4%
Logroño (D2)	-45.4%	60.5%	12.7%	-13.3%	-41.2%	55.1%
Vitoria (D1)	-41.7%	53.8%	18.9%	-19.6%	-39.4%	51.0%
Soria (E1)	-41.2%	56.6%	13.2%	-18.9%	-39.2%	53.9%
Marseille	-33.3%	39.8%	15.8%	-15.1%	-30.6%	36.9%
Rome	-35.2%	42.6%	13.8%	-14.3%	-31.1%	37.8%
Palermo	-66.1%	108.3%	7.2%	-10.1%	-29.9%	49.7%

The influence of the temperature setting on the sensible energy demand is more significant for the warmest cities (Spanish climatic zones A and B, and Palermo) where the reductions are higher than -50%, and the increases can be greater than 100%.

The reductions and the increases in the latent energy are similar, being around 15-20% for the coldest cities and 6-15% for the warmest. Nevertheless, as the latent energy demand is considerably smaller than the sensible energy demand, the impact on the total energy demand is not very significant.

For the total heating energy demand, reductions range between -30.6% and -46.5% and increases between +36.9% and 65.4%.

The results obtained for the traditional dwelling are shown in Figure 7.4 and Table 7.5**¡Error! No se encuentra el origen de la referencia.** for the purposes of comparison.

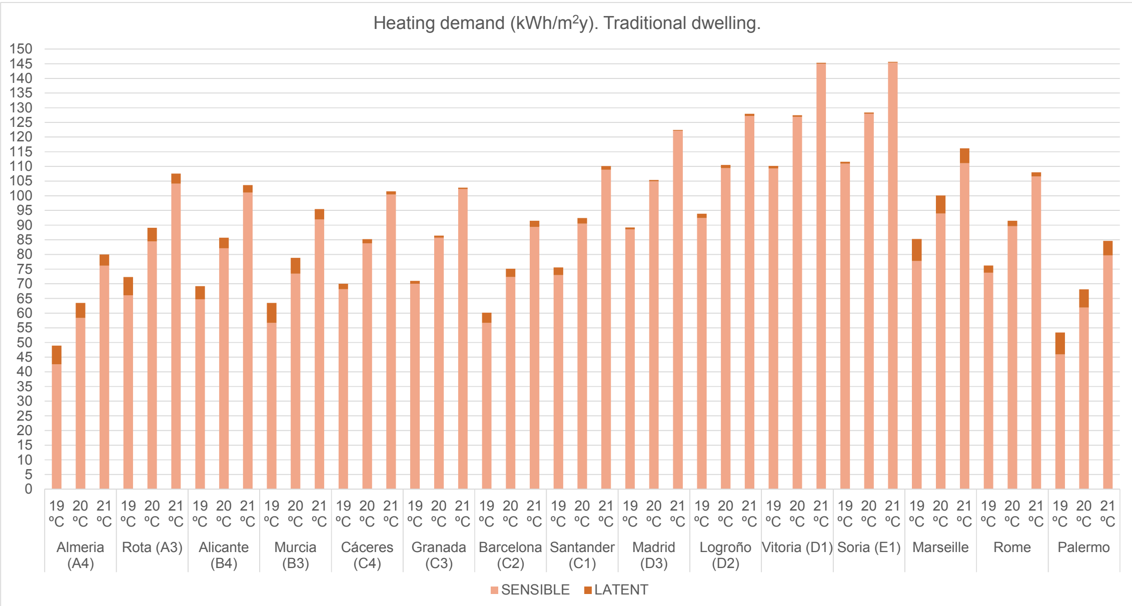


Figure 7.4. Heating energy demand (kWh/m²year). Traditional dwelling.

It should be noted that the scale on the Figure 7.3 and Figure 7.4 has had to be changed as result of the significant heating demand savings obtained for a nZEB compared to the traditional dwelling.

The result shows homogeneity in the savings and increments for the sensible heating demand in absolute values and there are not many differences between the climatic zones. The reductions range from 15.6 kWh/m²y to 17.6 kWh/m²y and the increases from 16.5 kWh/m²y to 19.8 kWh/m²y.

As regards the impacts (%) shown in Table 7.5, the percentages are lower for a traditional dwelling than for a nZEB dwelling. The average reduction in the total heating demand is -17.6% for a traditional dwelling and -35.7% for a nZEB dwelling while the average increment is 19.0% and 50.0%, respectively.

Table 7.5.Impact on heating energy demand depending on thermostat setting (moving from 20ºC. Traditional dwelling.

	Sensible		Latent		Total heating	
Temp (ºC)	**19ºC**	**21ºC**	**19ºC**	**21ºC**	**19ºC**	**21ºC**
Almeria (A4)	-27.2%	30.4%	26.1%	-24.6%	-22.9%	26.0%
Rota (A3)	-21.7%	23.4%	31.9%	-28.4%	-18.9%	20.7%
Alicante (B4)	-21.2%	23.0%	26.9%	-26.4%	-19.2%	21.0%
Murcia (B3)	-22.8%	25.2%	26.2%	-35.0%	-19.5%	21.1%
Cáceres (C4)	-18.6%	19.9%	27.5%	-26.0%	-17.9%	19.1%
Granada (C3)	-18.3%	19.4%	36.7%	-29.5%	-17.8%	18.9%
Barcelona (C2)	-21.6%	23.6%	24.2%	-24.3%	-19.9%	21.8%
Santander (C1)	-19.4%	20.2%	42.0%	-32.8%	-18.2%	19.2%
Madrid (D3)	-15.6%	16.4%	43.6%	-35.6%	-15.4%	16.2%
Logroño (D2)	-15.5%	16.2%	34.0%	-28.7%	-15.1%	15.8%
Vitoria (D1)	-13.9%	14.3%	51.4%	-37.8%	-13.6%	14.0%
Soria (E1)	-13.3%	13.6%	52.2%	-37.7%	-13.1%	13.5%
Marseille	-17.2%	18.3%	20.2%	-19.8%	-14.8%	16.0%
Rome	-17.7%	19.0%	27.9%	-26.6%	-16.7%	18.0%
Palermo	-25.8%	28.7%	20.2%	-19.8%	-21.6%	24.2%

7.7.2. Cooling demand depending on a constant set temperature

Simulations have been performed for set temperatures of 25ºC (as required by the Spanish norm), 26ºC (as required for most current international standards) and 27ºC (as required by the German standard for some climatic regions). The results for cooling energy demand are shown in Figure 7.5.

As expected, the impact on the sensible cooling demand was less significant when the set temperature was increased from 26ºC to 27ºC compared to reducing it to 25ºC. However, as in the case of the sensible heating demand, this variation was more important in the warmest cities.

When the set temperature was reduced from 26ºC to 25ºC, the greatest increment in the sensible energy demand was for one of the hottest cities, Palermo, where it increased by 6.2 kWh/m^{2}y. The smallest increase was for Santander, where the increment was 3.4 kWh/m^{2}y, followed by the coldest cities, Vitoria and Soria, with an increment of 3.9 kWh/m^{2}y.

When the set temperature was increased from 26ºC to 27ºC, the greatest savings were also for Palermo with an absolute reduction of 5.7 kWh/m^{2}y and the smallest savings were for Vitoria, where the sensible energy demand was reduced by 3.1 kWh/m^{2}y.

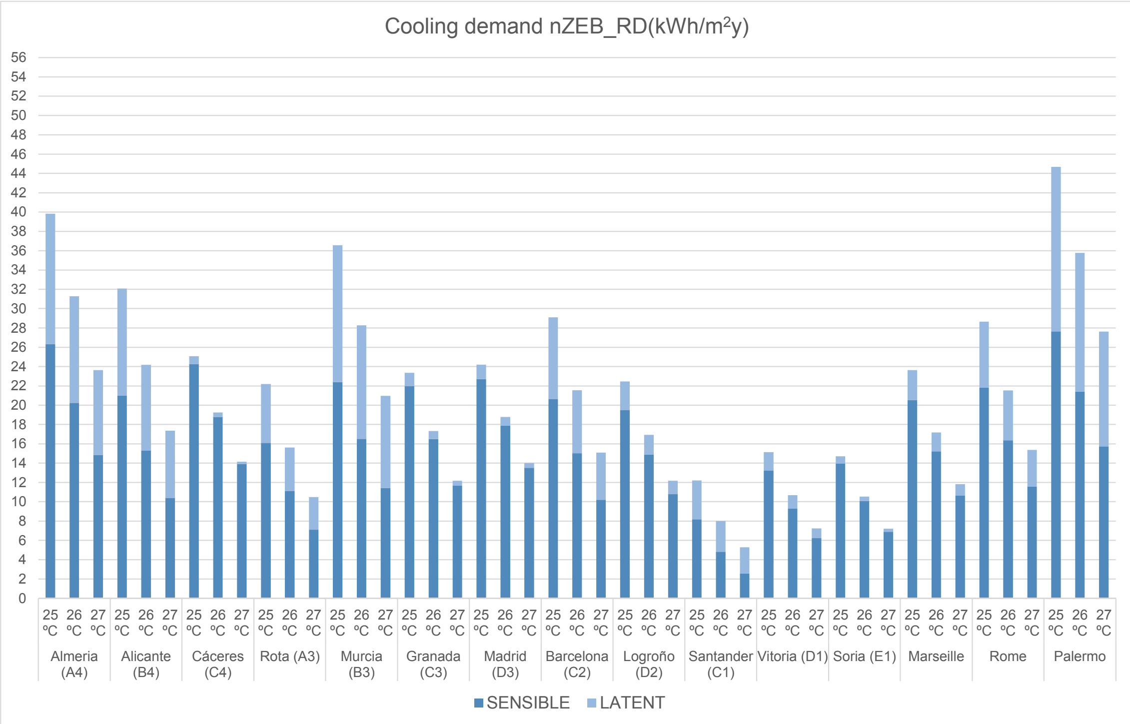


Figure 7.5. Cooling energy demand (kWh/m²year). HRV system. (nZEB_RD)

The influence on the latent energy was obviously smaller because the relative humidity setting remained invariable at RH 60%. The effect was very low for cities not located on the Mediterranean coast, where the latent energy demand was very small. For Mediterranean cities, reducing the set temperature leads to an increase in the latent energy demand while increasing the set temperature from 26ºC to 27ºC has a saving effect. The reduction in the latent energy demand is smaller when increasing the set temperature to 27ºC than the increase when reducing the temperature to 25ºC.

For Cáceres, Granada, Madrid and Soria, cities with a very insignificant latent energy demand, this demand is almost negligible when the set temperature is 27ºC. Nevertheless, as the latent energy demand is smaller than the sensible cooling demand, the impact on the total energy demand is less significant.

Table 7.6 shows the impact on the cooling energy demand when moving the thermostat from 26ºC to 25ºC and to 27ºC.

The influence of the temperature setting on the sensible cooling energy demand is more independent of the climate data than it is on the sensible heating demand. The increment and reductions are more equal for all the cities. The reductions range between -24.5% (Madrid) and -46.5% (Santander) and the increases range from +29.1% (Palermo) to +69.9% (Santander).

As regards the total heating energy demand, reductions range between -22.8% (Palermo) and -33.9% (Santander) and increases between +24.9% and 52.6%, also for Palermo and Santander respectively.

Table 7.6. Impact on cooling energy demand depending on thermostat setting (moving from 26ºC). HRV system (nZEB_RD).

	Sensible		Latent		Total cooling	
Temp (ºC)	**25ºC**	**27ºC**	**25ºC**	**27ºC**	**25ºC**	**27ºC**
Almeria (A4)	30.0%	-26.7%	22.3%	-20.2%	27.3%	-24.4%
Alicante (B4)	37.2%	-32.0%	24.8%	-21.5%	32.6%	-28.2%
Cáceres (C4)	29.1%	-26.0%	78.2%	-45.5%	30.3%	-26.4%
Rota (A3)	45.1%	-36.0%	34.5%	-25.3%	42.0%	-32.9%
Murcia (B3)	35.6%	-30.9%	20.8%	-18.7%	29.4%	-25.8%
Granada (C3)	33.2%	-29.2%	66.5%	-39.8%	34.8%	-29.7%
Madrid (D3)	26.9%	-24.5%	66.7%	-42.3%	28.8%	-25.4%
Barcelona (C2)	37.2%	-32.1%	30.3%	-25.3%	35.1%	-30.0%
Logroño (D2)	31.2%	-27.5%	43.6%	-32.2%	32.7%	-28.1%
Santander (C1)	69.9%	-46.5%	26.4%	-14.7%	52.6%	-33.9%
Vitoria (D1)	42.0%	-33.1%	40.6%	-26.6%	41.8%	-32.3%
Soria (E1)	38.7%	-31.5%	60.1%	-35.5%	39.7%	-31.7%
Marseille	35.1%	35.1%	57.1%	-38.8%	37.6%	-31.2%
Rome	33.5%	-29.2%	32.0%	-26.4%	33.1%	-28.6%
Palermo	29.1%	-26.5%	18.6%	-17.3%	24.9%	-22.8%

The results obtained for the traditional dwelling are shown in Figure 7.6 Table 7.7 for the purposes of comparison.

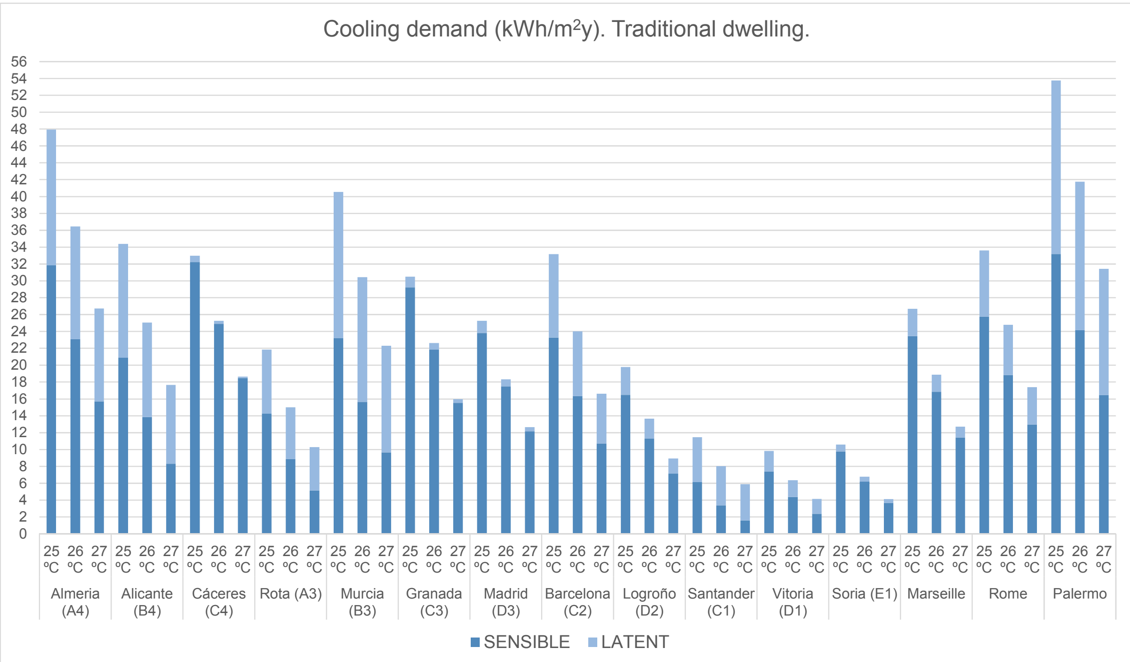


Figure 7.6. Cooling energy demand (kWh/m²year). Traditional dwelling.

Table 7.7. Impact on cooling energy demand depending on thermostat setting (moving from 26ºC). Traditional dwelling.

	Sensible		Latent		Total Cooling	
Temp. (ºC)	**25ºC**	**27ºC**	**25ºC**	**27ºC**	**25ºC**	**27ºC**
Almeria (A4)	37.9%	-31.9%	20.6%	-17.8%	31.5%	-26.7%
Alicante (B4)	50.9%	-40.0%	20.3%	-16.5%	37.2%	-29.5%
Cáceres (C4)	29.5%	-25.8%	91.5%	-49.0%	30.5%	-26.2%
Rota (A3)	60.7%	-41.9%	23.8%	-16.0%	45.6%	-31.3%
Murcia (B3)	48.2%	-38.4%	17.3%	-14.4%	33.2%	-26.7%
Granada (C3)	33.6%	-29.0%	72.3%	-41.3%	34.9%	-29.4%
Madrid (D3)	36.2%	-30.5%	68.9%	-40.8%	37.8%	-30.9%
Barcelona (C2)	42.5%	-34.4%	28.8%	-23.2%	38.1%	-30.8%
Logroño (D2)	46.2%	-36.6%	37.7%	-25.2%	44.7%	-34.6%
Santander (C1)	82.4%	-52.7%	14.6%	-7.6%	43.1%	-26.6%
Vitoria (D1)	68.9%	-45.6%	22.3%	-11.9%	54.3%	-35.1%
Soria (E1)	57.8%	-41.0%	40.9%	-20.3%	56.4%	-39.2%
Marseille	39.3%	-32.2%	59.1%	-37.5%	41.4%	-32.8%
Rome	36.9%	-31.1%	31.3%	-25.7%	35.5%	-29.8%
Palermo	37.6%	-31.9%	16.8%	-14.9%	28.8%	-24.7%

For cooling, the scales in the Figure 7.5 and Figure 7.6 are the same because the savings obtained for a nZEB compared to the traditional dwelling are not as relevant as for the heating demand.

It can be seen in Table 7.7 that the impact (%) on sensible cooling demand, unlike sensible heating demand, is higher for a traditional dwelling than for a nZEB dwelling. The average reduction of the total cooling demand is -30.3% for a traditional dwelling and -28.7% for a nZEB dwelling. The average increment is 39.5% for a traditional dwelling and 34.8% for a nZEB.

Additional simulations have been performed for some cities whose percentage of total latent energy demand is higher than 25% when the comfort limits are the same as those recommended in the international standards: 20ºC for winter, 26ºC for summer and a maximum of 60% RH. These selected cities are Almería, Alicante, Rota, Murcia and Barcelona, all located on the Mediterranean coast. Palermo was not selected because it has similar climate data to that of Almeria. These simulations were performed substituting in the nZEB dwelling model an ERV in place of the HRV to assess the impact on the energy demand in summer when dehumidification is needed. The results for the cooling energy demand are shown in Figure 7.7 and the relative impacts are shown in Table 7.8.

The sensible cooling demand is slightly higher than when an HRV is used, but the relative impact due to a change in the temperature settings is the same whether using an HRV or an ERV. The dehumidification demand when using an ERV was reduced between 14% and 29 % depending on the city, compared with an HRV for a 26ºC temperature setting. For all the cities, the impact on the latent cooling demand when modifying the set temperature is similar when using an ERV.

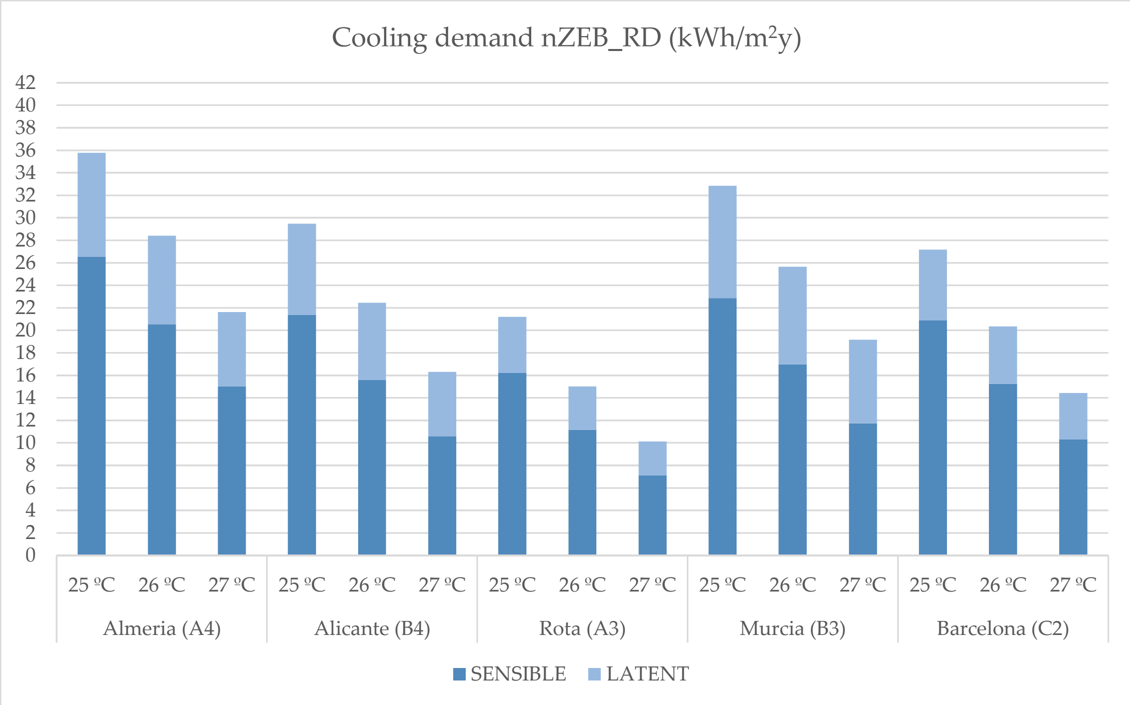


Figure 7.7. Cooling energy demand (kWh/m²year). ERV system.

Table 7.8. Impact on cooling energy demand depending on thermostat setting (moving from 26ºC). ERV system.

	Temp. (ºC)	Armería (A4)	Alicante (B4)	Rota (A3)	Murcia (B3)	Barcelona (C2)
Sensible	25ºC	29.3%	37.1%	45.7%	34.6%	37.1%
	27ºC	-26.8%	-32.1%	-35.9%	-31.0%	-32.2%
Latent	25ºC	17.1%	18.2%	28.1%	15.4%	22.8%
	27ºC	-16.3%	-16.7%	-23.3%	-14.2%	-19.7%
Total	25ºC	25.9%	31.3%	41.1%	28.1%	33.5%
	27ºC	-23.9%	-27.4%	-32.6%	-25.3%	-29.1%

7.7.3. Latent demand depending on a constant relative humidity setting.

Simulations have been performed for temperature settings of 20ºC (winter) and 26ºC (summer) and relative humidity settings of 60%, 65%, and 70% with a humidity ratio of 0.012 kg/kg dry air (as specified in the ASHRAE standard 55). The simulations have been done only for the cities located on the Mediterranean coast (Almería, Alicante, Rota, Murcia and Barcelona) as the latent energy demand is very low for the others. Palermo is not included because its data is similar to that of Almería. Figure 7.8 shows the results when an HRV is installed and Figure 7.9 when an ERV is installed.

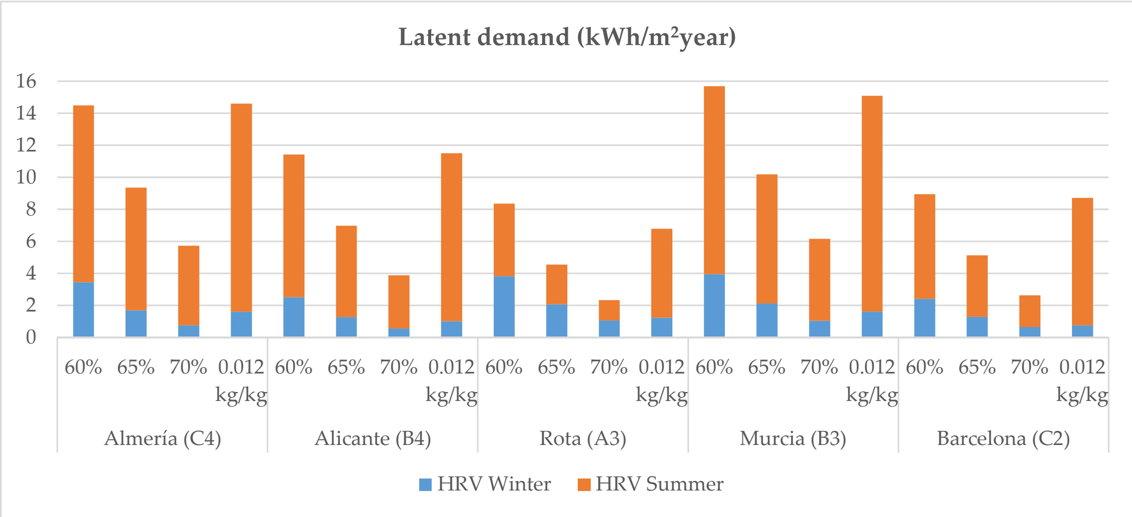


Figure 7.8. Latent energy demand (kWh/m²year). HRV system.

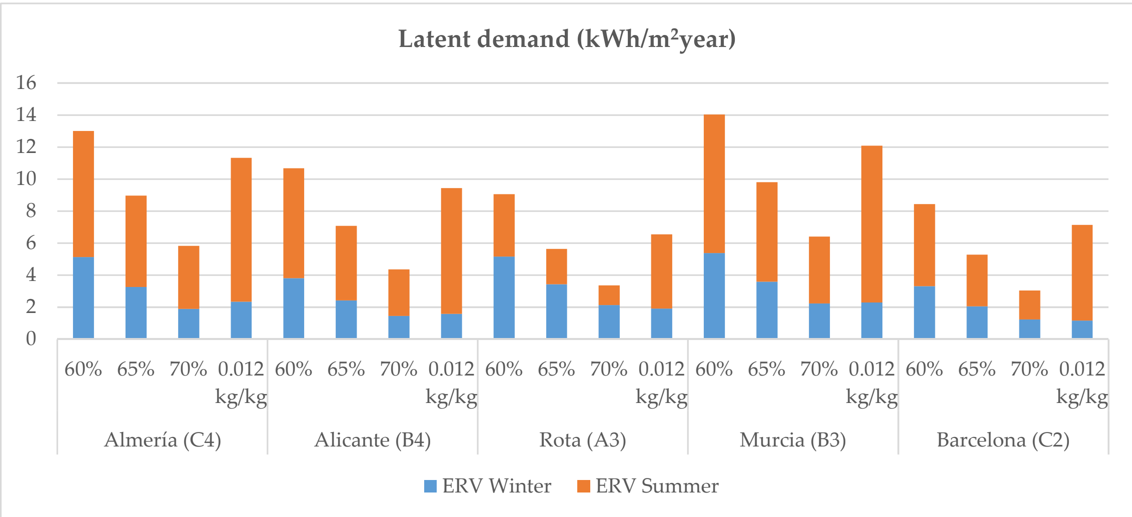


Figure 7.9. Latent energy demand (kWh/m²year). ERV system.

The latent energy demand during winter for RH 70% and a humidity ratio of 0.012 kg/kg dry air is almost negligible. For Alicante, Rota and Barcelona the latent energy demand is almost the same whether using an HRV or an ERV. For Almería and Murcia (cities with the highest latent energy demand) the extra reduction obtained using an ERV instead of an HRV is 10% for RH 60% and negligible when the relative humidity setting is increased.

Using an ERV, there is a reduction between 3.2 kWh/m²y and 4.2 kWh/m²y of the latent energy demand (-31.0% and -37.8%) when the RH setting is increased from 60% to 65%. The reduction reaches between 5.4 kWh/m²y and 7.2 kWh/m²y (-55.3% and -62.9%) when the RH is increased to 70%.

7.7.4. Energy demand for variable temperature setting: Adaptive model.

Figure 7.10 shows the comfort temperature profiles (set temperature) when applying the European model ((7.3) and (7.4)), the Portuguese model (7.5), the Greek model (only for the summer season, (7.6)) and the constant set temperature (20-26ºC) for one city from each Spanish climate area.

Figure 7.10. Temperature comfort profiles.

For the warmest cities adaptive models provide higher comfort temperatures in both winter and summer; however, for the coldest the difference is not as noticeable although they are lower in summer. The comfort set temperature given by the Portuguese equation compared with that given by the European equation is higher in summer and lower in winter for all the cities. Consequently, the air conditioning energy demand will be lower. The Greek equation gives lower set temperatures than the Portuguese and similar to the European for the hottest cities; however, the values are similar to the Portuguese for the coldest ones.

For the colder cities, Vitoria and Soria, the European model sets the comfort temperature at 22.88ºC for winter, which is much higher than the temperature set by the Portuguese model.

In summary, the Portuguese model is the best in terms of energy demand for Spanish cities and therefore the Portuguese comfort temperature profile has been included in the TRNSYS model. Figure 7.11 shows the total sensible and latent energy demands for set temperatures of 20º (winter) - 26ºC (summer) and the adaptive model according to the Portuguese equations for direct comparison. The RH setting remains constant at 60% (summer).

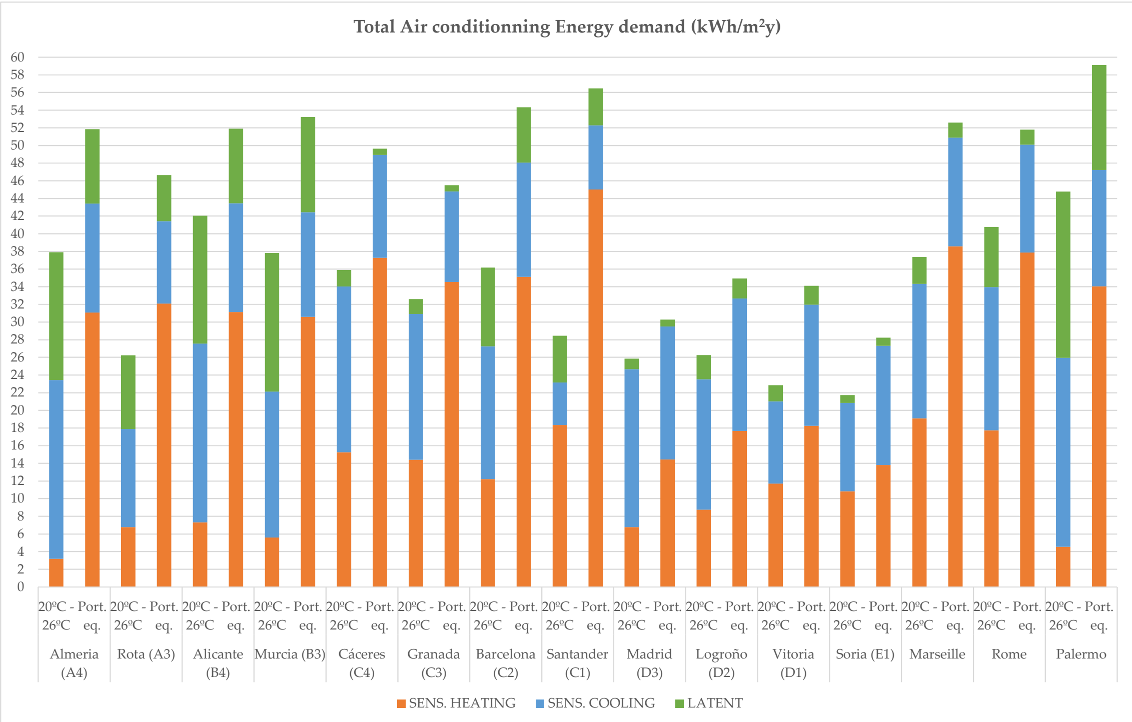


Figure 7.11. Total energy demands (kWh/m²year). HRV system.

The sensible heating demand is considerably higher for all the cities when applying adaptive models and the increase is much more significant for the warmest cities. The dehumidification energy demand during winter almost disappears, due to the increase in the comfort set temperature when applying the Portuguese equation. For this reason the latent demand represented in Figure 7.11 is the total latent energy demand because practically all this demand is produced in the summer.

The cooling energy demand decreases but there is a substantial increase in the total sensible energy demand for all the cities. This is more significant for the warmest cities due to the strong impact on the heating demand.

The worst result is for Santander where the total energy demand is doubled, followed by Rota which has an increase of 77.8%. The least affected are Madrid and Alicante with increases of 17.1% and 23.4 %, respectively.

7.8. Conclusions.

Simulations were performed to assess the impact of comfort parameters on the air conditioning energy demand for a residential nZEB dwelling and for a traditional dwelling. Fifteen cities located around the Mediterranean area were selected for this study: twelve cities located in Spain, one in France and two in Italy.

The following conclusions can be drawn from this study:

1) The impact (%) on the heating energy demand when changing the winter set temperature is more significant than the impact on the cooling energy demand (%) when changing the summer set temperature for an nZEB in all the selected cities except Santander. The contrary occurs in all the cities for a traditional dwelling.

2) The impact of the winter set temperature on the heating demand (%) is higher for a nZEB dwelling than for a traditional dwelling.

The heating energy savings when moving the set temperature from 20ºC to 19ºC are between 30% and 46% for nZEB and between 13 % and 23% for a traditional dwelling. The impact on the heating demand is more significant for the coldest cities for a nZEB dwelling while for a traditional dwelling higher reductions are obtained for the warmer cities.

The heating energy demand is increased between 40% and 60% when moving the set temperature from 20ºC to 21ºC for nZEB and between 15 % and 25% for a traditional dwelling. The impact on the heating energy demand is more significant for the warmer cities for both nZEB and traditional dwellings.

3) The impact of the summer set temperature on the cooling demand (%) is slightly lower for a nZEB dwelling than for a traditional dwelling.

The cooling energy savings when moving the set temperature from 26ºC to 27ºC are between 23% and 34% for nZEB and between 25 % and 35% for a traditional dwelling.

The cooling energy demand is increased between 25% and 52% when reducing the set temperature from 26ºC to 25ºC for nZEB and between 29 % and 56% for a traditional dwelling. The impact on the cooling energy demand is greater for the coldest cities for both nZEB and traditional dwellings.

4) The impact on the sensible cooling demand of changing the temperature settings is the same for HRV and ERV in Mediterranean cities.

5) The study of the influence on the latent energy demand for different RH settings in Mediterranean cities reveals that the impact on this demand when changing the RH setting is similar when either an HRV or an ERV is installed in the ventilation system. Only Almeria and Murcia (the cities with the highest humidity levels) obtain a 10% extra saving on latent energy demand when an ERV is installed instead of an HRV for RH60%.

Using an ERV, the reduction in latent energy demand is more than 30% when the RH setting is increased from 60% to 65% and up to 60% when the RH is increased to 70%.

6) The equation proposed by McCartney et al.[156] to obtain the comfort temperature depending on the running mean outdoor temperature (T_{RM80}) for Portugal, Greece (summer) and Europe has been applied to the selected Spanish cities. The comfort temperature obtained from the Portuguese model is better for energy savings than that obtained from the European model. The adaptive Portuguese model is effective for energy savings during the summer season for the warmest cities, but is not well adapted for winter as very high heating demands have been obtained for all the cities. The reduction in the cooling demand is lower than the increase in the heating demand. However, the equation reveals satisfactory results for the dehumidification demand.

To sum up, the results reveal that comfort parameter settings have a higher impact on the air conditioning energy demand for a nZEB than for a traditional dwelling. It is demonstrated that by adopting extended comfort ranges, significant energy savings would be achieved in countries with temperate climates for nZEB. For this reason, the current standards and regulations should be reviewed. It is recommended that a new adaptive control algorithm should be developed to define optimized comfort temperatures in the different climate areas in the south of Europe to ensure energy savings in nZEB.

Chapter 8

Conclusions and original contributions

8. Conclusions and original contributions

This chapter describes the main conclusions derived from the present dissertation, the original contributions and lines of future research.

8.1. Conclusions

The main conclusions derived from the present dissertation can be grouped into three broad categories. The first is related to ventilation air systems, the second to the air infiltrations and the third to comfort parameters.

<u>Ventilation air systems</u>

The ventilation air flows and strategies set out in the regulations of the USA, Germany, the UK, France and Spain have been compared, together with the Passivhaus standard. The regulated or recommended air ventilation flow rates are similar but the control procedures are very different.

Ventilation thermal loads account for almost the total thermal loads for residential nZEB/Passivhaus buildings located in mild climates. Only buildings located in warmer places, such as the south of Spain, are capable of fulfilling the air conditioning demand of nZEB without HRV.

The south of the Mediterranean coast has a high energy demand because the latent energy needed to condition the ventilation air in dwellings is greater than 40%, representing a high potential for ERV as opposed to HRV. Cities located mid-way down the Spanish Mediterranean coast have a latent energy demand due to ventilation air of between 20% and 40% of the total energy demand. In this case, for the cities where the percentage of the latent energy in the ventilation air is between 23% and 27%, the use of an ERV instead of an HRV is not justified by the results obtained. A more in-depth and specific analysis is recommended for the cities with a percentage between 30% and 40%. However, the latent energy for cities located at the north of the Mediterranean sea represents less than 20% of the total energy and here the use of an ERV is not recommended.

The demands for latent and sensible energy do not arise at the same time for most of the year, and this has an influence on the kind of recovery system appropriate for each climate condition and also on the by-pass control strategy. A membrane-based recovery system seems not to be the best choice as both transfers occur at the same time.

The effectiveness of several control strategies for ERV with the objective of optimizing the air conditioning demand has been established from research carried out for eleven cities located on the Mediterranean coast in southern Europe. The optimal strategy for the ERV during winter is control based only on the sensible energy. The use of an HRV instead of an ERV results in lower values for the air conditioning demand in all cities except Palermo (the most humid city studied). The optimal strategy found for the summer season is based on the enthalpy control only in the case that the outdoor air temperature is lower than the indoor temperature.

The reduction in energy demand resulting from installing an ERV and applying the optimized control strategy proposed in this dissertation (for sensible effectiveness of 0.9 and latent effectiveness of 0.6) is very significant compared to the absence of a recovery system. Nevertheless, it is not very considerable when compared to the use of an HRV.

An increase in the sensible efficiency of the ERV directly causes a reduction in the sensible energy demand but, as demonstrated in this research, this obvious fact cannot be applied to the latent efficiency for nZEB located in the south of Europe where in some conditions (mainly in winter) the humidity will be transferred in the wrong direction for energy savings. The optimal value for latent efficiency is between 0.5 and 0.7 (depending on the city) for places with medium latent loads and 0.8 for Palermo, the city with the greatest latent energy.

A recommended way of reducing the cooling demand, considered by many regulations, is night ventilation and free cooling. However, as concluded in this dissertation, opening windows during summer nights is a very effective way of reducing the sensible demand under nZEB requirements, but it is not appropriate for latent energy which substantially increases. Furthermore, a double ventilation air flow during summer nights (free cooling) reduces the sensible cooling demand but increases the latent demand so that the total energy is reduced by only 1.5% during summer in cities located in the south of Spain.

Air infiltrations

Airtightness has already been demonstrated to be an impacting parameter on air conditioning demand for nZEB in cold countries, but its influence in warmer climates, expected to be much lower, has still not been evaluated. This research demonstrates that the maximum value set by Passivhaus independently of the climatic zone could be relaxed for nZEB located in southern Europe. The impact on energy demand due to infiltration air flow is higher in cities located in colder climates due mainly 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.

The variation in the air infiltration flow rate throughout the year due to the temperature effect has been calculated, and the notable variances found indicates the benefit of taking this effect into account when setting a n_{50} limit for nZEB. However, the Passivhaus standard establishes a constant value throughout the year.

The n_{50} limit for nZEB could be relaxed from 0.6 ACH (the value stated by Passivhaus) to 1 ACH for nZEB located in the south of Europe, and even more to 2 ACH for those located in the south of the Mediterranean. The new values will give the same percentage increase in air conditioning demand as provided by 0.6 ACH in northern Europe and they are low enough to ensure that the ventilation system will be energy efficient.

<u>Comfort parameters</u>

There is a lack of research examining the impact of comfort parameters on energy demand in warm climates, and specifically the impact has not been tested on nZEB. In this dissertation the impact of the temperature and humidity settings has been calculated for nZEB in fifteen cities located in the south of Europe.

The results for different temperature settings during winter reveal a very significant influence on the sensible heating demand. The impact on air-conditioning energy demand is more significant when changing the winter set temperature than the summer set temperature for all the selected cities.

The impact on the sensible cooling demand of changing temperature settings is the same for HRV and ERV in Mediterranean cities. The study of the influence on the latent energy demand for different RH settings reveals that the impact on the latent energy demand is similar when either an HRV or an ERV is installed.

The results reveal that comfort parameters should be reviewed for residential nZEB in southern Europe. It is demonstrated that by adopting extended comfort ranges, significant energy savings would be achieved in countries with temperate climates such as Spain. However, existing adaptive models for Portugal, Greece and Europe have not provided good results for air conditioning energy demand in the case of Spain, especially in winter. A new adaptive control algorithm to define the comfort temperature in the different climate areas in Spain could lead to optimized comfort parameters in terms of energy savings.

8.2. Future research

The research presented in this thesis is a small contribution to the understanding of the capability and performances of nZEB located in warm climates and an endorsement of the development and implementation of nZEB requirements in the south of Europe. With the aim of encouraging the construction of more sustainable buildings, several lines of future research have been identified, as described below.

* Given the disparity of strategies required depending on climate data in different parts of Europe, energy maps need to be drawn showing the potential latent energy that could be recovered.
* Future work should include a detailed economic analysis. Moreover, the energy demand has to be converted to energy consumption. The energy consumption of a dehumidifier could be twice that of an ERV. Dehumidifiers have a non-negligible cost. In some cases, the extra cost of an ERV instead of an HRV could be justifiable if the dehumidifier can be removed.
* An analysis of energy consumption cost versus investment cost should also be carried out.
* A feasibility study and functional design study should be conducted to develop a pioneering recovery device with an interchangeable core: a sensible core for

winter and a latent core for summer. The core seems to be the cheapest part of the recovery device, according to Zenhder as a supplier of this equipment. An economic study of this solution should be also be done.

* Another new design option, as demonstrated in this research, should be investigated in depth. This is to develop an innovative heat recovery device which contains two cores working in parallel or in series. The air flow path through the recovery device should be optimized, passing through one or two cores depending on the outdoor and indoor air conditions.
* A research project entitled *"Estrategias de diseño y funcionamiento de sistemas de recuperación entálpica en climas mediterráneos"* has been signed with Zehnder to develop new working strategies for air ventilation systems.

8.3. Original contributions

8.3.1. Published Articles

S. Guillén-Lambea, B. Rodríguez-Soria, J.M. Marín, *"Review of European ventilation strategies to meet the cooling and heating demands of nearly zero energy buildings (nZEB)/Passivhaus. Comparison with the USA."* Renew Sustain Energy Rev 2016;62:561-74. doi:10.1016/j.rser.2016.05.021.

S. Guillén-Lambea, B. Rodríguez-Soria, J.M. Marín, *"Evaluation of the potential Energy Recovery for ventilation air in dwellings in the South of Europe."*, Energy Build. 128 (2016) 384-393. doi:10.1016/j.enbuild.2016.07.011.

S. Guillén-Lambea, B. Rodríguez-Soria, J.M. Marín, *"Control strategies for Energy Recovery Ventilators in the South of Europe for residential nZEB. Quantitative analysis of the air conditioning demand"*, Energy Build. 146 (2017) 271-282. doi.10.1016/j.enbuild.2017.04.058

8.3.2. Articles under review/ in preparation

S. Guillén-Lambea, B. Rodríguez-Soria, J.M. Marín, *"Comfort settings and energy demand for residential nZEB in warm climates. The Spanish case"*, Applied Energy *(Under review).*

S. Guillén-Lambea, B. Rodríguez-Soria, J.M. Marín, *"Infiltration effect on air conditioning demand. Computational simulations to set airtightness parameters of residential nZEB in the South of Europe" (In preparation).*

8.3.3. Conference contributions

S. Guillén-Lambea, B. Rodríguez-Soria, J.M. Marín, J. Sierra-Pérez, *"Impact of infiltrations in energy demand of a dwelling. Sensitivity to infiltrations for Mediterranean climate"*. 10th International Conference on Advanced Building Skins, November 3-4 2015, (Bern, Switzerland). ISBN 978-3-98120538-1.

B. Rodríguez Soria, **S. Guillén Lambea**, C. Navarro Gutiérrez, J. Sierra-Pérez. *"Validation of the PHPP program calculations in Mediterranean climates for ENERPHIT standard".* International Conference on Advanced Building Skins, November 3-4 2015, (Bern, Switzerland). ISBN 978-3-98120538-1.

B. Rodríguez Soria, A. Gracia Ramos, **S. Guillén Lambea,** C. Navarro Gutiérrez, J. Sierra Pérez. *"Caracterización y simulación energética de tipologías edificatorias prefabricadas de los años 70 en el ministerio de defensa."* Ponencia en III Congreso Nacional de I+D en Defensa y Seguridad, November 19-20 2015, (Vigo, Spain). ISBN 978-94-944537-1-7.

S. Guillén-Lambea, B. Rodríguez-Soria, *"Revisión del límite máximo de infiltraciones del standard Passivhaus para climas mediterráneos".* Ponencia Invitada 8ª Conferencia española Passivhaus, November 2-4, 2016, (Pamplona, Spain). ISBN 978-84-617-5728-2.

8.3.4. Workshops

Technical workshop PEP: 'Passivhaus, presente y futuro de los ECCN'. **S. Guillén-Lambea,** *"Recuperación del calor en viviendas ECCN".* Colegio Oficial de Arquitectos de Aragón (COAA), October 26, 2016, (Zaragoza-Spain).

8.3.5. Predoctoral Internship

Visiting scholar in División de Ingenierías del Campus Irapuato-Salamanca, Guanajuato University (México), from June 2nd to September 15th (16 weeks). Project: '*Exchange of results on energy optimization in buildings*'.

Supervisor: PhD. Jesús Martínez Patiño.

8.3.6. Research projects

Participant as researcher on the following research projects:

"Desarrollo de un plan estratégico de rehabilitación energética según metodologías nZEB y ACV para el ministerio de defensa. Caso práctico: tipología de edificios prefabricados". CUD 2014-11. From January 31, 2015 to January 31, 2016. Lead researcher: B. Rodríguez-Soria.

"Estrategias de diseño y funcionamiento de sistemas de recuperación entálpica en climas mediterráneos". Research Project with Zehnder. December 30, 2015 to December 31, 2017.

"Análisis del comportamiento energético de los contenedores utilizados en la ejecución de bases militares del ejército de tierra. Evaluación de medidas para disminuir su demanda energética y mejorar sus condiciones de confort". From January 31, 2017 to January 31, 2018. Lead researcher: B. Rodríguez-Soria.

8.4. Conclusiones

Las conclusiones más importantes derivadas de esta tesis doctoral pueden agruparse en tres categorías principales. Las primeras son las relativas al sistema de ventilación propiamente dicho, las segundas las derivadas del estudio de la influencia de las infiltraciones y las terceras las relacionadas con los parámetros del confort de la vivienda.

Sistema de ventilación

Se ha realizado una comparativa de los caudales y modos de funcionamiento del sistema de ventilación indicados en las normativas de USA, Alemania, UK, Francia y España además de las recomendaciones establecidas por el estándar Passivhaus. Se concluye que los caudales de ventilación regulados o recomendados son muy similares pero los modos de funcionamiento muy dispares.

Las cargas térmicas originadas por el sistema de ventilación son prácticamente el total de las cargas térmicas en una vivienda nZEB/Passivhaus situada en climas suaves, aunque únicamente las viviendas situadas en climas cálidos, como los del sur de España, son capaces de cumplir con los requisitos de demanda energética de climatización de una nZEB sin que sea necesario recuperar el calor del aire de ventilación.

En el sur de la costa mediterránea, la demanda de energía latente necesaria para acondicionar el aire de ventilación es superior al 40%, lo que representa un alto potencial de recuperación de energía, por lo tanto la instalación de un ERV es recomendable frente a la instalación de un HRV. Las ciudades situadas en latitudes ligeramente superiores, como las situadas en mitad de la costa mediterránea española, tienen una demanda de energía latente ocasionada por el aire de ventilación entre el 20% y el 40% de la demanda total. En este caso las ciudades donde el porcentaje de energía latente en el aire de ventilación está entre el 23% y el 27%, el uso de un ERV en lugar de un HRV no está justificado con los resultados obtenidos. Se recomienda un análisis más profundo y específico para las ciudades con un porcentaje entre 30% y 40%. La energía latente representa menos del 20% en las ciudades situadas al norte del mar Mediterráneo y por lo tanto la utilización de un ERV es desaconsejable.

Las demandas de energía latente y sensible no acontecen al mismo tiempo durante la mayor parte del año, lo que influye y determina la selección del equipo de recuperación apropiado para cada zona climática así como el modo de funcionamiento del by-pass. Un intercambiador de membrana en el cual ambas transferencias suceden al mismo tiempo parece no ser la opción más óptima.

Se han seleccionado once ciudades situadas en la costa mediterránea del sur de Europa para determinar el modo de funcionamiento más óptimo del sistema ERV con el objetivo de minimizar la demanda de climatización. Durante el invierno, un control basado exclusivamente en la energía sensible resulta el más apropiado, ya que el con la implementación de un HRV se obtienen mejores resultados en todas las ciudades exceptuando la ciudad de Palermo (ciudad con los valores de humedad más altos). En verano, un control basado en la entalpia del aire es más efectivo, pero únicamente cuando la temperatura del aire exterior es inferior a la temperatura interior.

La reducción de la demanda energética originada por la instalación de un ERV funcionando con un control óptimo (para una eficiencia sensible de 0.9 y latente de 0.6) es muy significativa en comparación con la ausencia de un sistema de recuperación. Sin embargo, no es muy notable cuando se compara con la instalación de un HRV.

Un aumento en la eficiencia sensible de un HRV induce directamente una reducción de la demanda de energía sensible, este hecho obvio no puede aplicarse a la eficiencia latente de un ERV instalado en una nZEB situada en el sur de Europa, donde en algunas condiciones (principalmente en invierno) la humedad se transfiere en la dirección equivocada. El valor óptimo para la eficiencia latente está entre 0.5 y 0.7 (dependiendo de la ciudad) para los lugares con cargas latentes medias y es de 0.8 para Palermo, la ciudad con la mayor energía latente.

Una forma de reducir la demanda de refrigeración, considerada explícitamente en muchas normativas, es la ventilación nocturna y la ventilación mecánica controlada (Free Cooling). Sin embargo, la apertura de ventanas durante las noches de verano es una manera muy efectiva de reducir la demanda sensible, pero no es apropiado para la energía latente la cual aumenta sustancialmente. Igualmente, duplicar el caudal de aire de ventilación durante las noches de verano (Free Cooling) reduce la demanda sensible de refrigeración, pero incrementa la demanda latente, resultando en una reducción de energía total de únicamente un 1.5%, durante el verano en ciudades situadas al sur de España.

<u>Infiltraciones de aire</u>

Una alta estanqueidad al aire es uno de los requisitos necesarios para una vivienda nZEB situada países fríos debido a su demostrada alta influencia en la demanda de climatización, pero su impacto en climas más cálidos, el cual es esperable que sea mucho menor, todavía no ha sido evaluado. Esta investigación demuestra que el valor máximo de las infiltraciones establecido por Passivhaus, independientemente de la zona climática, podría relajarse para viviendas nZEB situadas en el sur de Europa. El impacto en la demanda energética de las infiltraciones es mayor en las ciudades ubicadas en climas más fríos debido principalmente a dos efectos: primero, un mayor salto térmico entre el exterior y el interior aumenta el flujo de aire debido a infiltraciones y en segundo lugar porque la temperatura del aire exterior es menor.

Se ha obtenido la variación en el caudal de infiltración de aire a lo largo del año debido al efecto de la temperatura, las notables variaciones encontradas indican la conveniencia de tener en cuenta este efecto para establecer el límite de n_{50} para las viviendas nZEB. Sin embargo, el estándar Passivhaus establece un valor constante a lo largo del año.

El límite n_{50} podría incrementarse de 0.6 ACH (valor exigido por Passivhaus) hasta, al menos, 1 ACH para viviendas nZEB en el sur de Europa, e incluso hasta 2 ACH para las situadas en el sur del Mediterráneo. Estos nuevos límites aumentarán en el mismo porcentaje la demanda de climatización que la originada por 0,6 ACH en el norte de Europa y además son lo suficientemente bajos como para asegurar que el sistema de ventilación trabajará adecuadamente.

Parámetros de confort

No existen investigaciones sobre el impacto de los parámetros de confort en la demanda climatización de viviendas nZEB en climas cálidos. En esta tesis se ha calculado el impacto de los valores de temperatura y humedad en quince ciudades situadas en el sur de Europa.

Los resultados para los diferentes límites en la temperatura de confort en invierno revelan una influencia muy significativa en la demanda sensible de calefacción. El impacto en la demanda de climatización es más significativo para variaciones en la temperatura de confort en invierno que en verano para todas las ciudades analizadas.

El impacto en la demanda sensible de refrigeración originada por la variación de la temperatura de confort es el mismo para una vivienda con un sistema HRV que con ERV en las ciudades mediterráneas. La influencia en la demanda de energía latente debida a la variación de la RH de confort es similar cuando se instala un ERV o un HRV.

Los resultados indican que deben de revisarse los parámetros de confort establecidos actualmente para su trasposición al sector residencial nZEB en el sur de Europa. Se demuestra que ampliar los límites de confort hasta los establecidos en las normativas de países situados en el norte de Europa, permitirá lograr unos ahorros energéticos significativos en países con climas templados como es el caso de España. Sin embargo, los modelos adaptativos de temperatura existentes para Portugal, Grecia y Europa no han proporcionado buenos resultados para la demanda de energía de climatización en el caso de España, especialmente en invierno. Un nuevo algoritmo de control adaptativo para definir la temperatura de confort en las diferentes zonas climáticas españolas podría ayudar a optimizar los parámetros de confort en términos de ahorro energético.

8.5. Trabajos futuros

La investigación presentada en esta Tesis es una pequeña contribución a la comprensión de la capacidad de ahorro energético y el funcionamiento de una vivienda nZEB situada en climas cálidos y un apoyo al desarrollo e implementación de los requisitos nZEB en el sur de Europa. Con el objetivo de extender la construcción generalizada de edificios sostenibles, se han identificado varias líneas de trabajo para continuar esta investigación, las cuales se desarrollan a continuación.

* Se considera interesante y necesario trazar mapas de energía europeos mostrando la energía latente en el aire, la cual es potencialmente recuperable.
* Se estima necesario realizar un análisis económico detallado. Para ello, es necesario realizar la conversión de demanda de energía a consumo de energía. El consumo de energía de un deshumidificador podría ser dos veces superior al de un ERV. Además los equipos deshumidificadores tienen un coste no despreciable. En algunos casos, el coste extra de instalar un ERV en lugar de un HRV podría justificarse si eso permite eliminar el deshumificador.

* Se considera recomendable realizar un análisis del coste del consumo de energía frente a la inversión realizada para los sistemas de ventilación estudiados.
* Se propone realizar un estudio de factibilidad y un diseño funcional con el objetivo de desarrollar de un dispositivo de recuperación pionero que disponga de un cuerpo intercambiable: un recuperador sensible para el invierno y uno latente para el verano. El cuerpo del intercambiador es un componente económico del sistema de recuperación, según Zenhder fabricante de estos equipos. Todo ello acompañado de un análisis económico.
* Se propone estudiar otra nueva opción de diseño, se trata en desarrollar un equipo innovador de recuperación de calor que contenga dos cuerpos (uno sensible y otro latente) que podrían trabajar en serie o en paralelo. Debería de optimizarse el recorrido del flujo de aire a través del equipo, que podría atravesar uno o varios cuerpos en función de las condiciones de aire exterior e interior.
* Como tareas futuras consolidadas, se ha firmado con Zehnder un proyecto de investigación titulado "Estrategias de diseño y funcionamiento de sistemas de recuperación entálpica en climas mediterráneos" para desarrollar nuevas estrategias de funcionamiento para el sistema de ventilación de aire.

9. References

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