Review of international regulations governing the thermal insulation requirements of residential buildings and the harmonization of envelope energy loss.

Beatriz Rodríguez-Soria[a], Javier Domínguez-Hernández[a, *], José M. Pérez-Bella[a], Juan J. del Coz-Díaz[b]

[a] *Department of Construction Engineering, Engineering and Architecture School, University of Zaragoza (UZ), María de Luna, s/n, 50018, Zaragoza, Spain*

[b] *Department of Construction Engineering, University of Oviedo, Edificio Departamental Viesques nº 7, 33204 Gijón, Spain.*

Abstract

There is currently a lack of harmonization in the building energy efficiency requirements that are mandated by different countries. Energy efficiency is defined by the energy yield of the facilities and by the envelope energy losses. These energy losses are mainly conditioned by the thermal envelope transmittance, the compactness factor, and the indoor temperature.

This article compares the requirements imposed on these three energy factors in residential buildings by various countries of the European Union (Germany, France, the UK, and Spain) and the United States of America. The article also discusses the causes of the divergences in the requirements and their degrees of disparity. The article further compares the requirements of the Passivhaus construction standard, which is highlighted by the European Union as an example of residential buildings with virtually zero energy consumption (nearly zero-energy buildings), similarly to the buildings that European countries will be forced to build by 2020.

Within the current regulations, the thermal transmittance is the only factor that is used to compare the thermal insulation of buildings. However, this article demonstrates that the thermal transmittance is not a valid parameter for the comparison and harmonization of the envelope energy losses because countries set different transmittance values for each climate zone, which are defined on the basis of different ranges of degree-day variation and are calculated using different base temperatures. Furthermore, this article proposes a new methodology that can be used to regulate the thermal insulation of buildings to ultimately harmonize the envelope energy losses across all countries.

Keywords

International regulations; energy efficiency; residential buildings; envelope energy losses

[*] Corresponding author. Department of Construction Engineering, University of Zaragoza (UZ), María de Luna, s/n, 50018, Zaragoza, Spain. Tel.Fax: +34 976 76 21 00.
E-mail address: javdom@unizar.es (Javier Domínguez-Hernández)

1. Introduction

A current worldwide concern involves the efforts that are aimed at reducing energy consumption and CO_2 emissions [1], which are mainly produced by industry, transportation, and construction activities [2, 3]. The building sector is responsible for approximately 40% of the consumption and greenhouse gas emissions [2, 3, 4]. Two-thirds of these emissions result from residential buildings [5-8], which exhibit the greatest potential for energy savings [9, 10].
In light of this fact, guidelines have been published in the United States of America (USA) that contain recommendations for achieving a 50% reduction in the energy consumption of non-residential buildings (residential buildings are not regulated) [11]. In 2012, the National Global Change Research Plan of 2012-2021: A Strategic Plan for the U.S. Global Change Research Program [102] was approved. This plan aims to monitor, investigate, and report the current status of CO_2 emissions and energy consumption and provides solutions to prevent climate change. However, this plan does not commit to any concrete measures to reduce CO_2 emissions. Over the past year, several guidelines have been published, which include possible modifications to existing laws that govern such emissions [13-15].
In 2002, the European Union (EU) adopted the first mandatory Directive on Energy Efficiency in Buildings [16], which was amended in 2010 (and is currently enforced) to comply with new targets approved in 2007 to curb climate change. These objectives are collected within a package of measures to be complied with by EU countries called *"20-20-20"* [17]. One of the objectives of *"20-20-20"* is a 20% reduction in energy consumption and CO_2 emissions by 2020 and the prevention of global warming. Other objectives include an increase in the competitiveness of member countries [18-20] and the reduction of economic imbalances that result from the growing energy dependence on fossil fuels [21-25]. This directive also requires that all new buildings to be constructed in the EU starting in 2020 consume virtually zero energy (nearly zero-energy buildings) [17]. In the absence of a precise definition of these buildings' characteristics, the Passivhaus construction standard is used as a reference standard [26].
The 2010 Directive on Energy Efficiency in Buildings indicates that the energy efficiency requirements set by the member states vary considerably, and a number of these requirements are far from the optimal level of profitability [17]. Thus, in 2011, the EU warned of the need to harmonize these requirements in all of the member countries [27-29]. The lack of harmonization was due mainly to the fact that the Directive did not demand quantitative requirements and to the lack of a standard methodology for the calculation of the energy performance of buildings [9, 28]. It has also been confirmed that this lack of harmonization occurs internationally. Although the methodology was defined by a regulation in 2012 [30], quantitative values for factors that define the energy efficiency of buildings do not yet exist.
This article intends to harmonize these quantitative values. The comparison and analyses are focused on the study of residential buildings. The topics covered in this article are the following:

1. Determination of the degree of disparity between the requirements set by various countries for the principal factors that define the thermal envelope energy loss and analysis of their causes.

The main design factors that affect the envelope energy loss and therefore the energy demand due to the thermal loads of air-conditioned buildings are the thermal envelope transmittance, the compactness factor, and the indoor temperature [17, 31-37]. Therefore, these factors are the most important factors that limit the total power consumption [37-39] because the energy consumption during their use ranges between 80% and 85% of the total lifecycle energy consumption [37-40]. Currently, all of the analyzed regulations set maximum energy consumption limits for an entire building, including its facilities, such that insulation deficiencies can be compensated by more efficient equipment or by the installation of renewable energy sources. The installation and maintenance of these measures are more costly than the placement of an adequate insulation thickness.

This article reviews the rules established in four European countries (Germany, France, the United Kingdom (UK), and Spain) and the United States (Section 2). In each of these countries, the thermal envelope transmittance, the compactness factor, and the indoor temperature requirements will be analyzed. These requirements will be compared with the requirements of the Passivhaus construction standard. In this review, both the values required by the different regulations (Sections 3.3, 3.4, and 3.5) and the parameters used to regulate these values will be analyzed (Section 3.2).

This article will show that the transmittance, which is currently the only factor that governs the thermal insulation of buildings in the regulations under study, is not a valid parameter for the comparison and harmonization of the envelope energy loss. The reason for this fact is that each country currently defines climate zones for which different transmittance limits are set based on different ranges of degree-days and calculated with different base temperatures (Section 3.4).

2. Proposal of a methodology to harmonize the envelope energy loss.

A series of steps to achieve this harmonization on an international basis will be presented. These steps start with the creation of a degree-day map that is common to all countries and results in the implementation of a new energy factor that univocally controls the thermal insulation required to harmonize the envelope energy loss.

2. Legislative framework governing the design factors under study

2.1. Regulation of design factors at the supranational level

Both the EU and USA regulate the energy efficiency factors in buildings through mandatory regulations with which all member states must comply. The following summarizes the method by which both regulate these factors. The main difference between these regulations is that the EU only provides qualitative guidelines, whereas the USA mandates quantitative values that various energy factors must achieve.

The complete regulatory framework is presented in Figure 1.

Table 1. Regulatory framework in the countries under study. This information was compiled by the author.

2.1.1. USA

The Code of Laws of the United States of America (U.S.C.) compiles and codifies the general and permanent federal laws of the USA. The foundations and requirements of the Energy Conservation and Production Act (ECPA) [41] are found in this document. To develop the ECPA, the Department of Energy (DOE) approved several amendments to the Energy Efficiency Design Standards for New Federal Commercial and Multi-Family High-Rise Residential Buildings and New Federal Low-Rise Residential Buildings [42]; the most recent amendment was published in 2011. It specifies that the reference document regulating the energy efficiency requirements in commercial buildings and multi-family high rise residential buildings with more than three stories is the Standard 90-1-2010, which was published by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). Of the Building Codes developed by the International Code Council (ICC), the International Energy Conservation Code (IECC) [43-45] applies to low-rise residential buildings (3 stories or fewer). This code's guidelines can specifically vary by state, county, or city to meet local requirements; this variation reflects both the regional construction practices and specific energy efficiency objectives [44]. Of the two regulations that govern the thermal transmittance, the ASHRAE 90-1-2010 standard is more restrictive and complete [46].

In addition to these regulatory, ANSI facilitates the development of American National Standards (ANS) by accrediting the procedures of standards developing organizations. In many instances, U.S.A. standards are taken forward to International Standard Organization (ISO).

2.1.2. EU

At the EU level, the supranational regulations are known as European Directives, and their single purpose is to unify the objectives and factors that should be considered to fulfill their requirements. The Directive that regulates the energy efficiency of buildings is Directive 2010/31/EU. This directive's main objective is to promote the energy efficiency of buildings in the European Union by taking into account weather conditions, indoor climate requirements, and cost-effectiveness [17]. Moreover, the European Committee for Standardization (Comité Européen de Normalisation, CEN) publishes a series of standardized regulations designated European Standards (ENs); the purpose of ENs is to set the calculation fundamentals and the verification of various elements and procedures. These ENs should later receive the status of a national standard in all of the CEN member countries.

Each EU country, according to the provisions of the Directives and ENs, develops its own national regulations. It is in these national regulations where a set of numerical values of the energy factors are subsequently set to achieve the objectives of energy efficiency that are required by the Directive.

2.2. Normative governing the design factors in different countries

It has been observed that the USA sets quantitative values for these factors at the federal level, although a degree of variation within states is observed if these are necessary to adhere to the local construction practices. In contrast, the European 2010 Directive does not provide quantitative data, which are included in the normative of each country. Of the EU countries, the regulations of Germany, France, the UK, and Spain have been selected because these represent different climates.

2.2.1. Germany

In Germany, the energy efficiency of buildings and the guidelines to achieve the specified energy savings are regulated by the 1976 Law of Energy Saving (Energieeinsparungsgesetz, EnEG), the latest revised text of which was published in 2009 [47]. Over several years, various energy saving ordinances, which state the requirements, have been published. Currently, the 2009 EnEV Energy Conservation Ordinance (Energieeinsparverordnung, EnEV) [48] is in effect; this ordinance regulates, among other aspects, the values of various thermal envelope parameters that are required for compliance with this regulation. To adapt the legislation to the 2010 Directive, a document was published in 2012 to detail the guidelines that are necessary to progressively amend the law. It is expected that all changes to be implemented will take effect in 2014 [49]. Regarding the indoor temperature, the DIN 18599-2010 standard [50] establishes the thermal comfort parameters that must be considered in the calculation of the energy efficiency of buildings.

2.2.2. France

In France, the general habitability conditions that buildings must fulfill, as well as the construction processes and contractual relations, are established in the R. 111-20 Law: Construction and Habitability Code (Du Code de la construction et de l'habitation) [51]. The energy efficiency requirements for residential buildings and other required values that define it, are established in the Order of May 24, 2006: Concerning the thermal characteristics of new housing and its components (Relatif aux caractéristiques thermiques des bâtiments nouveaux et des parties nouvelles de bâtiments) and in Decree No. 2006-592 of 24 May 2006: Concerning thermal characteristics and construction energy goals (Relatif aux caractéristiques thermiques et à la performance énergétique des constructions), as well as in subsequent occasional amendments that were published in 2010 [52-55]. The standard that regulates the indoor climate conditions is the NF EN ISO 7933 [56].

2.2.3. UK

In the UK, the criteria for the calculation and verification of the compliance requirements for the energy efficiency of buildings were developed in general terms for all of the constituent countries in the UK. These criteria are detailed in the Standard Assessment Procedure (SAP 2009) [57]. Each constituent country (England and Wales, Scotland, and Northern Ireland) subsequently publishes its own regulations, which dictate the ultimate objectives of energy efficiency and the numerical values that specific energy factors must achieve. The common law of 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 [58]. These performances are developed under a compendium of fourteen documents, which are known as the Building Regulations of 2000. Of these, the document governing the energy efficiency of residential buildings is the 2010 edition of Approved Document L1A: Conservation of fuel and power-new dwellings [59]. However, the indoor climate conditions are regulated by British Standard (BS) EN 7730 [60].

2.2.4. Spain

In Spain, the minimum habitability conditions of buildings and the legal conditions of the construction process are regulated by the Building Planning Law of 1999 (Ley de Ordenación de la Edificación) [61]. These standards are developed under a compendium of documents published in 2007 that are designated the Technical Building Code (Código Técnico de la Edificación) [62]. Of this normative documentation, the DB HE 1: Limitation of Energy Demand is the rule that regulates the thermal insulation requirements of the envelope [63]. There are two alternatives for the fulfillment of these insulation requirements: the simplified option, which requires maximum transmittance values for the enclosures depending on the type of construction and maximum transmittance values depending on the location of the building, and the general option, which requires that the annual energy demand of the planned building be lower than that of a reference building with the same geometry (and whose enclosure transmittances correspond to the maximum transmittances required in the simplified option). The indoor climate characteristics that should be achieved by buildings are included in DB HE 2: Regulation of Thermal Facilities of Buildings (Reglamento de Instalaciones Térmicas de los Edificios) [64].

2.3. Regulation of the factors analyzed in the Passivhaus standard

The Passivhaus construction standard was developed in Germany by the Darmstadt Passivhaus-Institute. The first buildings constructed under this standard were built in central and northern Europe and were promoted by the CEPHEUS European Project (Cost Efficient Passive Houses as European Standards). Currently, this type of construction is spreading across Europe, including toward the countries in the south. To accomplish this regulation, a portion of the design criteria are been modified to adapt the standard to the needs of Mediterranean climates [65-66]. This type of housing is notable for its low energy consumption, and it limits its heating and cooling demands to 15 kW·h/(m^2·year). To achieve this level, this regulation provides the transmittance values that must be achieved by enclosures. This construction standard is internationally recognized: other countries, such as the UK and Germany, use these energy efficiency requirements as the objectives to be achieved by their building regulations. As previously mentioned, the EU uses the requirements contained in this standard as design principles for the construction of nearly zero-energy buildings [26].

3. Comparative analysis of the building envelope thermal transmittance, the building compactness factor, and the indoor temperature

3.1. Definition of the energy parameters under study

3.1.1. Thermal envelope transmittance

The definition of the thermal envelope developed by the IECC includes basement walls, exterior walls, floors, roofs, and any other building element enclosing the conditioned space. These limits include the boundary between all conditioned space and any exempt or unconditioned space [45].

The concept of the thermal transmittance of the enclosure (U-Factor) is defined as the coefficient of heat transmission (air to air) through a building component or assembly, equal to the time rate of heat flow per unit area and unit temperature difference between the warm side and cold side air films (W/(m^2 • K) in the rest of Europa and Btu/(h • ft^2 • ℉) in United Kingdom and USA) [45]. The thermal transmittance of an enclosure is calculated according to Equation 1:

$$U = 1/R_i + \sum \lambda_i / e_i + 1/R_e \quad (1)$$

where λ_i is the thermal conductivity of each material that composes the enclosure in W/(m·K), e_i is the thickness of each layer of material in meters, and R_i and R_e are the surface thermal resistances corresponding to the interior and exterior air, respectively, in m^2·K/W.

The abovementioned countries limit the thermal envelope transmittance through several parameters:

- The *transmittance limit of each element* of the envelope, depending on the enclosure construction type (U_{max}).
- The *average transmittance limit of a set of enclosures*, depending on its location in the building, which primarily differentiates between walls, floors, roofs, and gaps (U_{med}).
- The *overall heat transfer coefficient of the building* (H), which is the average of the average maximum transmittance of each enclosure weighted by the surface area. This parameter is calculated according to Equation 2:

$$H = \sum U_i \bullet A_i / \sum A_i \text{ in } W/\left(m^2 K\right) \quad (2)$$

where U_i is the thermal transmittance of each enclosure in W/(m^2·K) and A_i is the area of each enclosure with the specified transmittance in m^2.

The maximum values of these transmittances are specified to limit the energy loss through the thermal envelope of the buildings. The energy losses that occur through each enclosure of the envelope are calculated using Equation 3:

$$\text{Energy loss through the enclosure in a year } (\text{in W}) = \Sigma\, U \cdot A \cdot (\text{degree– days per year}) \quad (3)$$

where U is the thermal transmittance of the enclosure (W/(m^2·k)), A is the area of the enclosure (m^2), and the annual degree-days indicate the sum of the existing differences between the average outside temperature and a reference temperature (base temperature), which is the starting temperature at which it is necessary to air condition the rooms, for each day of the year. The number of degree-days is calculated as the sum of the degree-days for heating and the degree-days for cooling, which are calculated using Equations 4 and 5, respectively:

$$HDD = \sum_1^N (T_{base} - \overline{T_i}) \text{ in } K \quad (4)$$

$$CDD = \sum_1^N (\overline{T_i} - T_{base})^+ \text{ in } K \quad (5)$$

where N is the number of days in the winter (ec. 5) or in the summer (ec. 6), T_{base} is the reference temperature to which the degree-days are calculated, and $\bar{T}_i$ is the mean daily temperature calculated by adding the maximum and minimum temperatures for the day, then dividing by 2. The + super-script indicates that only positive values of the bracketed quantity are taken into account [67].

3.1.2. Compactness factor

The compactness factor is defined as the ratio of the volume to the outer surface of the building enclosure. This factor is related to the heat storing capacity of the building and its ability to avoid heat loss through its enclosure. A notably compact building is one that has a high volume-to-surface ratio [23]. Equation 3 defines the compactness factor of a building:

$$C_f = S_e / V \left(m^2 / m^3\right) \quad (6)$$

where S_e is the envelope surface of the building and V is the inner volume of the building en m^3.

Several studies have shown that a greater reduction in the energy consumption is achieved with a smaller relationship between the outer surface and the volume enclosed by the enclosure of the building [30-32], especially in cold climates [33]. Therefore, the maximum transmittance values that should be set relate to this factor [34].

In fact, some countries (such as Germany and France) require different overall heat transfer coefficients, depending on the building typology, to differentiate between housing blocks and single-family houses. This differentiation is based on the different compactness of each building typology.

3.1.3. Indoor temperature

The indoor temperature is the temperature of the air inside a room. The ranges of values within which this temperature must fall are regulated as the operating temperature in all of the standards discussed in this study. The operating temperature is calculated as shown in Equation 7 [68]:

$$T_{op} = \left(h_c * T_{amb} + h_r * T_{rm}\right) / \left(h_r + h_c\right) \text{ in K} \quad (7)$$

where T_{op} is the operating temperature in K, T_{amb} is the indoor temperature in K, T_{rm} is the mean radiant temperature of the inner surface of the envelope that delimits the enclosure in K, and h_c and h_r are the respective convection coefficients in $W/(m^2 \cdot K)$. T_{rm} is usually similar to the temperature of the indoor air, but it is more accurate to calculate the T_{rm} weighted by the area and the temperature of each of the walls, floors, and ceilings if there is a relatively warm (e.g., roof in the summer) or cold (e.g., windows in the winter) surface.

The range of the indoor temperature, and therefore the operating temperature, is not always the same but depends on various factors that determine the most suitable temperature that provides thermal comfort to the room. This thermal comfort index is measured as the percentage of people dissatisfied (PPD), which predicts the percentage of people who notice that the room is either too cold or too hot [69]. The ideal room temperature to achieve a given PPD depends on several parameters, highlighting:

- The metabolic rate is the speed at which an organism uses the available energy and is estimated by measuring the release of heat. This parameter, which is measured in met or W/m^2 (1 met = 58 W/m^2), depends on the intensity of the activity. If the metabolic rate increases, the ideal operating temperature may be lower.
- The thermal insulation of clothing is measured by Clo (1 Clo = 0.155 $m^2 \cdot$ ℃/W) and is estimated according to the combination of clothing: the thermal insulation of a naked person has a value of 0.0 Clo, whereas the thermal insulation of someone wearing a business suit has a value of 1.0 Clo. If the thermal insulation is higher, the ideal operating temperature may be lower.
- The air speed increases the cooling or heating of the body and the sensation of thermal discomfort and other discomforts when turbulence is perceived. In sedentary conditions, the air speed should be limited to less than 0.25 m/s under cold conditions and to less than 0.50 m/s under hot conditions because discomfort is caused by temperature differences.
- A high relative humidity limits the evaporation of sweat, particularly when combined with high temperatures and either low air speed or intense activities. These factors would create an uncomfortable sensation that could be offset by other factors.

The numerical values selected for each factor are listed in Section 3.5, which shows a comparison of the temperature ranges that are required by the different countries.

3.2. Regulation of energy factors in the normatives of the analyzed countries

This section lists the parameters that define the standards that regulate each energy factor under study. Table 2 shows a summary of the regulations of the thermal envelope transmittance and the compactness factor, whereas Table 3 presents the indoor temperature regulations.

Table 2. Compactness factor and thermal envelope transmittance requirements in the regulations studied

The thermal envelope transmittance is directly regulated by two parameters: the transmittance limit, which depends on the enclosure construction type (U_{max}), and the average transmittance limit, which depends on the location of the enclosure (U_{med}). German, British, and Passivhaus standards only regulate the U_{max} parameter, whereas the USA only regulates the U_{med} parameter. In contrast, Spain and France set maximum values for both parameters, and France also limits the maximum allowed transmittance of the envelope joints.
In all of the countries studied, except the UK, the envelope transmittance value limits are stated, and thus the planned facilities are considered in the calculation of the energy consumption and CO_2 emissions of the building to verify that the values are below the limits set by the regulations. The normative of England and Wales does not establish univocal numerical maximum transmittance values for all buildings (these regulations only set the

transmittance limits necessary such that there is no condensation in the enclosures). Unlike the regulations in the other countries that were surveyed, the selection and calculation of the planned facilities are performed first, followed by the calculation of the thermal envelope transmittance to satisfy the maximum CO_2 emission and energy consumption set by SAP. A guide document that was prepared by the Housing Research Foundation provides transmittance data for different building types (with different combinations of facilities) that are in compliance with these maximum values [70].

In the USA, in addition to the requirement of a maximum U-value for the full enclosure with all of its layers (comparable to the U_{med}), the regulations also stipulate compliance with a minimum thermal resistance (R-value, measured in m^2·K/W) of the interior of the enclosure. Unlike the European standards, which stipulate that the designer must always calculate the transmittance of the selected enclosures, the ASHRAE Standard 90-1-2010 provides these values for different construction types and various thermal resistances of the insulation in an appendix.

In the Passivhaus standard, the ultimate design goal of the envelope is to achieve an energy demand of less than 15 kW·h/m^2·year for both heating and cooling. The transmittance values required for different envelope types to achieve this level are provided. These values were studied for the weather conditions in Central Europe and are the most restrictive of all of the regulations examined. The extrapolation of the required insulation values for Mediterranean climates is questioned due to its dubious economic profitability [66, 71-75].

Indirectly, the enclosure transmittance is also regulated by the overall heat transfer coefficient of the building. It has been noted that Germany and France set values for this parameter, whereas other countries do not regulate it. The Passivhaus standard provides only an approximate value.

With the exception of Germany, all of the countries studied divide their geography into different climate zones, in which different transmittance values are required. Each of these climate zones includes all of the geographical areas that exhibit a number of annual degree-days within a given range. As shown in Table 2, there is also a significant variation in the number of climate zones that each country defines. The most extreme case is Germany, which requires the same transmittance for the whole country. In France, three climate zones are defined according to the temperature and relative humidity: H1, H2, and H3. To set different transmittances values, the regulations distinguish only two zones: one includes zones H1 and H2 and part of zone H3 (the sections that are located at an altitude greater than 800 m), and the other includes the sections of zone H3 that are located at an altitude less than 800 m. In Spain, different transmittance values are required depending on five different climate zones, which were defined depending on the severity of the winter climate: A, B, C, D, and E. These climate zones are in turn divided into different subzones depending on the severity of the weather in the summer. In the USA, different transmittances were set depending on eight climate zones, which are numbered from 1 to 8. Each of these zones is divided into different subzones depending on the relative humidity.

It is therefore evident that there is a lack of agreement both in the measures used to regulate the factors under study and in the quantitative values that are set for each of these factors.

Table 3. Temperature regulations in the standards examined in this study

Table 3 shows that the regulating temperature (through the operating temperature) is quite harmonized. This harmonization is due to the existence of the international ISO 7933 standard [76], which provides a calculation method and adequate operating temperature value ranges based on the parameters that are defined in Section 3.1.3. The quantitative values that are required for each energy factor are analyzed and compared below.

3.3. Comparison of the thermal envelope transmittances

3.3.1. Preliminary Considerations

To allow the comparison of the transmittances among all of the normative requirements with their corresponding equivalent values, one must select the required transmittance in geographical zones that are within the same range of degree-days. Thus, regions with very similar annual degree-day values were included in the comparison. The problem that has been identified with this analysis is that each country sets transmittances based on the definition of climate zones, and these zones are determined using different criteria of degree-day variations and different base temperatures. To compare the range of degree-days that each country includes in each of its climate zones and to verify the magnitude of their differences, one must find a map of the degree-days in Europe and the USA that is calculated using the same base temperature and using degree-day ranges that have the same range of variation. The uniformity of winter maps is prioritized because heat loads are higher in the winter than in the summer in the areas that were studied. These maps are shown for a base temperature of 18.5℃ and a range of 1000 hea ting degree-days (Figure 1). The selected areas in each country are indicated by a cross on the heating degree-day map.

Figure 1: Degree-days for heating and the degree-days for cooling, in USA and Europe. T_{base}: 18.5ºC

3.3.2. Analysis of the problems detected

Table 4 shows the total variation in degree-days (Figure 1) and the number of climate zones defined for each country studied in Europe and the USA.

Table 4. Variation in the number of heating and cooling degree-days and the number of climate zones that are defined in the countries under study

As shown, Spain is the country that defines the most climate zones in relationship with the existing variation in the number of degree-days. France, England and Wales, and the USA have an equivalent division, whereas Germany, despite being the country (of those studied) with the greatest variation in degree-days throughout its territory, does not define distinct climate zones. Thus, the energy losses occurring through the envelope when setting such transmittances will be notably different, even when comparing the transmittances required in regions with similar degree-days.

This difference occurs because each country sets transmittances according to its climate zones (instead of calculating the necessary transmittance levels based on the actual number of degree days), each of which have a notably different variations of degree-days in each country. Thus, the transmittance, as currently defined through the creation of climate zones with different criteria among the different countries, is not a valid factor for the comparison and harmonization of the envelope energy loss and therefore the thermal insulation requirement. The comparative values of the transmittances imposed by the different regulations are shown below to qualitatively compare the restrictive nature of each country.

3.3.3 Comparison tables

Geographical zones with winter degree-days in the range of 3000 to 4000 were selected for the comparison. This range of winter degree-days was selected because it is the only range that is found in all of the countries that were considered in this analysis. For each country, the comparison includes the transmittance of the climate zone corresponding to the selected geographic area.

The climate zones in which the selected regions are located in each country, as shown in Figure 2, are the following:

- Because Germany requires the same transmittance value throughout the country, any zone is valid for the comparison.
- In France, the selected region belongs to the climate zone that includes zones H1, H2, and the parts of zone H3 with an altitude greater than 800 m.
- In England and Wales, the southern coastal zone was selected. Of all of the possible transmittance options provided by the Housing Research Foundation study to comply with the required CO_2 emissions, the most common combination was used, which corresponds to a housing block with a gas-powered radiator for heating and solar panels for hot water [70].
- In Spain, the region within the range of degree-days selected is in zone E.
- In USA, the selected area is in climate zone 5.

The transmittance limit values depending on enclosure construction type (U_{max}, Table 5), and the average transmittance limit value depending on the location of the enclosure in the building (U_{med}, Table 6) detailed by all of the regulations under study are compared below.

Table 5. Comparison of the transmittances limits of each type of enclosure defined by the different regulations

As shown in Table 5, the French legislation has the highest number of construction types for which different transmittances are determined. Thus, the actual insulation limits that can be achieved in each construction type are more closely adapted, e.g., the insulation required for curtain walls compared with the insulation required for other walls. In many countries, where these types are not listed as distinct types of construction, the insulating requirements are the same as those for other enclosures.

Table 6 provides a comparison of the average transmittance limits that are required by the different standards depending on the location of the enclosures. These transmittances can be used to calculate the overall heat transfer coefficient of the building to comprehensively compare the different insulation requirements between the standards. Thus, to obtain the coefficient that provides an equivalent value in all of the regulations, it was calculated for all of the cases, with the same thermal envelope (which is composed of a surface percentage of walls, floors, ceilings, and standard windows). The Spanish Institute for Diversification and Energy Savings (IDAE) [77] defines the standard envelope as one in which the sum of the wall surfaces is equal to the sum of the surface areas of the floor and the roof. In addition, the percentage of glass window/doors existing in the walls is 30%. These surface values are considered average in houses. Table 6 includes the resulting value for each country. A sample calculation for the particular case of Germany is shown in Equation 8:

$$\mathrm{H} = 0.5 * \left(\left(0.2*0.7+1.3*0.3\right)\right) + 0.5 * \left(\left(0.28+0.20\right)/2\right) = 0.385 \text{ in } \mathrm{W}/\left(\mathrm{m}^2\cdot\mathrm{K}\right) \quad (8)$$

Table 6. Average envelope transmittance limit values for climates with similar degree-day intervals

Of all of the regulations discussed above, the least demanding are the Spanish regulations, whereas the most demanding are the German and the Anglo-Welsh regulations, which are also those which most closely approach the near-zero energy consumption achieved by the Passivhaus building standard. The values of the ASHRAE standard are situated between the French and the Spanish regulations and are higher than the average values described by the European requirements.

3.4. *Compactness factor*

Only the Passivhaus standard provides a numerical value to regulate the compactness factor of the buildings, and this is the only value recommended. In the French and German regulations, a maximum numerical value for the compactness factor is not provided, but the disaggregation of buildings is penalized by setting different maximum values for the overall heat transfer coefficients of the buildings (ec. 2) depending on the building type (the classification of which is based on the differences in the compactness of the buildings) to differentiate between housing blocks and single-family houses. In Germany, housing blocks must have a specific heat transfer coefficient of less than 0.65 $W/m^2\cdot K$, whereas single-family houses must have a specific heat transfer coefficient between 0.4 and 0.5 $W/m^2\cdot K$. The German regulations also require a lower H when the ratio of the area of a dwelling to the height of the building is more unfavorable, e.g., double-height spaces are penalized.

In French law, this parameter is known as U_{BAT}. For single-family houses, $U_{BAT,max} = U_{BATbase} * 1.20$, whereas $U_{BAT,max} = U_{BATbase} * 1.25$ for housing blocks. Furthermore, single-family houses have more restrictive transmittance limits for the joints of the envelope elements.

In all of the other standards, the compactness factor is not considered in single-family buildings compared with residential blocks. In fact, in the regulations of both Spain and England/Wales, single-family houses are allowed to consume more energy ($kW\cdot h/(m^2\cdot year)$) [78, 79] than housing blocks. In another way, the single family buildings would be required to have lower transmittance limits than housing blocks to obtain the same energy rating. Thus, as shown in Table 7, there is a great disparity in the regulation of this factor.

Table 7. Compactness factors and penalizations in building insulation included in the different regulations analyzed

3.5. *Indoor temperature*

The indoor temperature is the only factor that is included in the EN reference standards that allows harmonization of the values in all of the regulations. This factor is regulated through the operating temperature, as specified in Section 3.1.4 and in Equation 7. Two European standards govern the operating temperatures needed to achieve thermal comfort in rooms. These standards include the EN ISO 7730:2006: Ergonomics of the thermal environment standard [69] and the EN 15251:2008: Indoor environmental input parameters for the design and assessment of the energy performance of buildings addressing indoor air quality, thermal conditions, lighting, and acoustics [81]. Table 8 shows the recommended operating temperature ranges listed in both ENs and in the regulations analyzed in this article. These temperatures were selected considering the typical residential building values for the parameters defined in Section 3.1.3:

- A PPD of 15%, which is designated as suitable in EN ISO 7730:2006 for residential use; this norm has been adopted by each of the abovementioned countries. However, the EN 15251: 2008 standard indicates that the expectation for new and renovated buildings should correspond to a PPD of less than 10%. Therefore, the operational temperature values shown in Table 7 include both of these PPD values.
- A metabolic rate of 1.2 met (sedentary activity rate, typical for residential usages).
- A clothing thermal insulation of 1 Clo in the winter and 0.5 Clo in the summer.
- An air speed of less than 0.25 m/s under cold conditions and less than 0.50 m/s under hot conditions.
- A relative humidity of 60% in the summer and 40% in the winter.

Table 8. Room temperature required by the studied standards

The indoor temperature range is a factor that is harmonized among the different EU countries because there is an EN that establishes the maximum range of accepted values. Harmonization also exists with respect to the regulations of the United States because there is an international ISO standard that all countries have adapted, as indicated in Section 2. The existence of an international standard that provides quantitative values, contributing to the harmonization of the regulatory requirements among the different countries, was confirmed.

The more stringent regulations are the Spanish and French regulations (because the German regulations allow the mean values to be exceeded occasionally, as shown in Table 8). For a given outdoor temperature, the establishment of a more restrictive indoor temperature involves more powerful air conditioning facilities and therefore increased energy consumption. The other standards have similar values.

Furthermore, both the German and the French regulations require different temperatures depending on the enclosure usage. Independent temperature control systems should be used for areas that are used differently to ultimately optimize the energy consumption [86].

Of all of the regulations and standards studied, the Passivhaus standard allows a wider range of temperatures. As specified in the standard itself [65], the range is extended due to the high level of insulation that is required in the envelope. Due to this level of envelope insulation, the internal temperature of the walls is notably close to the indoor temperature (air temperature), which reduces the radiation heat exchanged between the people and the walls. Therefore, by increasing the mean radiant temperature of the walls, a lower indoor temperature is required to achieve the same operating temperature; thus, thermal comfort can be achieved at indoor temperatures close to 18℃ [65]. As discussed in Section 3.3.3, the difference between the transmittance required in windows and the rest of the construction elements is lower in the Passivhaus standard than in the other regulations. This fact, combined with the criterion for preventing the creation of thermal bridges, prevents the cold-wall effect, which leads to the need for a lower average air temperature in the building to obtain the same sensation of thermal comfort.

Therefore, the indoor temperature required for thermal comfort in houses depends directly on the value and uniformity of the thermal insulation of the building envelope (i.e., its transmittance). By increasing the insulation, the required indoor temperature decreases (and thus the air conditioning needed), which saves double the amount of energy, as demonstrated in scientific studies [36].

4. Proposed methodology to harmonize the maximum allowable energy loss through the building envelope

The lack of harmonization in the definition of climate zones, in addition to the absence of quantitative transmittance reference values for all of the countries, make that the envelope energy losses vary from one country to another. As a result, it is difficult to unify criteria and energy efficiency objectives in buildings across different countries. For this purpose, a methodology is proposed to harmonize the maximum allowable energy loss through the building envelope. This methodology considers the three factors that were discussed in the article and consists of the following stages:

1°. Regulation of a *"maximum limit of envelope energy losses"* (i.e., due only to heat transfer in building enclosures) by supranational organizations. This parameter would not be influenced by other factors that determine the energy consumption of buildings, such as the building facilities.

2°. Generation of a world map of degree-days such that all countries calculate the envelope energy losses using the same base temperature of 20℃ that is recommended by EN15251: 2008. This approach would ensure that the energy losses calculated in all of the countries are equivalent and comparable.

3°. Calculation of the overall heat transfer coefficient of the building (H) that allows to comply with the defined maximum limit of envelope energy losses regulated in item 1 depending on the degree-days of the region where the building is located and given the total area of the envelope. The introduction of this factor in the methodology implies the consideration of the compactness factor of the building. The coefficient would be calculated using Equation 10:

$$\mathrm{H\ (in\ W/m^2 \cdot K)} = \textit{maximum limit of envelope energy losses} \,/\, \mathrm{A_{Total}} \left(\mathrm{degree-days\ per\ year} \right) \quad (10)$$

4°. Selection of the transmittance of each enclosu re such that is complies with the overall heat transfer coefficient of the building calculated in Section 3. This transmittance should also be adapted to the procedures, practices, and construction techniques, which are often different in different countries.

5. Future research lines

A value of maximum limit of envelope energy losses should be established according to the global energy strategies and international directives agreed by different countries. This value could also be adapted according to the particular situations and needs of each nation by setting harmonization deadlines. Although the construction techniques and materials used vary substantially among countries, the harmonization of this maximum limit would result in a gradual homogenization of the construction practices in any zone with similar degree-days. Therefore, several lines of future research may be suggested:

A compromise between the energy and the cost-optimal levels for each country should be set. This research point is very important because, from an economic standpoint, the proposed constructive solutions should achieve an optimal energy consumption that would allow an economical amortization.

In turn, this homogenization should encourage more sustainable practices. For this purpose, a database with different constructive solutions that can fulfill the established maximum limit should be generated, considering the building materials, the local knowledge and the construction techniques available in each region. Several comprehensive analyses should be performed to verify the sustainability (e.g., life cycle analysis) of each proposed solution.

6. Conclusions

In this article have been analyzed and compared the regulatory requirements that are set by the United States and several EU countries for three key factors that determine the energy consumption of buildings: the thermal envelope transmittance, the compactness factor, and the indoor temperature. The requirements of the Passivhaus standard have been considered to be the optimal energy reference. This standard is an example of the construction of nearly zero-energy buildings, which will be required by the European Directive 2010/31/EU by the year 2020.

This study found that the factor with less divergence across countries is the indoor temperature because there is an international standard that sets the maximum range of accepted indoor temperature values. In contrast, the compactness factor and the transmittance values of the thermal envelope are not harmonized in the countries that were analyzed in this study because these parameters are unregulated at the international level (and at the supranational level in the case of Europe). Moreover, it has been found that the establishment of climate zones in each country is based on different ranges of degree-day variations, which are calculated using different base temperatures. This lack of harmonization suggests large variations of the envelope energy losses regulated in each country.

To solve this problem, a methodology was proposed that includes a global definition and global requirements of the maximum limit of envelope energy losses. Additionally, a world map of degree-days should be developed such that all countries calculate this parameter using the same base temperature. Therefore, the calculated energy losses would be equivalent and comparable. The overall heat transfer coefficient of a building would accordingly be calculated using this parameter and the degree-days shown in the developed map. Subsequently, the required transmittance values for the enclosures will be imposed at the national level.

7. Acknowledgments

This work was partially financed by the Spanish Ministry of Science and innovation co-financed with FEDER funds under the Research Project BIA2012-31609. Finally, the authors greatly appreciate the collaboration of the GICONSIME Research Group at the University of Oviedo.

References

[1] S.VijayaVenkataRaman, S.Iniyan, Ranko Goic. A review of climate change, mitigation and adaptation. Renewable and Sustainable Energy Reviews 16 (2012) 878-897.

[2] European Parliament. Directive 2006/32/EC of the European Parliament and of the Council of 5 April 2006 on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC (Text with EEA relevance). Official Journal L 114 de 27/04/2006 p. 0064 – 0085. Strasbourg, 2006.

[3] European Commission. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC Text with EEA relevance. Official Journal of the European Union. L 315-1 / L 315-56. 14/11/1012. Done at Strasbourg, 25 October 2012. THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION

[4] IPPC: Intergovernmental Panel on Climate Change. IPCC Fourth Assessment Report: Climate Change 2007 (AR4). IPPC (ISBN 92-9169-322-7), Geneva, 2008

[5] Aashish Sharma, Abhishek Saxena, Muneesh Sethi, Venu Shree,Varun. Life cycle assessment of buildings: A review. Renewable and Sustainable Energy Reviews 15 (2011) 871-875.

[6] Koukkari H, Kuhnhenne M, Braganc¸a L. Energy in the sustainable European construction sector. Repositórium Universidade do Minho: CEC-GTC - Comunicações a Conferências Internacionais: Sustainability of constructions. Braga, 2010.

[7] Gaterell MR, Mc Evoy ME. The impact of climate change uncertainties on the performance of energy efficiency measures applied to dwellings. Energy and Buildings 37 (2005) 982–995.

[8] Taylor PG, d'Ortigue OL, Francoeur M, Trudeau N. Final energy use in IEA countries: the role of energy efficiency. Energy Policy 38 (2010) 386463–386474.

[9] Itziar Martínez de Alegría Mancisidor, Pablo Díaz de Basurto Uraga, Iñigo Martínez de Alegría Mancisidor, Patxi Ruiz de Arbulo López. European Union's renewable energy sources and energy efficiency policy review: The Spanish perspective. Renewable and Sustainable Energy Reviews 13 (2009) 100-114.

[10] CEC. Communication from the commission. Action plan for energy efficiency: realising the potential. Commission of the European Communities, Brussels, 2006.

[11] The American Institute of Architects, the Illuminating Engineering Society of North America, the U.S. Green Building Council, and the U.S. Department of Energy. Advanced Energy Design Guides of ASHRAE. ASHRAE. Atlante, 1012.

[12] Strategic Planning Integration and Writing Teams, which report to the Subcommittee on Global Change Research of the NSTC's Committee on the Environment, Natural Resources and Sustainability. Plan 2012-2021: A strategic Plan for the U.S. Global Change Research Program. U.S. Global Change Research Program. National Coordination Office (NCO) for the USGCRP Washington, 2012.

[13] American Planning Association. Policy guide on planning & Climate change. American Planning Association. Adopted April 27, 2008 Updated April 11, 2011.

[14] PCAP 2012 National Advisory Committee. Presidential Climate Action Project. Building an Advanced Energy Economy. Security opportunity Stewardship. Longmont, October 2012.

[15] Environmental Protection Agency. Regulatory Plan and Semiannual Regulatory Agenda. United States. EPA-230-Z-10-002. 2010. Washington Dc, 2010,

[16] European Commission. Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings. Official Journal L 1, 4/1/2003, p. 65–71, Brussels, 2003

[17] 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, 18/6/2010, p. 13-35. Strasbourg, 2010.

[18] European Commission. Europe 2020: A strategy for smart, sustainable and inclusive growth. COM(2010). Brussels, 2010.

[19] European Commission, Energy 2020. A strategy for competitive, sustainable and secure energy. COM(2010) 639-final. Brussels; 2010

[20] European Commission. Green paper ''Doing more with less''. European Communities, Luxemburg, 2005

[21] Malin Song, Shuhong Wang, Huayin Yu, Li Ynag, Jie Wu. To reduce energy consumption and to maintain rapid economic growth: Analysis of the condition in China based on expended IPAT model. Renewable and Sustainable Energy Reviews 15 (2011) 5129-5134.

[22] OECD/IEA. Worldwide Trends in Energy Use and Efficiency: Key Insights from IEA Indicator Analysis – In support of the G8 Plan of Action. International Energy Agency / Organisation for Cooperation and Development, París, 2008. p. 94.

[23] Lombard L, Ortiz J, Pout C. A review on buildings energy consumption information. Journal of Energy and Buildings 40 (2008) 394–398.

[24] Dalia Streimikiene, Andzej Volochovic, Zaneta Simanaviciene. Comparative assessment of policies targeting energy use efficiency in Lithuania. Renewable and Sustainable Energy Reviews 16 (2012) 3613-3620.

[25] Haris Doukas, Alexandra G. Papadopoulou, John Psarras, Mario Ragwitz, Barbara Schlomann. Sustainable reference methodology for energy end-use efficiency data in the E.U.. Renewable and Sustainable Energy Reviews 12 (2008) 2159-2176.

[26] Buildings Performance Institute Europe (BPIE). Principles for Nearly Zero-energy Buildings. Paving the way for effective implementation of policy requirements. Published by Buildings Performance Institute Europe (BPIE) Brussel, 2011.

[27] European Commission. National Energy Efficiency Action Plans (NEEAPs): update on implementation Accompanying document to the Energy Efficiency. Plan 2011 COM (2011) 109. Brussels, 2011.

[28] European Commission. Energy Efficiency Plan 2011. COM(2011) 109. Brussels, 2011

[29] European Comision: Directorate-General for Energy and Transport. Implementation of the Energy Performance of Buildings Directive Country reports 2008. European Comision: EPBD Buildings Platform, Brussels, 2008

[30] European Commission. Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements Text with EEA relevance. Official Journal L 81, 21/3/2012, p. 18–36. Brussels, 2012.

[31] Aksoy UT, Inalli M. Impacts of some building passive design parameters on heating demand for a cold region. Building and Environment 41 (2006) 1742–1754

[32] Marks W. Multicriteria optimisation of shape of energy-saving buildings. Building and Environment 32-4 (1997) 331–339.

[33] Depecker P, Menezo C, Virgone J, Lepers S. Design of buildings shape and energetic consumption. Building and Environment 36 (2001) 627–635.

[34] Oral GK, Yilmaz Z. The limit U values for building envelope related to building form in temperate and cold climatic zones. Building and Environment 37 (2002) 1173–1180.

[35] R. Pacheco, J. Ordóñez, G. Martínez. Energy efficient design of building: A review. Renewable and Sustainable Energy Reviews 16 (2012) 3559-3573.

[36] E. Kossecka, J. Kosny, Influence of insulation configuration on heating and cooling loads in a continuously used building, Energy and Buildings 34(4)(2002)321–331.

[37] Gülten Manioglu, Zerrin Yılmaz. Economic evaluation of the building envelope and operation period of heating system in terms of thermal comfort, Energy and Buildings 38 (2006) 266–272.

[38] J. Morrissey ,R.E. Horne. Life cycle cost implications of energy efficiency measures in new residential buildings. Energy and Buildings 43 (2011) 915–924

[39] R. Horne, C. Hayles, Towards global benchmarking for sustainable homes: an international comparison of the energy performance of housing, Journal of Housing and the Built Environment 23(2)(2008)119–130.

[40] Sharma A, Saxena A, Sethi M, Shree V, Varun. Life cycle assessment of buildings: a review. Renewable and Sustainable Energy Reviews 15 (2011) 871–875.

[41] Senate and House of Representatives of the United States of America in Congress assembled: State Energy Conservation Program. Energy Conservation Reauthorization Act of 1998. Congressional Record-105th Congress (1997-1998). p. H9096- H9104. Section 365(f) of the Energy Policy and Conservation Act (42 U.S.C. 6325(f)). Washington, 1998.

[42] http://www.gpo.gov/fdsys/pkg/FR-2011-08-10/pdf/2011-20024.pdf. Last accessed: November, 2012. Department of Energy. 10 CFR Parts 433 and 435 [Docket No. EERE–2011–BT–STD–0005] RIN 1904–AC41. Energy Efficiency Design Standards for New Federal Commercial and Multi-Family High-Rise Residential Buildings and New Federal Low-Rise Residential Buildings.

[43] ASHRAE. Standard 90.1-2010 (I-P Edition) - Energy Standard for Buildings Except Low-Rise Residential Buildings (ANSI Approved; IESNA Co-sponsored). ASHRAE. Atlanta, 2010.

[44] Pacific Northwest National Laboratory for the U.S. Department of energy. Building Technology Program: Measuring State Energy Code Compliance. U.S. Department of energy, Office of Scientific and Technical Information. United States of America, 2010.

[45] International Code Consortium. The International Energy Conservation Code (IECC) 2012. U.S Department of Energy. International Code Council. (ISBN: 9781609830588). Country Club Hills, 2011.

[46] www.energycodes.gov. Last accessed: November, 2012. Building Energy Codes Program (BECP). Building Energy Codes 101: An Introduction. Published by U.S. Department of Energy's (DOE's). 2010

[47] Bundesministeriums der Justiz in Zusammenarbeit. Gesetz zur Einsparung von Energie in Gebäuden (Energieeinsparungsgesetz-EnEG). "Energieeinsparungsgesetz in der Fassung der Bekanntmachung vom 1. September 2005 (BGBl. I S. 2684), das durch Artikel 1 des Gesetzes vom 28. März 2009 (BGBl. I S. 643) geändert worden ist. Bundesgesetzblatt Jahrgang 2009. Ein Service des Bundesministeriums der Justiz in Zusammenarbeit mit der juris GmbH – Berlin, 2009

[48] http://www.heiz-tipp.de/ratgeber-1116-text_enev_2009.html. Last accessed: October, 2012. Online Ratgeber heiz tipp. Konsolidierte Fassung der Verordnung vom Energieeinsparung EnEV 2009 und seinen Anhängen. Version 29 von April 2009. f.nowotka, 2009 .

[49] Institut für Energie-Effiziente Architektur mit Internet-Medien. EnEV 2014: Was kommt wann? Schritt für Schritt zur Novelle der Energieeinsparverordnung. Ergänzte Ausgabe: 29. Stuttgart, 2012.

[50] DIN Joint Committee NA 005-56-20 GA. Estandarización DIN 18599-2010. Energy efficiency of buildings — Calculation of the energy needs, delivered energy and primary energy for heating, cooling, ventilation, domestic hot water and lighting — Part 10: Boundary conditions of use, climatic data. prepared by DIN Joint Committee NA 005-56-20 GA Energetische Bewertung von Gebäuden of the Normenausschuss Bauwesen (Building and Civil Engineering Standards Committee), which also lead-managed the work, and Normenausschuss Heiz- und Raumlufttechnik (Heating and Ventilation Standards Committee) with the co-operation of the Normenausschuss Lichttechnik (Lighting Technology Standards Committee). Berlin, 2010.

[51] http://www.legifrance.gouv.fr/affichCode.do?cidTexte=LEGITEXT000006074096. Last accessed: October, 2012. R. 111-20 du code de la construction et de l'habitation. Republique Francaise. 2012.

[52] Ministère de l'emploi, de la cohésion sociale et du logement. Arrêté du 24 mai 2006 relatif aux caractéristiques thermiques des bâtiments nouveaux et des parties nouvelles de bâtiments. NOR:SOCU0610625A. Journal officiel de la république française, 25 mai 2006, Texte 14 sur 155.

[53] Ministère de l'emploi, de la cohésion sociale et du logement. Décret no2006-592 du 24 mai 2006 relatif aux caractéristiques thermiques et à la performance énergétique des constructions. NOR:SOCU0610624D. Journal officiel de la république française, 25 mai 2006, Texte 12 sur 155.

[54] Ministère de l'emploi, de la cohésion sociale et du logement. Décret n°2010-1269 du 26 octobre 2010 relatif aux caractéristiques thermiques et à la performance énergétique des constructions. NOR: DEVU1020041D. Version consolidée au 28 octobre 2010. www.legifrance.gouv.fr. Le service public de la diffusion du troit. Les textes legislatifs et réglementaires.

[55] Ministère de l'écologie, de l'énergie, du développement durable et de la mer, en charge des technologies vertes et des négociations sur le climat. Arrêté du 29 septembre 2009 relatif au contenu et aux conditions d'attributiondu label «haute performance énergétique rénovation»NOR:DEVU0917396A. Journal officiel de la république française, 1eroctobre 2009, Texte 9 sur 190.

[56] AFNOR. NF EN ISO 7933. Ergonomie des ambiances thermiques - Détermination analytique et interprétation de la contrainte thermique fondées sur le calcul de l'astreinte thermique previsible. AFNOR. Paris, 2005

[57] SAP assessors. The Government's Standard Assessment Procedure for Energy Rating of Dwellings. Published on behalf of DECC by: BRE Garston, Watford WD25 9XX. Rrev October 2010, RdSAP 2009 added March 2011.

[58] Controller and Chief Executive of Her Majesty's Stationery Office and Queen's Printer of Acts of Parliament. Building Act 1984 UK. Printed in England by W. J. SHARP. London, 1984.

[59] HM Government. The Building Regulations 2000 - Approved document L1A: Conservation of fuel and power- New dwellings, 2010 edition. Published by NBS, part of RIBA Enterprises Ltd, (RIBA bookshops), 2010.

[60] British Standard / European Standard / International Organization for Standardization. BS EN 7730 Moderate thermal environments – Determination of the PMV and PPD indices and specification of the conditions for thermal comfort BS EN 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. The British Standards Institution. ISBN: 0580472078. London, 2006.

[61] Gobierno de España. Ley 38/1999, de 5 de noviembre, de Ordenación de la Edificación. Boletín Oficial del Estado núm. 266, pg 38925-38934. Madrid, 1999.

[62] www.codigotecnico.org. Last accessed: november 2012. Gobierno de España: Ministerio de Vivienda. Código Técnico de la Edificación, parte I. Madrid, 2010.

[63] www.codigotecnico.org. Last accessed: november 2012. Gobierno de España: Ministerio de vivienda. Código Técnico de la Edificación, parte II. Documento Básico HE: Ahorro de energía, Madrid, 2009.

[64] Gobierno de España: Ministerio de la presidencia. El nuevo RITE. 2008. Marcombo, S.A. first ed., Barcelona, 2008

[65] Uwe Wienke. L'edificio passive: Standarde-Requisiti-Esempi. Alinea Editrice S.R.L. Firence, 2002.

[66] Brian Ford, Rosa Schiano-Phan and Duan Zhongcheng. The passivhaus standard in European warm climates: A review of comfortable low energy homes. Passive-On Project. Edited and compiled bay: School of the Built Environment, University of Nottingham, 2007.

[67] 2009 ASHRAE Handbook—Fundamentals. CHAPTER 14: CLIMATIC DESIGN INFORMATION. I-P Edition. Copyright © 2009 by ASHRAE American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.1791 Tullie Circle NE Atlanta, GA 30329-2305. Electronic license.

[68] AEN/CTN 100 – CLIMATIZACIÓN. UNE EN 13779:2008. Ventilación de los edificios no residenciales. Requisitos de prestaciones de sistemas de ventilación y acondicionamiento de recintos. AENOR. Madrid, 2008.

[69] European Committee for Standardization CEN. EN ISO 7730:2006: 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 (ISO 7730:2005). European Committee for Standardization CEN, Brussels, 2006.

[70] Richards Partington Architects. Part L 2010 – where to start: An introduction for house builders and designers. Written and published for NHBC Foundation: Housing Research in partnership with BRE Trust, by. ISBN 978-0-9568415-1-3. Buckinghamshire 2011.

[71] Lollini, Barozzi, Fasano, Meroni, Zinzi. Optimisation of opaque components of the building envelope energy, economic and environmental issues. Building and Environment 41 (2006) 1001–1013.

[72] Beatriz Rodríguez Soria. Planteamiento de mejoras normativas en la eficiencia energética, la calidad de aire interior y el confort térmico en edificaciones residenciales en bloque. Base de datos TESEO. Gobierno de España. Ministerio de cultura, educación y deporte. Zaragoza, 2011.

[73] Manioglu G, Yilmaz Z. Economic evaluation of the building envelope and operation period of heating system in terms of thermal comfort. Energy and Buildings 38 (2006) 266–272.

[74] Jinghua Y, Changzhi Y, Liwei T. Low-energy envelope design of residential building in hot summer and cold winter zone in China. Energy and Buildings 40 (2008) 1536–1546.

[75] Comakli K, Yüksel B. Optimum insulation thickness of external walls for energy saving. Applied Thermal Engineering 23 (2003) 473–479

[76] International Standard Organization. ISO 7933:2004: Ergonomic of the thermal environment – Analytical determination and interpretation of heat stress using calculation of the predicted heat strain. ISO. Geneve, 2004.

[77] Instituto para la Diversificación y Ahorro de la Energía. Serie: Calificación de eficiencia energética de edificios. Guía nº 12: Opción simplificada. Viviendas. Memoria de cálculo. IDAE, Madrid, 2009.

[78] Department for Communities and Local Government of UK. Code for Sustainable homes. Technical Guide. Communities and Local Government Publications. London, 2010.

[79] Instituto para la Diversificación y Ahorro de la Energía. Serie Calificación de Eficiencia Energética de Edificios, Guía nº 7: Escala de calificación energética para edificios de nueva construcción. IDAE, Madrid, 2009.

[80] Arcadio García Lastra, Antonio García Laespada, Victor Soto Francés y José Manuel Pinazo Ojer. Serie: Documentos Técnicos de Instalaciones en la Edificación. DTIE 7.03: Entrada de datos a los programas LIDER y CALENER VyP. ATECYR, Madrid, 2008.

[81] AEN/CTN 100 - CLIMATIZACIÓN. EN 15251. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.). European Committee for Standardization CEN. Geneve, 2008.

[82] Deutsches Institut Fur Normung E.V. (German National Standard). DIN 4701: Energy Efficiency of Heating and Ventilation Systems in Buildings. Deutsches Institut Fur Normung E.V., Berlín, 2009.

[83] Ministére du Logement. Ministére de l'écologie, de l'énergie, du développement durable et de l'Aménagement du territoire. République française. Diagnostic de Performance Energétique. Guide recommandations. http://www.logement.gouv.fr , 2009. Last accessed: November 2012.

[84] Approved by the ASHRAE Standard Committee on January 24, 2004. ASHRAE Standard 55-2004: Thermal environmental Conditions for Human Occupancy. Published by ASHRAE Customer Service, Atlanta, 2004.

[85] 2009 ASHRAE Handbook—Fundamentals. Chapter 09:"Thermal Comfort". I-P Edition. Copyright © 2009 by ASHRAE American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.1791 Tullie Circle NE Atlanta, GA 30329-2305. Electronic license.

[86] Jin Woo Moon, Seung-Hoon Han. Thermostat strategies impact on energy consumption in residential buildings. Energy and Buildings 43 (2011) 338-346.

Figure 1

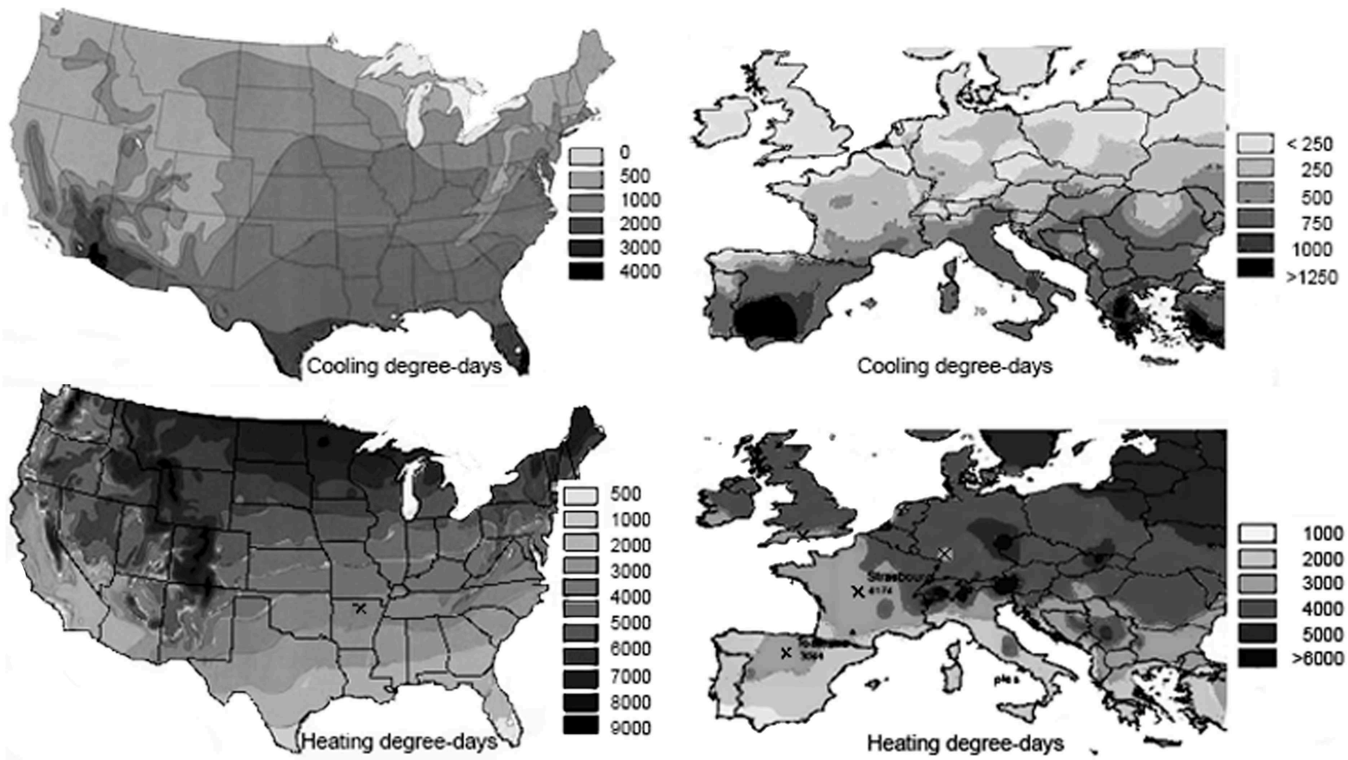
0
500
1000
2000
3000
4000
Cooling degree-days
< 250
250
500
750
1000
>1250
Cooling degree-days
500
1000
2000
3000
4000
5000
6000
7000
8000
9000
Heating degree-days
1000
2000
3000
4000
5000
>6000
Heating degree-days

Table 1

	At the supranational level		COUNTRY OR STATE		
			Country	General construction regulations	Main regulations governing the energy factors under study
EU	European Directives: 2010/31/EU		Germany	Energieeinsparungsgesetz-EnEG	Energieeinsparverordnung – EnEV DIN 18599-2010
			France	R. 111-20 du code de la construction et de l'habitation	Arrêté du 24 mai 2006 Décret No. 2006-592 du 24 mai 2006 NF EN ISO 7933
	European Standard (EN)		UK	Building Act 1984 (England and Wales)	SAP 2009 Building Regulations 2000: · Approved Document L1A/2010 BS EN 7730
			Spain	Ley Ordenación de la Edificación	Código Técnico de la Edificación: · DB HE-1 · RITE
	Qualitative insulation requirements		*Each country issues its own regulations with different numerical values.*		
USA	US Codes: Energy Conservation and Production Act	International Code Council (ICC): · International Energy Conservation Code 2009 (IECC)	*Each state adapts regulations for its construction practices or its own objectives but does not set lower quantitative values.*		
		ASHRAE Standards: · Standard 90-1-2010 · Standard 55-2004			
	American National Standards (ANS; e.g., ISO and IEC)				
	Quantitative insulation requirements				

Table 1. Regulatory framework in the countries under study. This information was compiled by the author.

Table 2

Entity	Regulation	Scope	Manner in which the design factors are regulated			
			Compactness factor (m^2/m^3)	Parameters governing the building thermal envelope transmittance ($W/(m^2 \cdot K)$)		
				U_{max}	U_{med}	H
EUROPEAN UNION						
EU	2010/31/EU	All types of buildings	Not Regulated	Not Regulated	Not Regulated	Not Regulated
Specific European Union Countries						
Germany	EnEV-2009	Commercial and residential buildings[(a)]	Defines different building typologies	Not Regulated	Sets the same value for the whole country	Value is conditioned by the building typology
France	Arrêté du 24 mai 2006	Residential buildings (except those used for less than 2 years).	Defines different building typologies	Sets the same limit for all climate zones	Defines two climate zones for which different limits are set	Value is conditioned by the building typology
England and Wales	Document L1A	New dwellings in England and Wales	Not Regulated	Not Regulated	Their limit value is the value that complies with the maximum CO_2 emissions depending on the facilities included	Not Regulated
Spain	DB-HE · 1	New houses	Not Regulated	Defines five climate zones for which different limits are set	Defines five climate zones for which different limits are set	Not Regulated
Passivhaus-Institut Darmstadt	Passivhaus Institute	All types of buildings	Suggests a maximum numerical value	Not Regulated	Defined in central and northern Europe[(b)]	Not Regulated
UNITED STATES OF AMERICA						
ASHRAE	Standard 90-1-2010	Commercial and residential buildings with more than 3 floors	Not Regulated	Defines eight climate zones for which different limits are set[(c)]	Same values as Umax	Not Regulated

[(a)] Residential (used at least 4 months per year) and non-residential buildings: distinguishes between new and existing buildings.

[(b)] Provides the same value for all of central Europe and is now being adapted to Mediterranean climates.

[(c)] Requires both a minimum R-value of insulation to be included in the enclosure in addition to a maximum U-value for the entire enclosure (with all of its layers).

Table 2. Compactness factor and thermal envelope transmittance requirements in the regulations studied

Table 3

Agency / Country	Regulation	Scope	$T_{op} = T_{amb} + T_{rm}/2$
INTERNATIONAL			
ISO	ISO 7933	Conditioned areas in all types of buildings	Offers a range
EUROPEAN UNION			
CEN	EN 1525	Conditioned areas in all types of buildings	Offers a range
Specific Country of European Union			
Germany	DIN 4701	Conditioned areas in all types of buildings	Offers a range
France	NF EN ISO 7933	Conditioned areas in all types of buildings	Offers a range
United Kingdom	BS EN 7730	Conditioned areas in all types of buildings	Offers a range
Spain	RITE	Habitable areas	Offers a range
Passivhaus-Institute	Passivhaus requirements	All type of buildings	Offers a range
UNITED STATES OF AMERICA			
USA	55-2004 Standard	Residential and commercial buildings	Provides a formula

Table 3. Temperature regulations in the standards examined in this study

Table 4

	Germany	France	U.K. (England and Wales)	Spain	Passivhaus	USA
Variation in the number of degree-days during the winter	2000 - >6000	2000 - 4000	3000 - 4000	1000-3000	2000 - >6000	1000 - 9000
Variation in the number of degree-days during the summer	< 250 - 250	<250 - 750	<250	250 - <1250	<250 - 500	0 - 4000
Number of climate zones for which transmittances are set	1	2	1	5	1	8
Approximate range of heating degree-days contained in each climate zone	4000	1000	1000	400	4000	1000

Table 4. Variation in the number of heating and cooling degree-days and the number of climate zones that are defined in the countries under study

Table 5

Construction type	Transmittance limits depending on the enclosure construction type (W/m²·K)					
	Germany[(a)]	**France**	**England and Wales**[(a)]	**Spain**	**Passivhaus** [(a)]	**USA (ASHRAE)**
Walls in contact with the outside and the ground	0.20[(b)]	*0.45*	0.25 (0.22[(c)])	0.74	0.15	0.45
Walls with unheated space	0.35[(d)]	0.45/b[(e)]	0.25	0.74	0.15[(a)]	0.45
Walls between residential and non-residential areas	0.20[(a)]	0.50	0.25[(a)]	0.74[(a)]	0.15	0.45[(a)]
Curtain walls	0.20[(a)]	2.60	0.25[(a)]	0.74[(a)]	0.15[(a)]	0.45[(a)]
Slab on grade floors	0.28	*0.36*	0.25 (0.17)	0.62	0.15	0.27
Sanitary forging or wrought adjacent to unheated space	0.28[(a)]	0.40	0.25 (0.17)	0.62[(a)]	0.15	0.27[(a)]
Concrete or masonry roofs or high-strength metal plates	0.20	0.34	0.20 (0.14)	0.46	0.15	0.36[(a)]
Metal roofing sheets	0.20	0.41	0.20 (0.14)	0.46	0.15	0.36
Other roof types	0.20	0.28	0.20 (0.14)	0.46	0.15	0.36
Windows and doors	1.30 (windows) 1.80 (doors)	2.60	2.00 (0.90)	3.10	0.80	1.99
Window blind boxes	-	3.00	-	-	Evitar puentes térmicos	

(a) The legislation does not contain this type of construction, and the data provided is similar to the data for another type of construction with the same function. In countries where only the transmittance limit is required for each envelope zone, the values of this transmittance limit are shown.

(b) Only exterior walls.

(c) In England, the values in parentheses are the limits to be achieved in 2013.

(d) Also includes basement walls.

(e) Loss reduction coefficient for defined unheated spaces.

Table 5. Comparison of the transmittances limits of each type of enclosure defined by the different regulations

Table 6

Location	Average transmittance limit depending on the location of the building enclosure ($W/(m^2 \cdot K)$)					
	Germany	France	England and Wales	Spain	Passivhaus	USA (ASHRAE)
Exterior walls	0.20	0.36	0.25 (0.30)[a]	0.57	0.15	0.45
Floors	0.28	0.27	0.18 (0.25)	0.48	0.15	0.27
Roofs	0.20	0.20	0.15 (0.20)	0.35	0.15	0.36 [c]
Glass windows/doors	1.30	1.80	1.60 (2.00)	2.70	0.80	1.99
Overall heat transfer coefficient in the building (H)[b]	**0.385**	**0.513**	**0.410**	**0.812**	**0.247**	**0.613**
Deviation (%) from the Passivhaus H	**55.87**	**107.69**	**65.99**	**228.74**	**0**	**148.18**

[a] The lowest value allowed with the best installations is shown in brackets.

[b] It is assumed that the external wall surface is equal to sum of the floor and the roof surfaces and that the percentage of windows/doors is approximately 30%.

[c] Transmittance value when the roof is over an attic.

Table 6. Average envelope transmittance limit values for climates with similar degree-day intervals

Table 7

Means to regulate the compactness factor	Germany [48]	France [52]	UK [78]	Spain [79, 80]	Passivhaus [65]	USA [44]
Using a specific value	No	No	No	No	Less than 0.6	No
By penalizing the maximum limit of H (%)[(a)]	+37.5 to +62.5%	+4.16%	No	No	No	No

[(a)] The difference (in percentage) of the values required for the specific heat transfer coefficient (H) of a single-family house regarding with a housing block.

Table 7. Compactness factors and penalizations in building insulation included in the different regulations analyzed

Table 8

	EN 15251 PPD <10%	EN 7730 PPD <15%	Germany [50, 82]	France [56, 83]	UK (England and Wales) [60]	Spain [64]	Passivhaus [65]	USA [84-85]
T_{op} housing (ºC)	18-27 [(a)]	19-27	20-24 [(b)]	19-22(26) [(c)] 15-18 night[(d)]	20 - 26	21 - 25	19-26	20-26.6 [(e)]
T_{op} bathrooms (°C)	18-27 [(a)]	19-27	24 [(b)]	22- 24	20 - 26	21 - 25	19-26	20-26.6 [(e)]

[(a)] The recommended temperature range defined in UNE 15251 for new and renovated buildings is 20ºC to 26ºC.

[(b)] Mean values required for the winter and summer during normal operation; however, the minimum and maximum values of 20ºC and 26ºC, respectively, can be exceeded on occasion.

[(c)] By day and only when the premises are occupied. The order of 24 May 2006 extends the upper limit to 26ºC.

[(d)] At night.

[(e)] The 55-2004 standard calculation with an optimal value of skin permeability of 0.06 was applied.

Table 8. Room temperature required by the studied standards