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

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

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

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

Abstract.

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 located in Italy and one in France as examples of the 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, as southern Europe, to define their thermal comfort parameters for nZEB.

Keywords

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

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

1. Introduction.

The residential sector in Europe is responsible for more than a third of the energy consumption and a comparable part of the CO_2 emissions associated with human actions [1]. Building policies are becoming more demanding in terms of improving the energy performance of buildings and reducing the associated CO_2 emissions. The Energy Performance of Buildings Directive (EPBD) 2010/31 [2] was created to regulate energy consumption in the building sector and requires that member states improve their regulations to ensure that nZEB targets will be reached. Moreover, indoor thermal conditions should be taken into account when putting the minimum energy requirements in place, but EU legislation does not include clear directions as to how this can be achieved.

Thermal comfort parameters in residential buildings have a strong impact on the energy demand [3] and must therefore be selected with extreme caution [4]. 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 [5,6] and more specifically the thermal comfort in residential buildings shows a strong dependency on recent outdoor temperatures [7].

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

It has been shown that the adaptive comfort models yields energy savings for natural ventilated buildings and ventilated systems without energy recovery. However, the Passivhaus standard, as a reference implementing nZEB requirements in Europe [8], imposes mechanical ventilation systems with energy recovery. Therefore, there should be further research to find out whether these comfort models offer the same advantages for constructions built under this standard.

Fifteen southern Europe cities were selected for this research. Their climate is defined by Köppen-Geiger climate worldwide classification as temperate climate [9,10], includes the Mediterranean area (in Europe: South of Spain, South of Italy, Greece, Turkey, Lebanon, Israel …and northern Africa countries such as Morocco and Tunisia), and areas of southern Australia and of southern USA. The Passivhaus standard has its own climate classification [11], since worldwide, it is divided in 7 climate areas. Europe has 5 climate areas (arctic, cold, cold temperate, warm temperate and warm) and Spain is divided in two areas (warm and warm temperate).

To deal with all the previous questions, energy simulations are performed for a dwelling built under the Passivhaus standard in different cities located in different climatic zones in the south of Europe (warm and warm temperate). The dwelling selected for the study has been modeled in TRNSYS [12]. The TRNSYS model has been validated with experimental data. Simulations provide sensible and latent energy demand throughout one year on an hourly basis, depending on the comfort parameters set and the climate data. Additionally, the results the nZEB dwelling were compared with those of a representative dwelling such as those currently being built in southern Europe.

Moreover, simulations have been 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, are evaluated for their possible inclusion in the nZEB requirements for warm climates.

2. Literature review.

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

Kwong et al. [13] provides a review of the energy efficiency in air conditioned tropical buildings by considering 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) [14,15]. Al Sanea [16] 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. [17] investigates 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 states than one degree increase in set point temperature is an important influencing factor in all climate zones.

Rohdin et al. [18] present the performance of nine passive houses built in Sweden, the energy use in these buildings is highly dependent on 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 Copenhagen and Madrid for a detached single family home (energy plus house) [19] showed that for Madrid moving the indoor temperature set point from 23ºC to 25ºC can decrease the cooling need by 23% and reveals the interest to quantify the energy saving potential with respect different temperature set points. The same authors publish a new study [20] presenting the results of thermal environment measurements and energy use of the single family house during a one year period. The operative temperature set-points were varied during the heating and cooling seasons concluding that the adaptive actions of the occupants would play a crucial role in the thermal comfort and on the annual energy performance of the building.

Ghahramani et al. [21] concluded that daily optimal set points based on outside temperature improves energy efficiency for office buildings. They point out the choice of the set points as a factor very influential (up to 30%) of energy savings, they simulated the DOE reference office buildings in all United States climates zones.

In their review of thermal comfort models, Yang et al. [3] state that the static Predicted Mean Vote (PMV) model works properly 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 is one of the first countries to include the adaptive thermal comfort approach in its building code in 2015 [22]. This action is reflecting the effectiveness of controlling the comfort set points from the energy savings point of view in cold climates. The still open question is if this action will be so effective and interesting for countries located at warmer climates.

There are numerous publications investigating the effect of relative humidity on human thermal comfort in hot and humid climates [23–25]. 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 the Mediterranean area.

The article [26] 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. There are researches related to the use of energy recovery devices to optimize the energy performance of buildings [27–30] but the adequacy of the use of ERV in warm climates is still an open question.

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

Section 3 includes a brief review of the thermal comfort concept and comfort models and Section 4 review the current European comfort standards which should be considered to provide thermal satisfaction to the occupants when optimizing the air conditioning energy demand.

3. Thermal comfort in buildings. Theoretical background.

The EN ISO 7730 standard [31] 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 [32]:

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

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.

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 [33]. 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 [34] and ASHRAE 55- 1992 [35] in which the temperature ranges are based on steady-state studies.

3.2. Adaptive thermal comfort model.

The adaptive model, incorporated in ASHRAE standard 55 [32], 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 [36] 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 be still 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 [38] 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. [5] 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 Eq. 2) for each country and a general equation recommended for use in Europe (Eq. 3 and 4):

$$T_{RM80}= 0.8T_{RMn-1} + 0.2T_{DMn-1} \quad (2)$$

Where T_{DMn-1} is the daily mean outdoor temperature on day n-1 (ºC)

$$Tc= 0.302T_{RM80} +19.39º \qquad T_{RM80} >10ºC \quad (3)$$

$$Tc= 22.88ºC; \qquad T_{RM80} >10ºC \quad (4)$$

Of the countries studied, Portugal and Greece have the most similar climate to the selected cities as they are located at similar latitudes. The equation obtained for Portugal (Eq. 5) is the following:

$$Tc= 0.381T_{RM80} +18.12 \quad (5)$$

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 (Eq.6):

$$Tc= 0.205T_{RM80} +21.69 \quad (6)$$

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 [39]. The most relevant international standards that should be considered for thermal comfort are ISO 7730:2005 [31], ASHRAE Standard 55: 2013 [40], and EN 15251:2008 [41].

4.1. ISO 7730:2005.

The international standard ISO 7730:2005 [31] provides methods to predict the thermal sensation and degree of discomfort of people by using the PMV and the PPD. Humphreys [42] 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 1.

4.2. ASHRAE Standard 55.

The first ASHRAE standard, 55 -1992 [35], 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 [43] 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 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 [32] specifies the relation between the environmental parameters and personal parameters to provide thermal conditions acceptable to a majority of the building occupants.

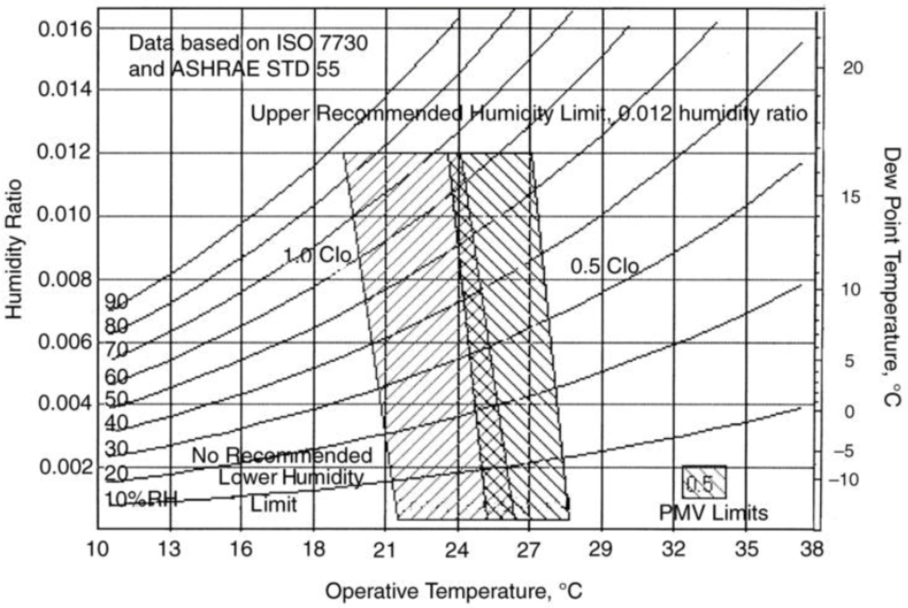

Figure 1. Comfort range for MV buildings. ASHRAE 55-2004 [43].

4.3. EN 15251:2008.

The EN 15251 standard [41] was designed to set limits for indoor conditions to ensure that the EPBD [2] 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 1.

4.4. 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 1 for comparison.

Table 1. Max. and Min. Operative temperature and RH range required or recommended by the standards for residential buildings.

Standard/ Norm	EN 15251 [a] [41]	ISO 7730 [31]	ASHRAE 55 [32]	Germany [44]	France [c] [45]	Italy[d] [46]	Spain [47]	Passivhaus [39]
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% [e]	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*

5. Model description.

A dwelling is taken from a real project built in Spain and a model with the selected dwelling has been developed using TRNSYS [28] software.

5.1 Software.

TRNSYS is a very powerful software tool widely used to carry out numerical studies on energy demand for all kinds of buildings, nZEB included [48,49]. The main Types used in the model are:

- Type56 [50] (Multizone building model) to simulate the dwelling.
- Type667 [51] to simulate the energy recovery system (Energy Recovery Ventilator (ERV) or Heat Recovery Ventilator (HRV)).
- Type 66 [52] in order to control the by-pass of the ERV or HRV. Type 66 triggers the Engineering Equation Solver [53] (EES) which calculates the by-pass valve position depending on the temperature, humidity and enthalpy of the air streams.

The simulations provide the air-conditioning energy demand on an hourly basis throughout one year for the selected cities.

5.2. TRNSYS model validation.

The data collected from a real detached house has been used to validate the TRNSYS model. It is located 70 Km north of Barcelona (Spain), not on the coast.

The house was built following the Passivhaus standard and was monitored and measured every 15 minutes from September 2015 until September 2016. The parameters and conditions of the monitored house as an example of nZEB are similar to those of the simulated nZEB dwelling. Their technical properties are shown in Table 2.

Table 2. Technical properties of real building and the simulated nZEB dwelling.

	Monitored house		Simulated Dwelling	
Room	**Area (m^2)**	**Ventilation air flow (%)**	**Area (m^2)**	**Ventilation air flow (%)**
Kitchen	32.00	Exhaust 45%	9.18	Exhaust 40%
Bathroom	5.30	Exhaust 35%	3.40	Exhaust 30%
Toilet	3.80	Exhaust 20%	3.00	Exhaust 30%
Bedroom 1	13.65	Supply 30%	12.16	Supply 20%
Bedroom 2	22.30	Supply 30%	12.00	Supply 20%
Bedroom 3	---	---	11.27	Supply 20%
Living room	18.00	Supply 40%	22.68	Supply 40%
Corridor	4.95	---	7.46	---
Total	100.00 (two floors)		81.15	

Enclosure parameters			
Window/ Ext. wall ratio	0.1 for north , 0.33 for south, 0.06 for east and 0.16 for west	0.35 for north, 0.37 for south, 0 for east and west	
	Transmittance U (W/m2K)	**Transmittance U nZEB Southern Europe (W/m2K)**	**Transmittance U nZEB Central and Northern Europe (W/m2K)**
External wall	0.127	0.340	0.150
Floor	0.165	0.260	0.150
Roof	0.122	0.260	0.150
Windows	1.060	1.400	0.800
Airtightness n50 (ACH)	0.32	0.60	

The monitored values are: 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 ambient air temperature was measured and incorporated in the model while other climate data such as the solar radiation loads were taken from Meteonorm meteorological file for Barcelona city (the closest city).

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 internal source loads have been obtained from the electrical energy consumption of the house. Regarding to occupation, a nominal value of 265 W sensible load and 245 W latent load have been considered (ISO 7730: 2005 [31]). For internal sources, a nominal load of 2.5 W/m^2 for lighting and other equipment and a computer with a monitor with a nominal 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 3.

Table 3. 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**
Multiplier factor for Sensible & Latent Loads due to occupancy	0.5	0.25	1	0.5	0.75	0.5	0.25	2	0.5	1
Multiplier factor for Lighting, Equipment and devices	0	0.5	0	1	0.5	0	0.5	1.5	1	0.5

The house has a mechanical ventilation system, the ventilation air flow during occupied hours is 120 m^3/h and the air flow rate for each room is shown in Table 3. The system includes an HRV which has a measured effectiveness of 0.84 at 120 m3/h.

The temperature set value for the house is 20ºC in winter. The measured heating demand for one year (September-2015/2016) was 2.5 KWh/m^{2}y and the ventilation system energy demand was 2.6 KWh/m^{2}y.

The heating demand in winter was obtained through the electrical consumption of the radiators (heating source), being 74.02 kWh (for electrical radiators) for February 2016, while the heating demand obtained for the same month with the TRNSYS model was 70.68 kWh. The error obtained is 4.5%, small enough to guarantee that the results obtained from the simulated dwelling are sufficiently consistent to obtain reliable conclusions. Furthermore, the results are comparative, the energy saving (%) obtained being dependent on the comfort set parameter which changes from one simulation to other. The TRNSYS model used for the real house is the same as that used for the simulations. The technical properties of the real building have been replaced by the Type 56 proposed nZEB dwelling as shown in Table 3.

5.3. Climate data and selection of cities.

Fifteen cities located in southern Europe, area which can be categorized as warm climate region were selected for this study.

The Basic Document HE1 of the Spanish Technical Building Code (CTE) [47,54] 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 (Table 4 and Figure 2), one city located at the south of France, Marseille and two cities from warm area of Italy: Rome and Palermo (Figure 2) were selected. The climate data files are taken from the Meteonorm meteorological database [55].

Table 4. Representative cities from each of the climatic zones defined in the Spanish legislation [54].

	Winter CS: Severity level A < B < C < D < E				
Summer CS: Severity level 4 > 3 > 2 > 1	A4 Almería	B4 Alicante	C4 Cáceres		
	A3 Rota	B3 Murcia	C3 Granada	D3 Madrid	
			C2 Barcelona	D2 Logroño	
			C1 Santander	D1 Vitoria	E1 Soria

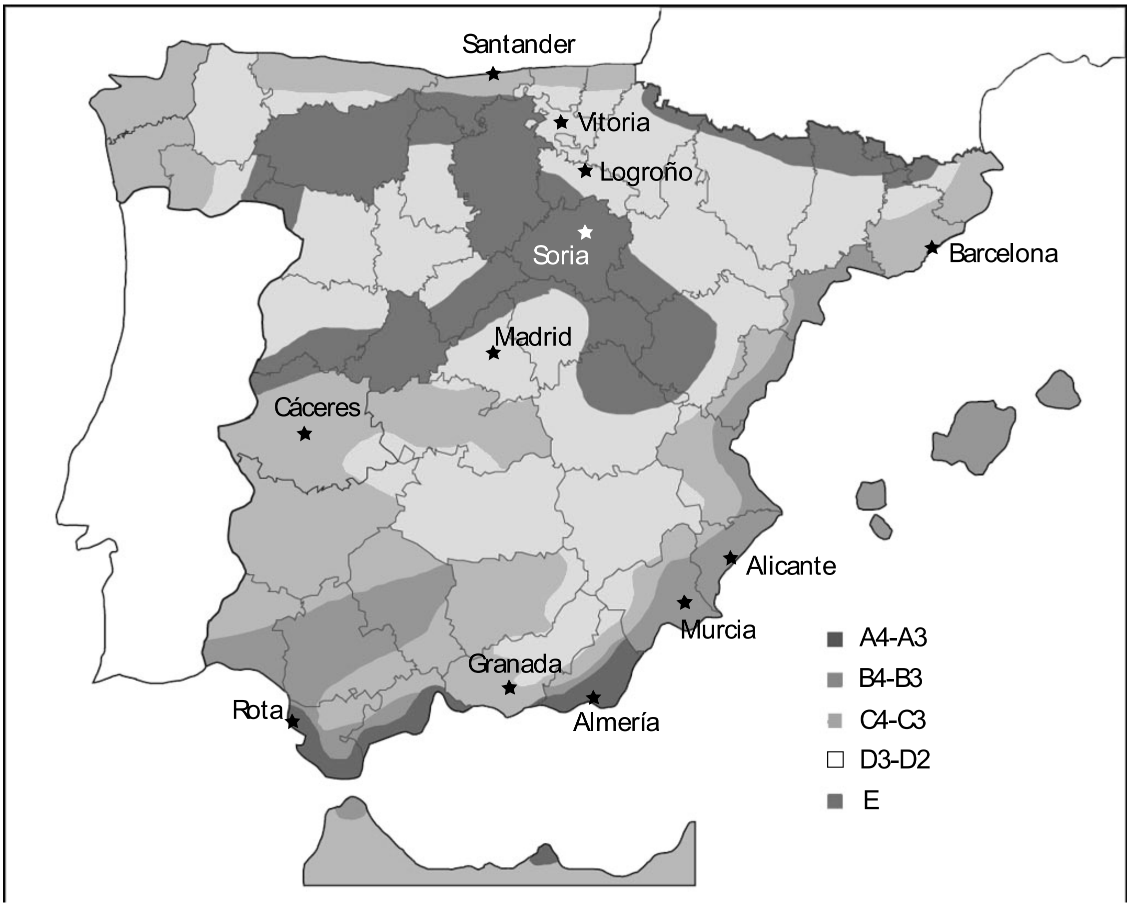

Figure 2. Winter climatic zones described in the Spanish legislation [54] .

Añadir junto al mapa detalle de donde están las otras ciudades europeas.

5.4. Dwelling description: nZEB model and traditional dwelling model.

A typical dwelling layout in Spain, for a family of four persons has been selected. The layout has previously been considered by the authors [56,57] to review international ventilation strategies and to study the annual envelope energy losses in different countries. The dwelling room areas are given in Table 2, the dwelling is located at the last floor of a block of houses with three floors.

A nZEB dwelling model according to Passivhaus standard was developed to check the impact of comfort parameters on the air conditioning demand and a second traditional dwelling model was done to compare the influence of those parameters in both types of buildings. The difference on both models are on the parameters which have the greatest impact on the nZEB dwelling air conditioning demand: the envelope transmittances, the air tightness and the air ventilation system.

1) For nZEB model, the envelope transmittance U-values are those recommended by Passivhaus for Mediterranean area for cities located in the Spanish winter climatic zones A, B and C and for the French

and Italian cities. The values recommended for Central & North of Europe for the Spanish cities located in winter climatic zones D and E.

For traditional dwelling model, the envelope transmittance U-values are those recommended by current Spanish regulations depending on the cities climatic area location (Table 5), as an example of existing dwellings. For Marseille and Rome the transmittance values for building enclosure are the values of Spanish climatic area C and for Palermo the values of Spanish climatic area A as those are their equivalent climate regions.

Table 5. Average transmittance limit depending on the location of the building enclosure (W/(m^{2}K)).

Average transmittance limit depending on the location of the building enclosure (W/(m^{2}K))							
TNRSYS Model	**nZEB dwelling model**		**Traditional dwelling model**				
Norm/Standard	*Passivhaus: Provides different values for Central & North of Europe and Mediterraneam countries.*		*DBHE1 (Spain)*				
Climatic zone	CENTRAL&NORTH	MEDIT.	A	B	C	D	E
Extenal 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 nZEB model correspond to the maximum value set for Passivhaus standard n_{50}=0.6 ACH (air changes by 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. [58] for air leakage in Catalan existing dwellings (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 and the traditional dwelling model does not have any recovery device.

Passivhaus standard, as an example of a nZEB standard, states that this value should be between 30 m^3/h and 32 m^3/h per person (for residential use) [39].The minimum air flow rate recommended in the regulations of some countries is reviewed by the authors in a previous paper [56]. Taking into account the Passivhaus recommendation and the fact that the simulated dwelling is suitable for a family of 4, the total air ventilation rate considered in the model is 120m^3/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 240m^3/h. The air flow distributions for each room are those recommended by a company (Zehnder Group Ibérica IC S.A) which develops and commercializes air ventilation systems and air heat exchangers for buildings certified under the Passivhaus standard. The values for each room are shown in Table 2.

The rest of the models parameters as the internal loads are the same as the model used for model validation.

6. Methodology.

After reviewing the comfort models and the current international standards, simulations were performed changing the temperature and humidity settings, as shown in Table 6, and evaluating their impact on the sensible and latent load. The values correspond to the minimum comfort temperature during winter and the maximum comfort temperature during summer. The heating demand is obtained from October to May and the cooling demand from June to September [59].

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 Section 3. The hypothesis has been verified on the nZEB model.

However this hypotheses cannot be applied to the traditional model were the operative temperature is lower than the air room temperature (temperature set for air conditioning demand) due to a worst envelope thermal insulation on the traditional model. The mean radiant temperature has been calculated with TRNSYS by obtaining the walls inside temperature on the living room and them applying equation (1) for a=0.5. The air temperature set for traditional model is finally one degree higher in winter to obtain equivalent operative temperature. No adjustment is needed during summer due to a lower air temperature difference between indoors and outdoors. (Bea esto voy a cambiarlo y a introducir en el modelo la temperatura operativa calculada cada hora, pero las simulaciones las haré este finde).

Table 6. Temperature and humidity settings for the simulations performed.

		$T_{operative}$ (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	20-26	RH 30-60%	Mediterranean cities HRV and ERV	
			RH 30-65%		

	WINTER AND SUMMER: Latent energy demand		RH 30-70% Max. 0.012 kg/kg dry air		------
Fourth set of simulations	Simulations performed at variable set temperature [5] and constant set humidity: heating and cooling demand	Portuguese model [5]	RH 30-60%	Spanish cities: HRV	---------

When installing a HRV on 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 has similar climate data than 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. [5]. As Spain was not included on their study, a comparison of the comfort temperatures obtained from the Portuguese model (Eq.5), from the Greek model (only existing for summer, Eq.6) and from the general equations (Eq. 3 and 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. 4) has been used to calculate the air conditioning energy demand.

7. Results and discussion.

7.1. Heating demand depending on a constant set temperature.

Simulations have been performed for set 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 if the T_{rm} of the inner surface of the envelope is close to the indoor temperature). The minimum RH setting is 30% and the maximum is 60%, but the humidification load for the selected cities is negligible.

For the nZEB dwelling, the heating demand obtained for each city is shown in Figure 3.

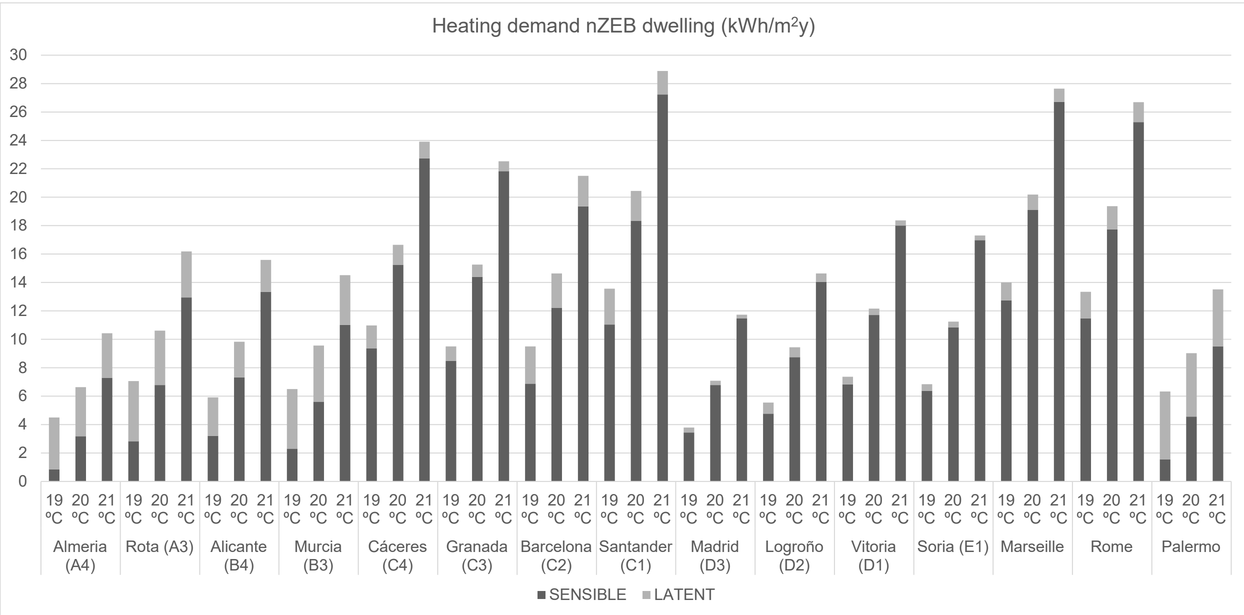

Figure 3. Heating energy demand (kWh/m^{2}year). HRV system (nZEB dwelling).

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 the worst. As expected, the impact on sensible energy is greater when the set temperature is increased from 20ºC to 21ºC than when it is lowered from 20ºC to 19ºC.

When the set temperature was reduced from 20ºC to 19ºC, the smallest savings were for 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 increased 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. While the smallest increase was for one of the hottest cities, 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.

The Table 7 shows the impact (%) on heating energy demand when moving the thermostat from 20ºC to 19ºC and to 21ºC.

Table 7. Impact on heating energy demand depending on thermostat setting (moving from 20ºC). HRV system (nZEB dwelling).

	Sensible		Latent		Total	
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 temperature setting on the sensible energy demand is more important for the warmest cities (Spanish zone climatic A and B and Palermo) the reductions are higher than -50%, and the increases can be greater than the 100%.

For the latent energy, the reductions and the increases are similar, being around 15-20% for the coldest cities and 10-15% 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 significant.

Looking to 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, which is representative of the buildings that are currently built in southern Europe, are show in Figure 4. and Table 8 for purpose of comparison.

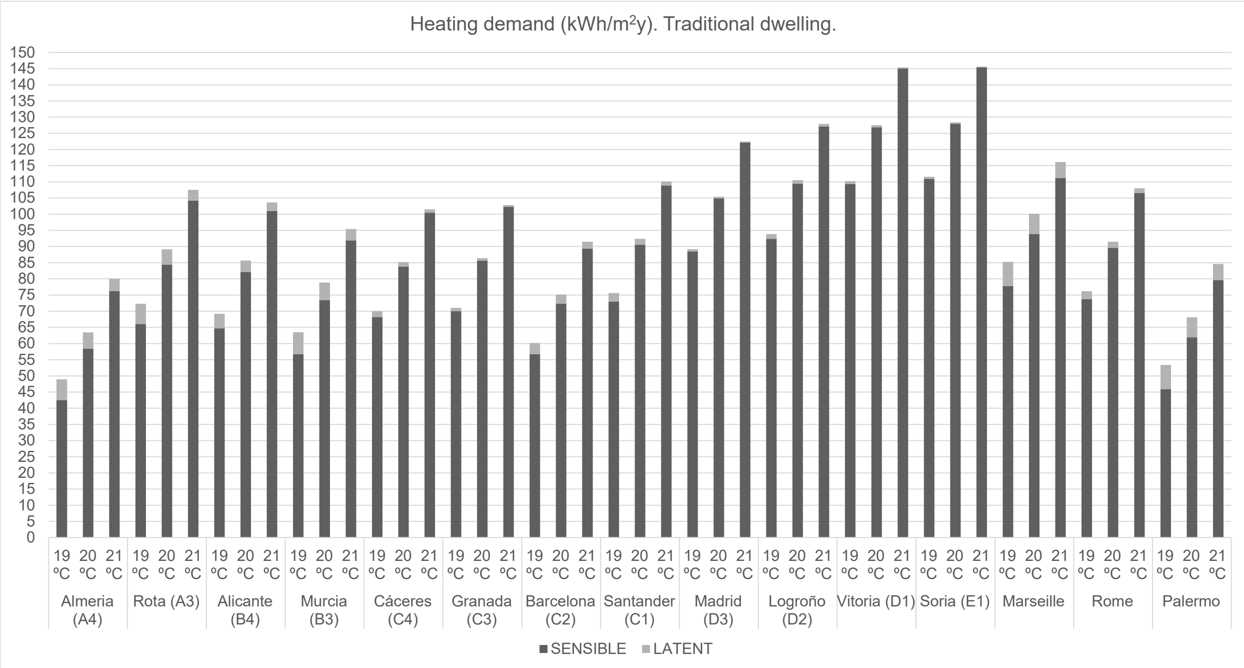

Figure 4. Heating energy demand (kWh/m^{2}year). Traditional dwelling.

As a first remark, the scale on the Figure 3 and Figure 4 has had to be changed as result of the important heating demand savings obtained for a nZEB comparing to the traditional dwelling.

The result shows an homogeneity on the savings and increments for the sensible heating demand in absolute values, they are not much differences between the climatic zones. The reductions ranges from 15.6 kWh/m^{2}y to 17.6 kWh/m^{2}y and the increases from 16.5 kWh/m^{2}y to 19.8 kWh/m^{2}y.

Looking at the impacts (%) showed on Table 8, the values are lower for a traditional dwelling than for a nZEB dwelling. The average reduction on the total heating demand is -17.6% for a traditional dwelling and -35.7% for a nZEB dwelling. The average increment is 19.0% for a traditional dwelling and the 50.0% for a nZEB.

Table 8. Impact on heating energy demand depending on thermostat setting (moving from 20ºC). Traditional dwelling.

	Sensible		Latent		Total	
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%

7.2. 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 (kWh/m^{2}year) are shown in Figure 5.

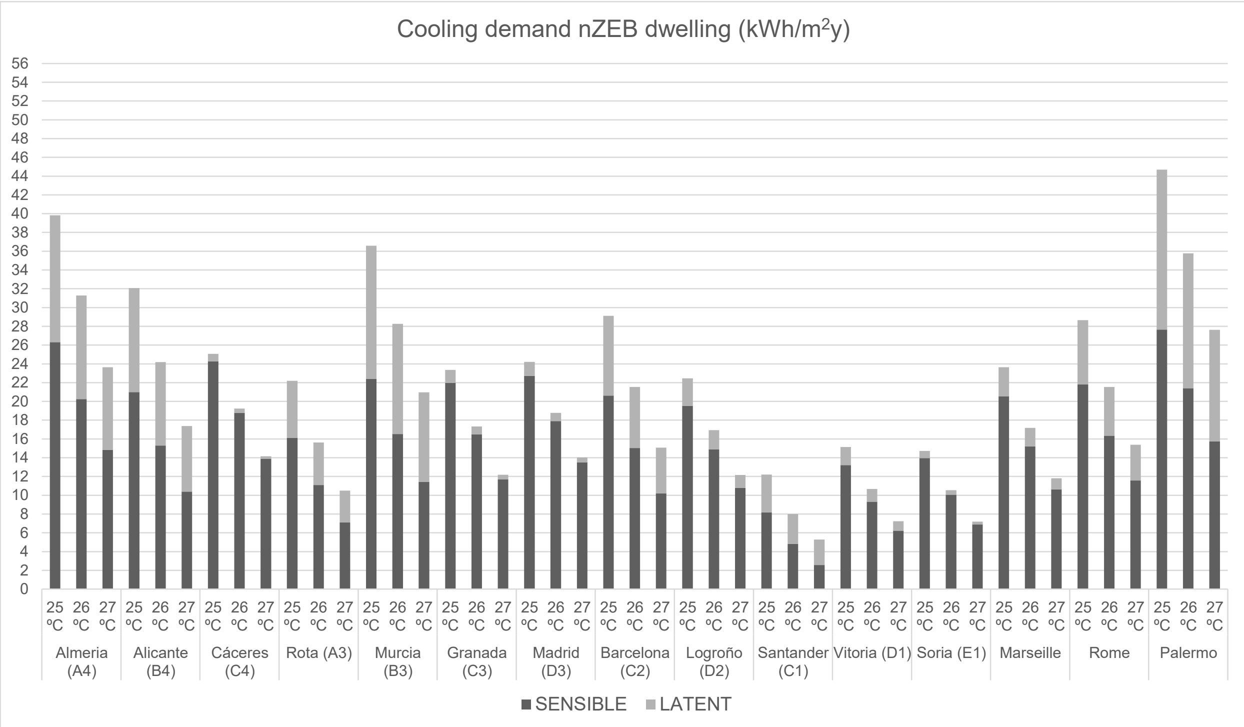

Figure 5. Cooling energy demand (kWh/m^{2}year). HRV system.

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.

When the set temperature was reduced from 26ºC to 25ºC, the greatest increment in the sensible energy demand was for one of the hottest city, Palermo, where the sensible energy demand increased by 6.2 kWh/m^{2}y. While 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.

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 on the latent energy demand. 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 9 shows the impact on cooling energy demand when moving the thermostat from 26ºC to 25ºC and to 27ºC.

Table 9. Impact on cooling energy demand depending on thermostat setting (moving from 26ºC). HRV system (nZEB dwelling).

	Sensible		**Latent**		**Total**	
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 influence of temperature setting on the sensible cooling energy demand is more independent of the climate data than the sensible heating demand. The increment and reductions are more equal for all the cities. The reductions ranges between -24.5% (Madrid) and -46.5% (Santander) and the increases ranges from +29.1% (Palermo) to +69.9% (Santander).

Looking to 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. The results obtained for the traditional dwelling are show in Figure 6 and Table 10 for purpose of comparison.

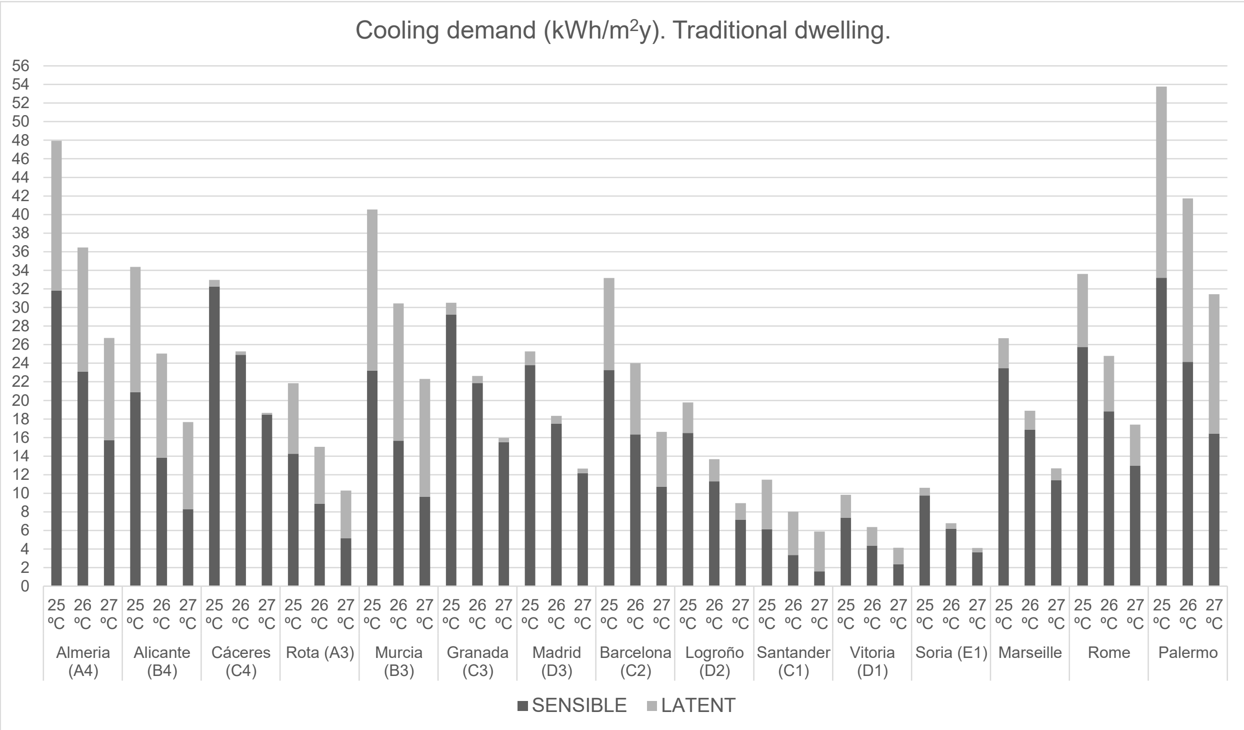

Figure 6. Cooling energy demand (kWh/m^{2}year). Traditional dwelling.

Table 10. Impact on cooling energy demand depending on thermostat setting (moving from 26ºC). Traditional dwelling.

	Sensible		**Latent**		**Total**	
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 scale on the Figure 5 and Figure 6 are the same because the savings obtained for a nZEB comparing to the traditional dwelling are not as relevant as for the heating demand. Looking at the impacts (%) for sensible cooling demand showed on Table 10, at the contrary than for sensible heating demand, the values are higher for a traditional dwelling than for a nZEB dwelling. The average reduction on 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 the 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 has similar climate data than Almeria. These simulations were performed substituting the HRV by an ERV as the objective is to assess the impact on the energy demand in cases where an ERV is placed in the ventilation system. The results for the cooling energy demand are shown in Figure 7 and the relative impacts are shown in Table 11.

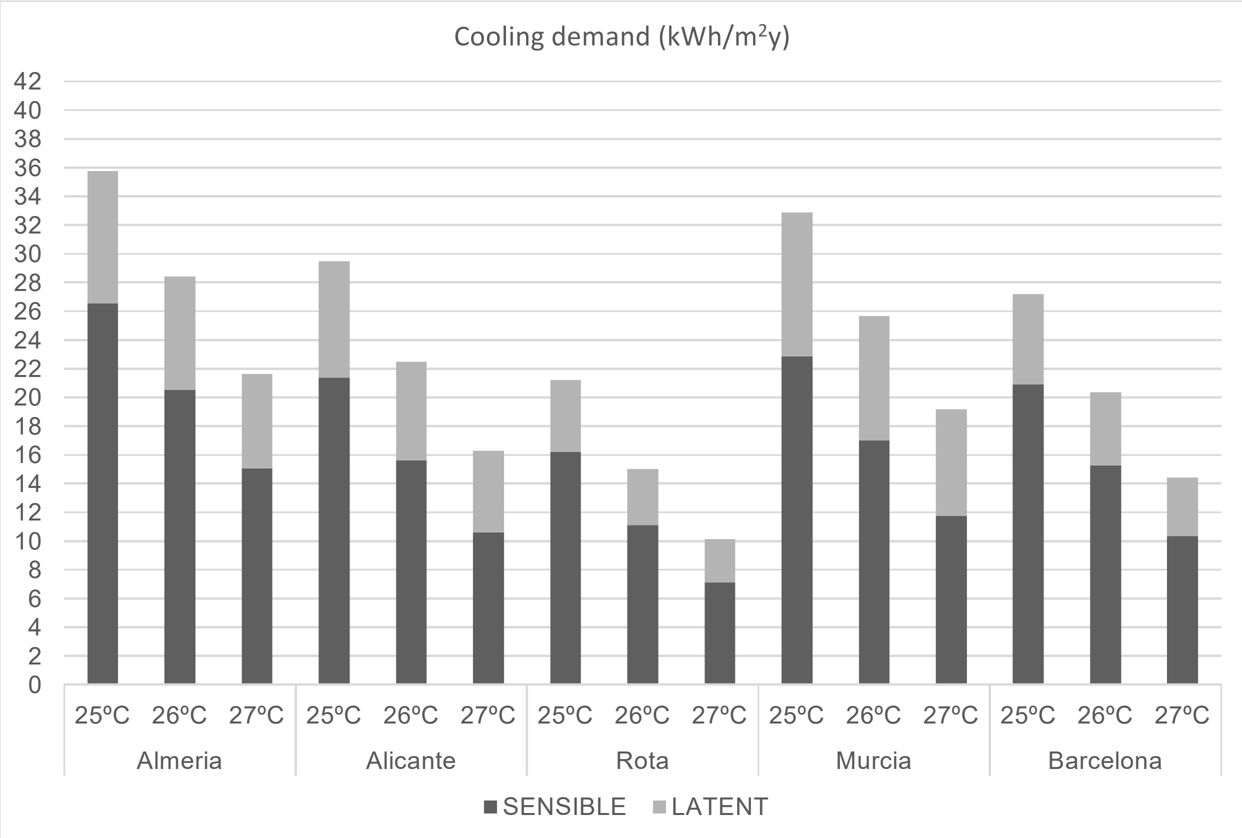

Figure 7. Cooling energy demand (kWh/m^{2}year). ERV system.

Table 11. Impact on cooling energy demand depending on thermostat setting (moving from 26ºC). ERV system.

		Almeria (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%
	25ºC	17.1%	18.2%	28.1%	15.4%	22.8%
Latent	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%

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.

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%, 70% and 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. Figure 8 shows the results when an HRV is installed and Figure 9 when an ERV is installed.

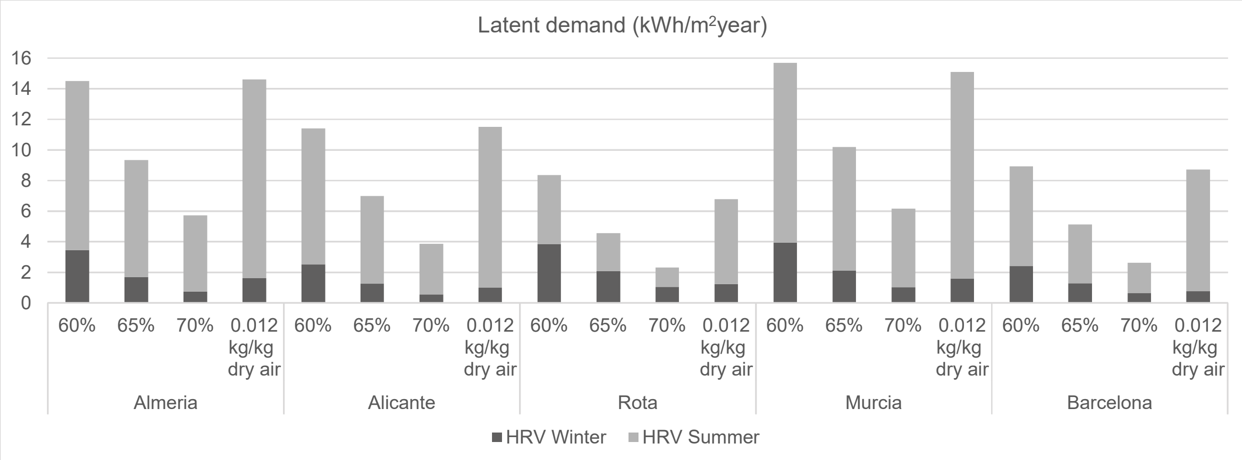

Figure 8. Latent energy demand (kWh/m^{2}year). HRV system.

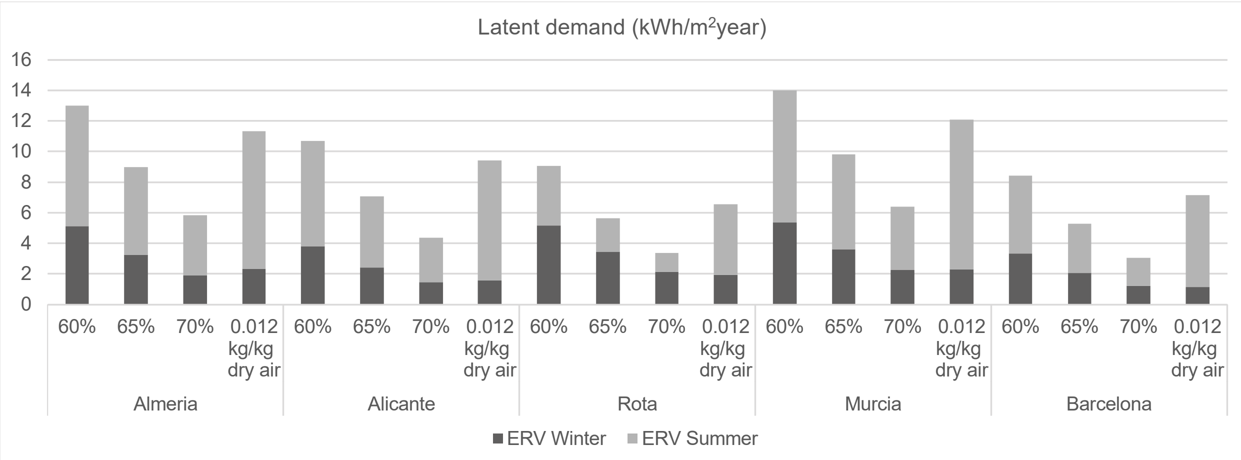

Figure 9. Latent energy demand (kWh/m^{2}year). ERV system.

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 an HRV is 10% for RH 60% and negligible when the relative humidity setting is increased.

7.4. Energy demand for variable temperature setting: Adaptive model.

Figure 10 shows the comfort temperature profiles (set temperature) when applying the European model (Eq. 3 and 4), the Portuguese model (Eq.5), the Greek model (only for the summer season, Eq.6) and the constant set temperature (20-26ºC) for one city from each Spanish climate area.

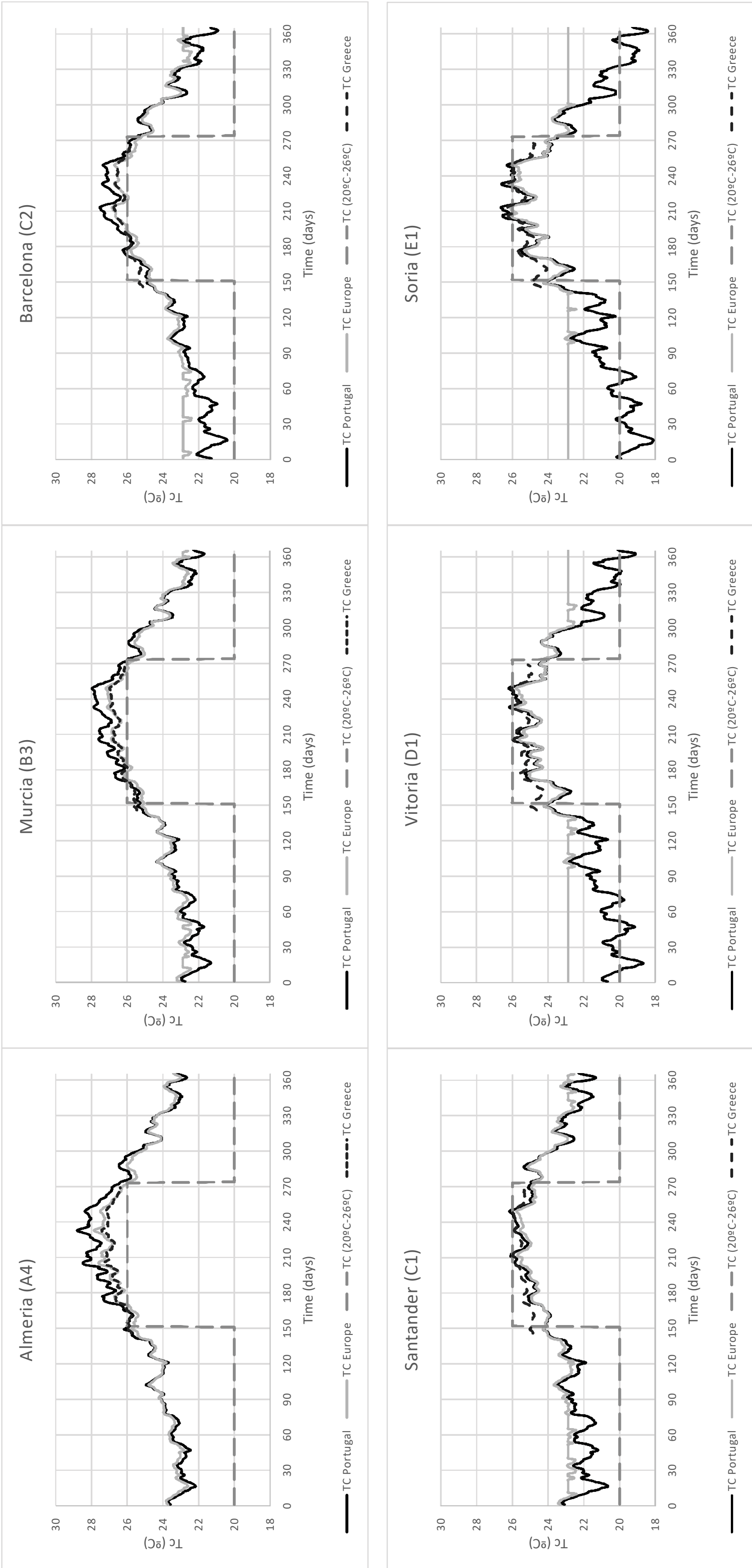

Figure 10. Temperature comfort profiles.

It is important to emphasize the great difference between the adaptive models and the constant set temperature. In the warmest cities adaptive models provide higher comfort temperatures in both winter and summer; however, in 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 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).

The sensible heating demand is considerably higher for all the cities. However, 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. During summer, it is also reduced for the Mediterranean cities. Almería has a reduction of 3.6 kWh/m^{2}y (32.4%) and Murcia of 2.3 kWh/m^{2}y (19.6%). There is a substantial increase in the total sensible energy for all the cities. This is more significant for the warmest cities due to the strong impact on the heating demand.

The total energy demand is increased for all the cities. 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 Soria with increases of 17.1% and 29.7%, respectively.

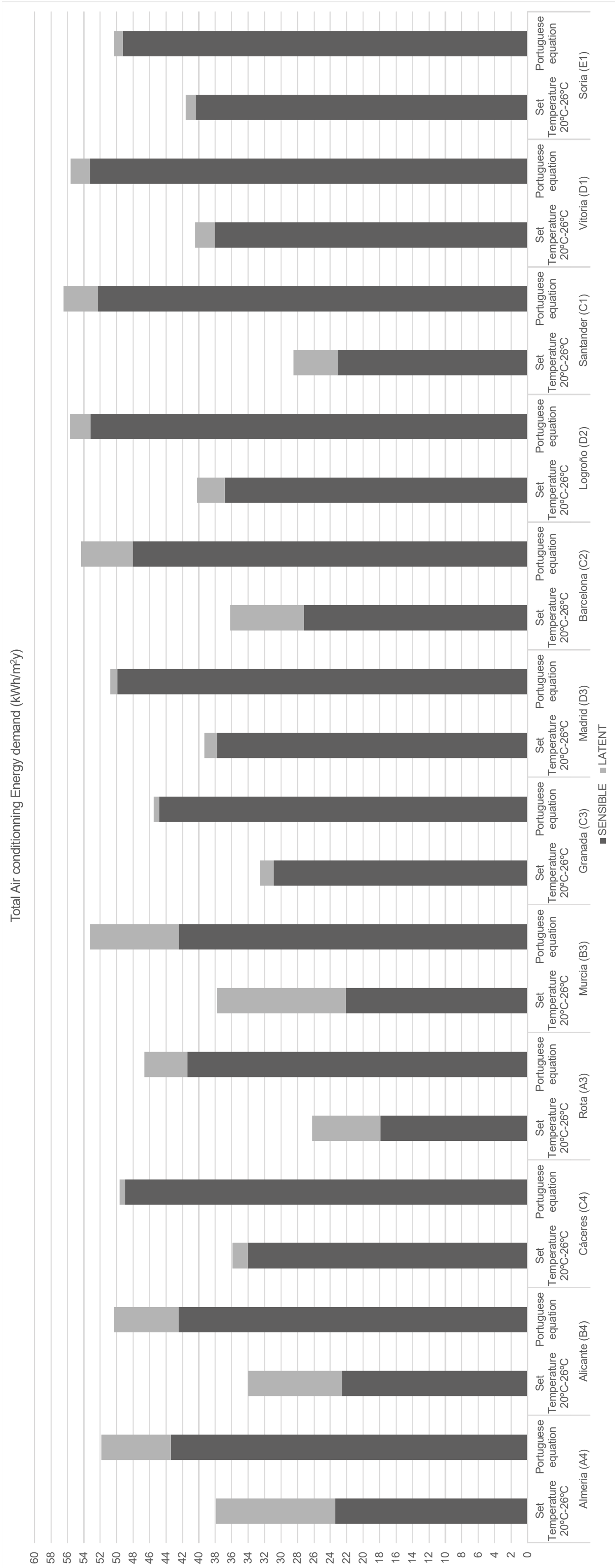

Figure 11. Total energy demands (Kwh/m^{2}year). Set temperature 20ºC-26ºC and adaptive model (Portuguese equations) [5]. HRV system.

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 were selected for this study: twelve cities located in Spain, one located in France and two located in Italy.

The following conclusions can be draw from this study:

1) 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.

2) The impact of the winter temperature set point on the heating demand (%) is higher for a nZEB dwelling than for a traditional dwelling.

The heating energy savings when moving the temperature set 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 important 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 when moving the temperature set from 20ºC to 21ºC between 40% and 60% for nZEB and between 15 % and 25% for a traditional dwelling. The impact on the heating energy demand is more important for the warmer cities for both nZEB and traditional dwelling.

3) The impact of the summer temperature set point on the cooling demand (%) is slightly lower for a nZEB dwelling than for a traditional dwelling.

The cooling energy savings when moving the temperature set 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 when reducing the temperature set from 26ºC to 25ºC between 25% and 52% for nZEB and between 29 % and 56% for a traditional dwelling. The impact on the cooling energy demand is more important for the coldest cities for both nZEB and traditional dwelling.

4) 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 in Mediterranean cities reveals that the impact on the latent energy demand when changing the RH setting is similar when either an HRV or an ERV is installed in the ventilation system. Using an ERV, there is a reduction between 3.2 kWh/m^{2}y and 4.2 kWh/m^{2}y 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/m^{2}y and 7.2 kWh/m^{2}y (-55.3% and -62.9%) when the RH is increased to 70%.

5) The equation proposed by McCartney et al.[5] 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 very effective for energy savings during the summer season for the warmest cities, but seems to be less 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 parameters should be reviewed for residential nZEB in warm climates. It is demonstrated that by adopting extended comfort ranges, significant energy savings would be achieved in countries with temperate climates for a nZEB. It is recommended to develop new adaptive control algorithm to define the comfort temperature in the different climate areas in the south of Europe to optimized comfort parameters in terms of energy savings for nZEB.

Acknowledgements

The authors wish to thank the company Zehnder Group Iberica IC, S.A for their collaboration during this study and the monitored data of the house used for the TRNSYS model validation.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

[1] Expert Group on Energy Efficiency. Realizing the Potential of Energy Efficiency. Washington: 2007.

[2] European Commission. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. Official Journal L153 2010:13–35.

[3] Yang L, Yan H, Lam JC. Thermal comfort and building energy consumption implications – A review. Appl Energy 2014;115:164–73. doi:10.1016/j.apenergy.2013.10.062.

[4] Moon JW, Han SH. Thermostat strategies impact on energy consumption in residential buildings. Energy Build 2011;43:338–46.

[5] McCartney KJ, Fergus Nicol J. Developing an adaptive control algorithm for Europe. Energy Build 2002;34:623–35. doi:10.1016/S0378-7788(02)00013-0.

[6] Aktacir MA, Büyükalaca O, Bulut H, Yılmaz T. Influence of different outdoor design conditions on design cooling load and design capacities of air conditioning equipments. Energy Convers Manag 2008;49:1766–73. doi:10.1016/j.enconman.2007.10.021.

[7] Peeters L, Dear R de, Hensen J, D'haeseleer W. Thermal comfort in residential buildings: Comfort values and scales for building energy simulation. Appl Energy 2009;86:772–80. doi:10.1016/j.apenergy.2008.07.011.

[8] Buildings Performance Institute Europe (BPIE). Principles for Nearly Zero-energy Buildings. Paving the way for effective implementation of policy requirements. Brussels: 2011.

[9] Peel BL, Finlayson BL, McMahon T a. Updated world map of the Koppen-Geiger climate classification.pdf. Hydrol Earth Syst Sci 2007;11:1633–44. doi:10.5194/hess-11-1633-2007.

[10] Kottek M, Grieser J, Beck C, Rudolf B, Rubel F. World map of the Köppen-Geiger climate classification updated. Meteorol Zeitschrift 2006;15:259–63. doi:10.1127/0941-2948/2006/0130.

[11] Passive House Institute (PHI). Criteria for Passive House Component certification n.d. http://passivehouse.com/03_certification/01_certification_components/02_certification_criteria/02_certification_criteria.htm (accessed March 7, 2017).

[12] Solar Energy Laboratory. TRNSYS 17. A Transient System Simulation tool. 2012.

[13] Kwong QJ, Adam NM, Sahari BB. Thermal comfort assessment and potential for energy efficiency enhancement in modern tropical buildings: A review. Energy Build 2014;68:547–57. doi:10.1016/j.enbuild.2013.09.034.

[14] AC R, J S, R de D. A preliminary evaluation of two strategies for raising indoor air temperature setpoints in office buildings. Archit Sci Rev 2011;Volume 54:148–56. doi:10.1016/j.apenergy.2015.12.115.

[15] Tzivanidis C, Antonopoulos KA, Gioti F. Numerical simulation of cooling energy consumption in connection with thermostat operation mode and comfort requirements for the Athens buildings. Appl Energy 2011;88:2871–84. doi:10.1016/j.apenergy.2011.01.050.

[16] Al-Sanea SA, Zedan MF. Optimized monthly-fixed thermostat-setting scheme for maximum energy-

savings and thermal comfort in air-conditioned spaces. Appl Energy 2008;85:326–46. doi:10.1016/j.apenergy.2007.06.019.

[17] Cetin KS, Manuel L, Novoselac A. Effect of technology-enabled time-of-use energy pricing on thermal comfort and energy use in mechanically-conditioned residential buildings in cooling dominated climates. Build Environ 2016;96:118–30. doi:10.1016/j.buildenv.2015.11.012.

[18] Rohdin P, Molin A, Moshfegh B. Experiences from nine passive houses in Sweden – Indoor thermal environment and energy use. Build Environ 2014;71:176–85. doi:10.1016/j.buildenv.2013.09.017.

[19] Kazanci OB, Olesen BW. The Effects of Set-Points and Dead-Bands of the HVAC System on the Energy Consumption and Occupant Thermal Comfort. Climamed´13 - 7th Mediterr Congr Clim Proc B 2013:224–32.

[20] Toftum J, Kazanci OB, Olesen BW. Effect of Set-point Variation on Thermal Comfort and Energy Use in a Plus- energy Dwelling. Wind 2016 2016.

[21] Ghahramani A, Zhang K, Dutta K, Yang Z, Becerik-Gerber B. Energy savings from temperature setpoints and deadband: Quantifying the influence of building and system properties on savings. Appl Energy 2016;165:930–42. doi:10.1016/j.apenergy.2015.12.115.

[22] The Danish Ministry of Economic and Business Affairs Danish Enterprise and Construction. Danish Building Regulations 2015 2015;2015:10–2.

[23] Indraganti M, Ooka R, Rijal HB, Brager GS. Adaptive model of thermal comfort for offices in hot and humid climates of India. Build Environ 2014;74:39–53. doi:10.1016/j.buildenv.2014.01.002.

[24] Schiavon S, Melikov AK, Sekhar C. Energy analysis of the personalized ventilation system in hot and humid climates. Energy Build 2010;42:699–707. doi:10.1016/j.enbuild.2009.11.009.

[25] Chen Y, Raphael B, Sekhar SC. Experimental and simulated energy performance of a personalized ventilation system with individual airflow control in a hot and humid climate. Build Environ 2016;96:283–92. doi:10.1016/j.buildenv.2015.11.036.

[26] Wan JW, Yang K, Zhang WJ, Zhang JL. A new method of determination of indoor temperature and relative humidity with consideration of human thermal comfort. Build Environ 2009;44:411–7. doi:10.1016/j.buildenv.2008.04.001.

[27] Zhang LZ. Energy performance of independent air dehumidification systems with energy recovery

measures. Energy 2006;31:1228–42. doi:10.1016/j.energy.2005.05.027.

[28] Guillén-Lambea S, Rodríguez-Soria B, Marín JM. Control strategies for Energy Recovery Ventilators in the South of Europe for residential nZEB. Quantitative analysis of the air conditioning demand. Energy Build n.d.:under revieew.

[29] Zhou YP, Wu JY, Wang RZ. Performance of energy recovery ventilator with various weathers and temperature set-points. Energy Build 2007;39:1202–10. doi:10.1016/j.enbuild.2006.12.010.

[30] Tafelmeier S, Pernigotto G, Gasparella A. Annual Performance of Sensible and Total Heat Recovery in Ventilation Systems: Humidity Control Constraints for European Climates. Buildings 2017;7:28. doi:10.3390/buildings7020028.

[31] ISO (International Organization for Standardization). 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. 2005.

[32] American Society of Heating Ventilating and Air-Conditioning Engineers. ASHRAE Standard 55-2010: Thermal environmental conditions for human occupancy. Georgia, Atlanta: 2010.

[33] Fanger PO. Thermal comfort, analysis and application in environmental engineering. Copenhagen: Danish Technical Press; 1970.

[34] ISO (International Organization for Standardization). ISO 7730:1984. 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. 1984.

[35] ASHRAE Standard 55-92: Thermal Environmental Conditions for Human Occupancy. 1992.

[36] Veselý M, Zeiler W. Personalized conditioning and its impact on thermal comfort and energy performance – A review. Renew Sustain Energy Rev 2014;34:401–8. doi:10.1016/j.rser.2014.03.024.

[37] Zhai Y, Zhang H, Zhang Y, Pasut W, Arens E, Meng Q. Comfort under personally controlled air movement in warm and humid environments. Build Environ 2013;65:109–17. doi:10.1016/j.buildenv.2013.03.022.

[38] Humphreys MA. Outdoor temperatures and comfort indoors. Build Res Pract (Journal CIB) 1978;6:92–105.

[39] Wassouf M. De la casa pasiva al estándar Passivhaus. La arquitectura pasiva en climas cálidos. Editorial Gustavo Gili; 2014.

[40] American Society of Heating Ventilating and Air-Conditioning Engineers. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Standard 55, Thermal Environment Conditions for Human Occupancy. 2013.

[41] European committee for Standardization. EN 15251:2007 Indoor environmental input parametres for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. 2008.

[42] Humphreys Revd M. Thermal comfort temperatures world-wide - the current position. Renew Energy 1996;8:139–44. doi:10.1016/0960-1481(96)88833-1.

[43] ASHRAE, Standard 55-2004. Thermal environment conditions for human occupancy. 2004.

[44] Verordnung Bundesrepublik Deutschland. EnEV. Zweite Verordnung zur Änderung der Energieeinsparverordnung. Vom 18 November 2013. Nr.67 2013.

[45] Minister of Construction and Housing and the Minister of Energy. Réglement Thermique 2012 (RT2012), Arrêté du 26 Octobre 2010 relatif aux caractéristiques thermiques et aux exigences de performance énergétique des bâtiments nouveaux et des parties nouvelles des bâtiments. 2010.

[46] Decreto del Presidente della Republica 74/2013, Article 3 2013.

[47] Gobierno de España. Código técnico de la Edificación, Parte I. 2010. www.codigotecnico.org (accessed October 22, 2016).

[48] Wang L, Gwilliam J, Jones P. Case study of zero energy house design in UK. Energy Build 2009;41:1215–22. doi:10.1016/j.enbuild.2009.07.001.

[49] Pineau D, Rivière P, Stabat P, Hoang P, Archambault V. Performance analysis of heating systems for low energy houses. Energy Build 2013;65:45–54. doi:10.1016/j.enbuild.2013.05.036.

[50] University of Wisconsin-Madison, Solar Energy Laboratory. Trnsys 17. Multizone Building modeling with Type56 and TRNBuild. 2013;5.

[51] Thermal Energy System Specialists TESS. TESSLibs 17. HVAC Library Mathematical Reference. 2014;6:161–5.

[52] University of Wisconsin-Madison, Solar Energy Laboratory. TRNSYS 17 . Mathematical Reference.

TRNSYS Libr Vol 4 Math Ref Sol Energy Lab Univ Wisconsin-Madison, USA 2009;4:1–486.

[53] Klein S, Alvarado F. Engineering equation solver. F-Chart Software, Box 2002:1–2.

[54] Ministerio de Fomento; Gobierno de España. Documento descriptivo climas de referencia 2015:1–7.

[55] Meteonorm n.d. http://meteonorm.com/ (accessed April 19, 2016).

[56] Guillén-Lambea S, Rodríguez-Soria B, Marín JM. 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.

[57] Rodríguez-Soria B, Domínguez-Hernández J, Pérez-Bella JM, del Coz-Díaz JJ. Quantitative analysis of the divergence in energy losses allowed through building envelopes. Renew Sustain Energy Rev 2015;49:1000–8.

[58] Montoya MI, Pastor E, Carrié FR, Guyot G, Planas E. Air leakage in Catalan dwellings: Developing an airtightness model and leakage airflow predictions. Build Environ 2010;45:1458–69.

[59] Gobierno de España. Documento Básico HE Ahorro de Energía 2013. http://www.codigotecnico.org/cte/export/sites/default/web/galerias/archivos/documentosCTE/DB_HE/DBHE-2013-11-08.pdf (accessed October 31, 2016).