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Resilience to increasing temperatures: residential building stock adaptation through codes and standards

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ABSTRACT

The resilience of the current Spanish residential building stock to increased temperatures is modeled. Homogenised daily temperature data recorded at 50 Spanish meteorological stations for the periods 1950 - 1979 and 1981 - 2010 were used to investigate anticipated climate warming on Spanish residential building stock by means of the degree day method. Impacts on residential buildings were investigated for three different future time periods (2011-2040, 2041-2070 and 2071-2100) for three representative Spanish provincial capitals. Future climate change scenarios comprising two statistical downscaling methods, three general circulation models, and two carbon emission scenarios were used to project local climate. Results show that 72% of current residential building stock in Spain is thermally unprotected. In addition, the energy demand for heating the building sector in Spain is expected to decrease between 30% (Barcelona, B2 scenario) and 36% (Valencia, A2 scenario) by 2100, while the respective energy demand for cooling could increase between 107% (Valencia, B2 scenario) and 296% (Madrid, A2 scenario) by 2100. To increase resilience to higher winter and summer temperatures, strategies for modifying the built environment are needed, particularly for the role of building codes and standards.

Keywords:
adaptation strategies, building performance, building regulations, building stock, climate change, degree days, overheating, thermal comfort, vulnerability, Spain.

1. INTRODUCTION

In recent years, the need to integrate climate change implications into public policy has been widely recognised. However, the discussion of climate policy integration has tended to focus on mitigation decisions mainly taken at international and national levels (Urwin and Jordan, 2008). The adaptation dimension has been less explored. Within the built environment perspective, attention has been primarily devoted to increases in frequency and intensity of natural hazards such as floods, storm events, heat-waves and droughts that impact people and the built environment (EEA, 2006; EEA, 2007; EEA, 2010; CEC 2009). This tendency has been promoted, to a large extent, by the insurance industry (EEA, 2007).

Over the next few decades, the existing building stock is likely to be exposed to significantly different climatic conditions compared to today (Lisø, 2006). Indeed, indoor thermal comfort will be different in the future from what was designed and anticipated. In warm climates, this may cause significant increases on building energy demand for cooling purposes. Climate adaptation can be implemented by increasing buildings' adaptive capacity. This is represented by their enhanced thermal performance to reduce the growing energy demand as a result of climate change. In this sense, it has been argued that both mitigation of greenhouse gases (GHGs) and adaptation to climate change should be added to our building codes and standards (Kwok and Rajkovich, 2010). The revision of standards also provides an opportunity to raise awareness of the shifting factors affecting the construction industry (Vivian et al., 2005).

In this context, and taking into account that the implications of climate change are characterised by strong latitudinal variations (IPCC, 2001; IPCC, 2007b), regional studies are proving to be an essential tool for scientists and decision-makers (Giannakopoulos et al., 2009). An analysis of recent temperature trends in Spain lead to the conclusion that maximum and minimum temperatures have risen significantly since 1970 (Staudt, 2004). In spite of appreciable regional variations, the average rating of temperature increase in Spain has been estimated at 0.6ºC per decade, slightly higher than what has been observed on a global scale (De Castro et al., 2005). Furthermore, current climate change scenarios for Spain (Brunet et al., 2008) predict higher temperatures for the entire country and for all four seasons. The reference framework for the evaluation of impacts, vulnerability and adaption to climate change in Spain was formally adopted on 2006 through the publication of the National Climate Change Adaptation Plan (Spanish Ministry of Environment, 2006). Having stated that climate change impacts will have consequences on the habitability of buildings, the action points in this Plan include reviewing the legal framework for construction and design as well as the creation of technical guidelines adapted to the new circumstances. However, these action points for the built environment have not yet been explicitly addressed as efforts have been focused on other sectoral areas.

This research presented here investigates the current Spanish residential building stock resilience to climate warming impact. Strategies and measures involving building codes and standards are considered for the adaptation of existing and future buildings. 'Resilience' is defined by IPCC (2007a) as the ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organisation, and the capacity to adapt to stress and change. Using a proper understanding of the current structure of the Spanish built environment and corresponding thermal building regulations, the implications of climate warming are investigated.

The energy performance of Spanish buildings was first regulated by the compulsory basic building norm NBE-CT 79 regarding thermal conditions in buildings (Spain, 1979). This prescriptive code was in force between 1980 - 2006 and set minimum thermal requirements for individual building envelopes by establishing maximum heat transmission coefficients and a maximum overall heat transmission coefficient for the entire building. Climatic zoning in NBE-CT 79 is carried out according to mean yearly degree days based at 15ºC and mean minimum temperatures in January. In 2006 as a result of transposition of European Directive 2002/91/EC, the Energy Performance of Buildings Directive (EPBD) (European Union, 2002) into national law, the Spanish Technical Building Code (TBC) (Spain, 2006) was adopted. Currently, the energy performance of new buildings in Spain is regulated through Section HE-1 on Energy Demand Limitation of this performance-based code. In this case, climate zoning has been carried out in accordance to the variable known as climatic severity, which includes the solar radiation and heating/cooling degree days based at 20ºC.

This paper explores two different perspectives. In the first, mean yearly degree days, heating degree days, cooling degree days and mean minimum temperatures in January are calculated using homogenised daily mean temperature data recorded at 50 Spanish meteorological stations from 1981 to 2010. This is then compared to data included in the compulsory basic building norm NBE-CT 79 regarding thermal conditions in buildings. In the second perspective, impacts on Spanish buildings built under NBE-CT 79 (from 1981 to 2006) are investigated for three different periods (2011-2040, 2041-2070 and 2071-2100) using the cooling and heating degree day method for three representative Spanish provincial capitals. The following section quantifies the current Spanish residential building stock's capacity to respond to increased temperatures. Several adaptation measures are suggested for inclusion in future building codes and standards using a top-down approach. Finally, conclusions and wider implications related to the need of addressing climate change adaptation in the built environment through current and future building codes are highlighted.

2. DATA AND METHODS

The main steps of this research are summarised below.

Step 1: Analyze the current structure of Spanish residential building stock
Data on the age and typology of the stock are essential factors with regard to the energy performance of dwellings (Meijer et al., 2009). Data related to existing buildings in Spain were extracted primarily from the 2001 Population and Housing Census carried out by the Spanish National Institute of Statistics (National Institute of Statistics, 2011). Primary data sources included the number of buildings mainly designed as dwellings according to the construction year (aggregated) and the Spanish province. These figures were completed with information contained in the databases of the Spanish Ministry of Public Works for 2002-2010 (Ministry of Public Works, 2011). In this case, the selected data covered annual final certificates for residential buildings, including main and secondary residences, for each of the Spanish provinces. Available data on the typology and physical quality of the existing Spanish residential stock are also investigated.

Step 2: Obtain climatic data
For the purposes of this study, long-term weather records were retrieved from AEMET (Spanish Meteorological Agency) servers.[1] Primary data sources included mean daily temperatures and minimum temperatures in January for each Spanish provincial capital (table 1)[2]. The World Meteorological Organization requires the calculation of climate normal values for consecutive 30 year time periods as this eliminates yearly interannual variations. The World Meteorological Organization also recommends updating the 30 year time periods at the end of each decade. In order to characterise current Spanish climate, results for normal values from the 1981-2010 period served as the basis of this research (Spanish Meteorological Agency, 2010). Meteorological observations with less than 15 years of records from 1981 to 2010 were not considered to be sufficiently complete and therefore were not included in this study (table 1). For the purposes of this study, the 30 year period prior to enactment of NBE-CT 79 (1950-1979) was also investigated (Spanish Meteorological Agency, 2010). In this case, a limited number of registered meteorological observations recommended excluding analysis of six Spanish provincial capitals (table 1).

LOCATION	STATION NAME	LATITUDE (ºN)	LONGITUDE (ºE)	ELEVATION (m)	DOCUMENTED OBSERVATIONS IN MEAN TEMPERATURE (1981-2010)	DOCUMENTED OBSERVATIONS IN MINIMUM TEMPERATURE IN JANUARY (1950-1979)	DOCUMENTED OBSERVATIONS IN MINIMUM TEMPERATURE IN JANUARY (1981-2010)
Albacete	Albacete	39.01	-1.86	674	10,220	910	868
Alicante	Alicante	38.37	-0.49	81	10,956	930	930
Almería	Aeropuerto de Almería	36.85	-2.36	21	10,948	897	930
Ávila	Ávila	40.66	-4.68	1,130	10,622	713	930
Badajoz	Aeropuerto de Badajoz	38.88	-6.83	185	10,957	775	930
Barcelona	Aeropuerto de Barcelona	41.29	2.07	4	10,945	930	930
Bilbao	Aeropuerto de Bilbao	43.30	-2.91	42	10,883	930	899
Burgos	Aeropuerto de Burgos	42.36	-3.61	903	10,956	930	930
Cáceres	Cáceres	39.47	-6.34	405	10,957	899	930
Cádiz	San Fernando	36.47	-6.21	28	10,490	723	899
Castellón	Castellón de la Plana	39.95	-0.07	35	10,918	868	930
Ciudad Real	Ciudad Real	38.99	-3.92	628	10,956	920	930
Córdoba	Aeropuerto de Córdoba	37.84	-4.85	90	9,430	600	775
Cuenca	Cuenca	40.07	-2.14	945	10,956	585	930
Gierona	Aeropuerto de Girona	41.91	2.76	143	10,778	620	930
Granada	Aeropuerto de Granada	37.19	-3.79	567	10,934	899	930
Guadalajara	Guadalajara	40.63	-3.17	670	9,516	558	806
Huelva	Huelva	37.28	-6.91	19	10,951	929	930

LOCATION	STATION NAME	LATITUDE (ºN)	LONGITUDE (ºE)	ELEVATION (m)	DOCUMENTED OBSERVATIONS IN MEAN TEMPERATURE (1981-2010)	DOCUMENTED OBSERVATIONS IN MINIMUM TEMPERATURE IN JANUARY (1950-1979)	DOCUMENTED OBSERVATIONS IN MINIMUM TEMPERATURE IN JANUARY (1981-2010)
Huesca	Aeropuerto de Huesca	42.083	-0.33	541	10,517	929	899
Jaén	Jaén	37.78	-3.81	582	9489	699	775
La Coruña	La Coruña	43.37	-8.42	58	10,956	930	899
Las Palmas	Las Palmas	28.09	-15.41	55	10,942	837	930
León	Aeropuerto de León	42.59	-5.65	916	10,957	888	930
Lérida	Lérida	41.63	0.59	192	10,954	619	930
Logroño	Aeropuerto de Logroño	42.45	-2.33	353	10,957	930	930
Lugo	Rozas	43.12	-7.46	445	9,089	-	744
Madrid	Aeropuerto de Madrid	40.47	-3.56	609	10,952	-	930
Madrid	Madrid Retiro	40.4	-3.72	667	-	930	-
Málaga	Málaga	36.72	-4.48	60	10,956	909	930
Murcia	Murcia	38.00	-1.17	61	10,957	924	930
Ourense	Ourense	42.33	-7.86	143	10,743	483	930
Oviedo	Oviedo	43.36	-5.87	336	10,957	217	930
Palencia	Autilla del Pino	41.00	-4.60	874	4,046	619	744
Palma de Mallorca	Palma	39.55	2.63	3	10,949	-	930
Pamplona	Bárdenas Reales de Navarra	42.20	-1.47	295	10,797	775	930
Pontevedra	Pontevedra	42.44	-8.62	108	10,956	496	930
Salamanca	Salamanca	40.96	-5.66	775	10,957	930	930
San Sebastián	Aeropuerto de San Sebastián	43.36	-1.79	4	10,957	930	930

LOCATION	STATION NAME	LATITUDE (ºN)	LONGITUDE (ºE)	ELEVATION (m)	DOCUMENTED OBSERVATIONS IN MEAN TEMPERATURE (1981-2010)	DOCUMENTED OBSERVATIONS IN MINIMUM TEMPERATURE IN JANUARY (1950-1979)	DOCUMENTED OBSERVATIONS IN MINIMUM TEMPERATURE IN JANUARY (1981-2010)
Santa Cruz de Tenerife	Santa Cruz de Tenerife	28.46	-16.26	35	10,957	930	930
Santander	Santander	43.49	-3.80	52	10,956	927	930
Segovia	Segovia	40.95	-4.13	1,005	10,224	805	899
Sevilla	Sevilla	37.40	-6.01	11	10,952	896	930
Soria	Soria	41.77	-2.48	1,082	10,926	930	930
Tarragona	-	-	-	-	-	-	-
Teruel	Teruel	40.35	-1.10	934	9,041	-	868
Toledo	Toledo	39.88	-4.05	515	10,957	930	930
Valencia	Valencia	39.48	-0.37	11	10,957	930	930
Valladolid	Valladolid	41.65	-4.77	735	10,955	924	930
Vitoria	Aeropuerto de Vitoria	42.87	-2.73	513	10,957	899	930
Zamora	Zamora	41.52	-5.73	656	10,955	911	930
Zaragoza	Zaragoza	41.63	-0.90	221	10,956	867	930

Table 1. Basic location characteristics of Spanish meteorological stations and number of documented observations during the 1950-1979 and 1981-2010 periods according to data available from AEMET.

Future climate warming impact was estimated from regionalised climate change projections for Spain provided by AEMET (Spanish Meteorological Agency, 2011). High resolution climate change scenarios for Spain are the result of applying two statistical downscaling methods to three different Atmospheric and Oceanic Global Circulation Models (Spanish Meteorological Agency, 2011). Global Circulation Models are the most advanced numerical tools currently available for simulating the response of the global climate system to increasing GHG concentrations (IPCC Data Distribution Centre, 2012). The CGCM2-Second Generation Coupled Global Climate Model (McFarlane et al., 1992), the ECHAM4-Atmospheric General Circulation Model (Roeckner et al., 1996) and the HadAM3H-Hadley Atmospheric Model (Hudson and Jones, 2002) were used in this research. Global Circulation Models depict the climate using a three dimensional grid over the globe, typically having a horizontal resolution of between 250 and 600 km, 10 to 20 vertical layers in the atmosphere and sometimes as many as 30 layers in the oceans. Their resolution is thus quite coarse relative to the scale of exposure units in most impact assessments (IPCC Data Distribution Centre, 2012). To fill the gap between the coarse-resolution grids used by Global Circulation Models and the regional needs of applications, FIC and INM statistical downscaling techniques were used. Statistical downscaling is a complex multi-disciplinary problem which requires a cascade of different scientific tools to access and process different sources of data, from Global Circulation Models outputs to local observations and to run complex statistical algorithms (Gutiérrez et al., 2008). FIC is a statistical downscaling technique based on a two-step analogue method developed by the Climate Research Foundation (FIC) broadly tested on national (Spain) and international projects (Torres et al., 2011). The INM method is a computationally efficient implementation of the standard analogues technique which clusters the reanalysis database into a set of weather classes (Gutiérrez and Cofiño, 2004). According to the Special Report on Emissions Scenarios (IPCC, 2000) and assessment reports from the Intergovernmental Panel on Climate Change (IPCC, 2001; IPCC, 2007b), simulations assumed GHG and aerosol emissions described by A2 and B2 scenarios. The A2 scenario is characterized by a world of independently operating, self-reliant nations, continuously increasing global population and regionally oriented economic development (IPCC, 2000). The B2 scenario describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2 and intermediate levels of economic development (IPCC, 2000). Outputs include future daily records of minimum and maximum temperatures with a grid scale of 50 km for three different future periods (2011-2040, 2041-2070 and 2071–2100) (Table 2).

EMPIRICAL METHOD	**CGCM2**	**ECHAM4**	**HadAM3H**
INM	A2, B2	A2, B2	A2
	2011-2040 2041-2071 2071-2100	2011-2040 2041-2071 2071-2100	2071-2100
FIC	A2, B2	A2, B2	A2, B2
	2011-2040 2041-2071 2071-2100	2011-2040 2041-2071 2071-2100	2071-2100

Table 2. Statistical downscaling simulations according to Atmospheric and Oceanic Global Circulation Models, forcing scenarios, and time periods.

Step 3: Analyze the influence of climatic variables on thermal building regulations.

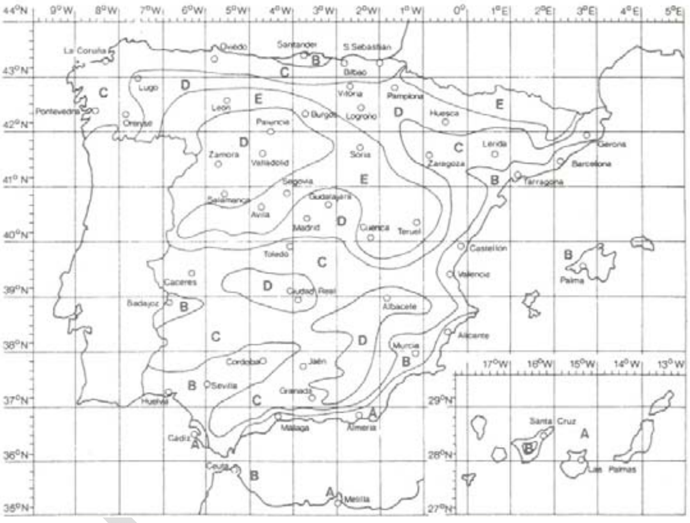
Since the regional climatic variability in Spain is very pronounced, energy performance requirements established by NBE-CT 79 (the first Spanish thermal building regulation) are based on climatic conditions. Climatic zoning in NBE-CT 79 is carried out according to mean yearly degree days and mean minimum temperatures in January.

As stated by UNE 24046:1958 (Aenor, 1958), degree days can be calculated for every day of a certain period of time as the addition of the difference between a base temperature and the mean daily temperature, when this daily temperature is lower than the threshold temperature. Monthly degree days can, therefore, be calculated as follows:

$$DD_{base} = \sum_{1}^{n} \left(T_{base} - T_{day}\right) \quad if \ T_{day} < T_{th} \qquad [1]$$

where T_{base} is the temperature the heating plant is assumed to provide, T_{day} is the average outdoor temperature for a day and T_{th} is the threshold temperature, which is the outdoor temperature at which the heating plant is turned on/off and, therefore, above which accumulated temperature differences are not counted. The number of days in a month being n, the aggregation of all monthly degree day values makes it possible to obtain annual degree day values.

In NBE-CT 79, both the base and threshold temperatures are assumed to be 15ºC. Consequently, the heating system is considered shut down when the indoor temperature reaches 15ºC (base temperature). It is also considered that the heating system functions when the outside temperature is lower than or equal to 15ºC (threshold temperature). NBE-CT 79 divides Spain into five areas (A - E) based on mean annual degree days based at 15ºC, where zone A represents the warmest area (with less than 400 annual mean degree days) and zone E is the coolest area (with more than 1,800 annual mean degree days) (figure 1). Based on this classification, NBE-CT 79 establishes maximum overall heat transmission coefficient for the entire building.

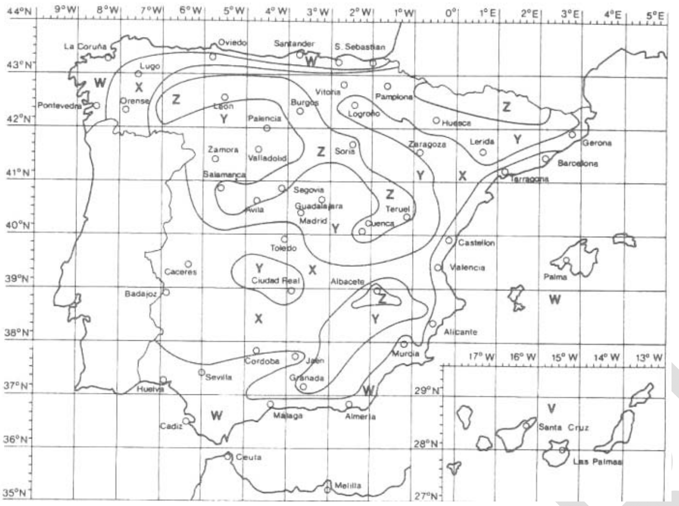


Zone	Annual degree days based at 15ºC
A	≤ 400
B	401÷ 800
C	801 ÷ 1300
D	1300 ÷ 1800
E	> 1800

Fig. 1. Climatic zoning based on annual degree days based at 15ºC in NBE-CT-79 (Spain, 1979).
Source: partially adapted from NBE-CT-79 (Spain, 1979).

In order to better investigate temperature changes from a seasonal perspective, heating and cooling degree days have also been calculated. According to the Spanish Technical Building Code, cooling degree days (CDD) were calculated as average degree days based at 20ºC in June, July, August and September, whereas heating degree days (HDD) were calculated as average degree days based at 20ºC in winter (January, February and December).

The second classification stated by thermal building norm NBE-CT 79 establishes five areas (V - Z), according to mean minimum temperature in January (figure 2). The V zone includes the warmest locations in January where the mean minimum temperature during this month is assumed to be 10ºC. The W zone includes locations with a mean minimum temperature in January of 5ºC while places in the X zone are assumed to have a mean minimum temperature in January of 3ºC. According to NBE-CT 79, the Y zone is understood to represent areas with a mean minimum temperature in January of 0ºC and the Z zone represents the coolest area, with a mean minimum temperature in January of -2ºC. Based on this classification, NBE-CT 79 establishes maximum heat transmission coefficients for individual closures.



Zone	Mean minimum temperature in January (ºC)
V	10
W	5
X	3
Y	0
Z	-2

Fig. 2. Climatic zoning based on mean minimum temperatures in January in NBE-CT-79 (Spain, 1979). Source: partially adapted from NBE-CT-79 (Spain, 1979).

Step 4: Calculate degree days

Mean annual degree days based at 15ºC and heating and cooling degree days based at 20ºC were calculated on the basis of daily mean temperature data from 1981 to 2010 for each Spanish provincial capital (Spanish Meteorological Agency, 2010). In order to avoid deviating from the Spanish standard (NBE-CT 79), mean annual degree days were estimated according to equation 1. Mean annual degree days based at 15ºC from 1981 to 2010 were compared to those used when designing buildings erected during the 1980-2006 period under NBE-CT 79. In this case, mean annual degree days are explicitly stated in UNE 24046:1958. Mean annual degree days based at 15ºC and heating and cooling degree days based at 20ºC were also calculated on a daily basis according to eq. 1 for two previous periods (1950-1979 and 1981-2010) (Spanish Meteorological Agency, 2010) and for three future periods (2011-2040, 2041-2070 and 2071-2100) under two forcing scenarios using two statistical downscaling methods and three Atmospheric and Oceanic Global Circulation Models (Spanish Meteorological Agency, 2011). Within the 2011-2040 period, units built under NBE-CT 79 will be between 5 -60 years of age. During the 2041-2070 period, the age of buildings will vary between 35 - 90 years. Finally for the 2071-2100 period, NBE-CT 79 buildings will be almost at the end of their lifespan (65-120 years). Future mean annual degree days based at 15ºC and heating and cooling degree days based at 20ºC were compared to those stated by UNE 24046:1958 or calculated for previous periods.

Step 5: Calculate mean minimum temperatures in January

Mean minimum temperatures in January were first calculated based on daily minimum temperatures in two different periods for each of the 50 Spanish provincial capitals (Spanish Meteorological Agency, 2010). The first period covers the 30 years prior to NBE-CT 79 (1950-1979), while the second period corresponds to current climate and covers 1981 - 2010. Mean minimum temperatures in January were also calculated for three future periods (2011-2040, 2041-2070 and 2071-2100) under two forcing scenarios (A2 and B2) using two statistical downscaling methods and three Atmospheric and Oceanic Global Circulation Models (Spanish Meteorological Agency, 2011). Recent and futures trends for mean minimum temperatures in January were compared to those calculated for the 1950-1979 period using registered data in AEMET databases (Spanish Meteorological Agency, 2010).

3. RESULTS

3.1 Current structure of Spanish residential building stock

Residential buildings are the main component of Spanish building stock, accounting for a total number of 9,898,141 units in 2010[3]. Of these, 5,834,195 units were built before 1980 without satisfying any minimum thermal building requirements (figure 3 and table 3). Most of the Spanish buildings erected before 1920 have ventilated pitched roofs made of wooden trusses supporting the tiles. In case of ventilated flat roofs, brick vaulting and partitions sit on metal or wood structures. Facades are typically load-bearing masonry walls[4] . Hinged timber casement windows with single glazing were widely used (figure 3 and table 3). Buildings erected within the 1921-1960 period in Spain have pitched roofs sitting on unidirectional slabs or flat roofs including slab, concrete slope, waterproofing and protection. Reinforced concrete frame structures with a structural grid of 3 or 4 m are widely used during this period. Facades are thinner and they are made of solid or perforated bricks. Although folding steel windows with single glazing are introduced during this period, wooden casement windows with single glazing are still widely used (figure 3 and table 3). Buildings erected later, during the 1961-1980 period also have pitched roofs leaning on unidirectional slabs. Ceramic and concrete lightweight blocks are introduced in flat roofs during this period. Reinforced concrete frame structures with a structural grid of 4-5 m are widely used. A hollow brick inner layer is added to the brick facades, creating an air cavity in the middle. Aluminium sliding windows with single glazing are highly common (figure 3 and table 3).

PERIOD	NUMBER OF ERECTED BUILDINGS	U-VALUES [W/m^2·K]			
		ROOF	EXTERIOR WALLS	WINDOWS	
				GLASS	FRAME
<1920	1,326,037	3.08 - 4.17	2.63	5.70	2.20
1921-1960	1,915,918	1.37 - 1.67	3.03	5.70	5.70
1961-1980	2,592,240	1.92	1.42	5.70	5.70

Table 3. Age distribution and main U-values of the Spanish residential building stock.
Source: Partially adapted from Valencia Institute of Building (2011).

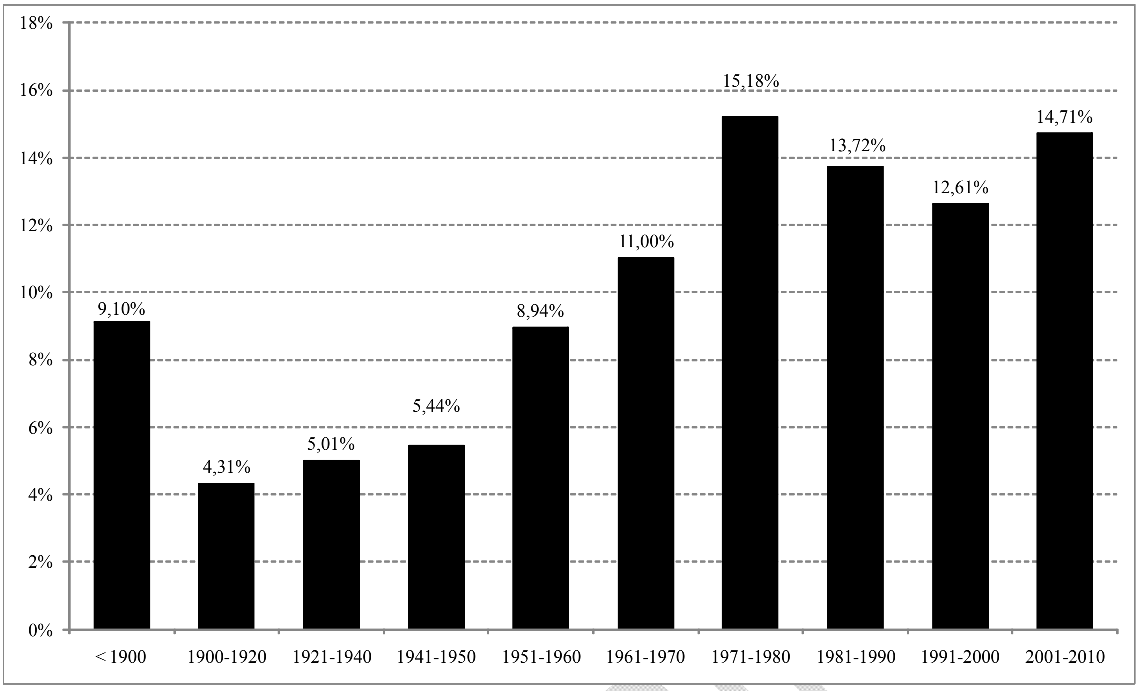


Fig. 3. Age distribution of Spanish residential building stock (2010).
Source: National Institute of Statistics (2011) and Ministry of Public Works (2011).

The 3,802,412 units built between 1980 - 2006 fall under the thermal requirements established by NBE-CT 79 (figure 3). The use of cavity walls with thermal insulation in the cavity is highly common in this period. Facades are usually rendered and painted.

Within the NBE-CT 79, insulation is also placed inside ventilated roofs and in non-ventilated flat roofs. Aluminium windows with double glazing are widely used and in some cases, thermal breaks are used. Assuming that minimum building energy performance requirements set in NBE-CT 79 became the standard for all buildings erected within the 1980-2006 period, table 4 shows typical U-values for these buildings.

CLOSURES	**U-VALUES [W/m^2·K]**				
	ZONE V	**ZONE W**	**ZONE X**	**ZONE Y**	**ZONE Z**
ROOFS	1.40	1.40	1.20	0.90	0.70
LIGHT FACADES	1.20	1.20	1.20	1.20	1.20
HEAVY FACADES	1.80	1.80	1.60	1.40	1.40

Table 4. Maximum U-values for individual closures according to NBE-CT 79 (Spain, 1979).
Source: Partially adapted from NBE-CT 79 (Spain, 1979).

Finally, 261,534 new residential buildings were added to building stock between 2007 and 2010 (figure 3) and therefore built under new thermal requirements established by the Spanish Technical Building Code (table 5). Construction techniques and systems used during the past period are still highly common. However, higher insulation layer thicknesses and higher performance insulation materials are used in order to meet higher requirements.

CLOSURES	**U-VALUES [W/m^2·K]**											
	ZONE A3	**ZONE A4**	**ZONE B3**	**ZONE B4**	**ZONE C1**	**ZONE C2**	**ZONE C3**	**ZONE C4**	**ZONE D1**	**ZONE D2**	**ZONE D3**	**ZONE E1**
FACADES	0.94	0.94	0.82	0.82	0.73	0.73	0.73	0.73	0.66	0.66	0.66	0.57
ROOFS	0.50	0.50	0.45	0.45	0.41	0.41	0.41	0.41	0.38	0.38	0.38	0.35
FLOORS	0.53	0.53	0.52	0.52	0.50	0.50	0.50	0.50	0.49	0.49	0.49	0.35
DOORS AND WINDOWS	Depending on the climate zone, percentage of doors and windows surface and orientation.											

Table 5. Maximum U-values for individual closures according to Spanish Technical Building Code (Spain, 2006).
Source: Partially adapted from Technical Building Code (Spain, 2006).

According to official data provided by the Spanish Ministry of Public Works (Ministry of Public Works, 2001), 32,597 residential buildings were refurbished during 2010 whereas 3,116 units were demolished. Taking into account that a ten year average of planning permissions (2001-2010) amounts to 26,465 for refurbishment purposes and 4,547 for demolition purposes, if the current rates were to continue then it is likely that Spanish residential building stock will not be completely renovated for over 188 years.

The current structure of the Spanish residential building stock shows that 59% of residential buildings in 2010 were built before 1980 without any building thermal requirements. This non-insulated building stock requires large amounts of energy to achieve current indoor thermal comfort levels. Nearly 38% of residential buildings already in use in Spain in 2010 were built under NBE-CT 79 (between 1980 and 2006). Therefore, those buildings that did not undergo later refurbishment processes still have inadequate thermal protection. According to a recent study carried out by the Institute for Energy Diversification and Saving, almost half of the Spanish dwellings (49%) have some type of air conditioning system (IDAE, 2011). The Mediterranean area has the highest proportion of households with an air conditioning system (67%).

3.2. Degree days

As climatic zoning in NBE-CT 79 was calibrated according to mean annual degree days based at 15ºC, the mean annual degree days based at 15ºC have been updated for each Spanish provincial capital taking into account the 1981-2010 period (table 6). For the majority of Spanish provincial capitals, mean annual degree days based at 15ºC have decreased significantly over the 1981-2010 period in relation to those considered by NBE-CT 79 (table 6). While according to Spanish thermal building regulation NBE-CT 79 mean annual degree days based at 15ºC in Spain used to range between 207.9 (Almería) and 2,142 (León), calculations updated for the 1981-2010 period place this number between 202.2 (Cádiz) and 2,005.4 (Burgos) (table 6).

Mean annual degree days based at 15ºC were found to have decreased in thirty four Spanish provincial capitals, representing 74% of the locations studied. According to results obtained, the highest increase in temperature was found to be in Palma de Mallorca (Balearic Islands), where the mean annual degree days based at 15ºC in the 1981-2010 period diminished 31% in relation to the period considered by Spanish thermal building regulation NBE-CT 79 (table 6). In mainland Spain and according to table 6, mean annual degree days based at 15ºC were found also to have significantly decreased in Valencia (28%) and La Coruña (26%). Other Spanish provincial capitals experienced lower decreases in mean annual degree days based at 15ºC such as Málaga (17%), Huelva (10%), Lérida (4%) and Zamora (2%) (table 6). The average decrease of mean annual degree days based at 15ºC in Spanish provincial capitals experiencing a warming climate is 10%. Although mean annual degree days based at 15ºC for the 1981-2010 period could be calculated for Las Palmas and Santa Cruz de Tenerife (both located in the Canary Islands), changes in annual degree days could not be properly analysed because NBE-CT 79 does not originally include numeric data for these locations.

The impact of climate warming is even more evident in eleven Spanish provincial capitals, where decreases in mean annual degree days based at 15ºC lead to a change in the climatic zoning initially established by NBE-CT 79. Cuenca, Segovia and Teruel were initially classified in an E zone by Spanish thermal regulation NBE-CT 79. However, mean annual degree day calculations based on the 1981-2010 period suggest that these locations should now be classified in a D zone (table 6). Similarly, and according to mean annual degree days based at 15ºC, Albacete, Ciudad Real, Logroño and Madrid were initially classified in a D zone. Updated calculations in table 6 suggest a C classification for these Spanish provincial capitals and their surrounding areas. Calculations for La Coruña also indicate a decrease in mean annual degree days based at 15ºC and consequently, the initial classification in a C zone needs to be updated to a B zone (table 6). Finally, Spanish thermal regulation NBE-CT 79 classified Palma de Mallorca, Sevilla and Valencia in a B climate zone. However, table 6 suggests that these locations should be classified in a warmer (A) zone.

LOCATION	NBE-CT 79 CLASSIFICATION BASED ON MEAN ANNUAL DEGREE DAYS BASED AT 15ºC		UPDATED CLASSIFICATION BASED ON MEAN ANNUAL DEGREE DAYS BASED AT 15ºC (1981-2010)	
Albacete	1,377.4	D	1,195.6	C
Alicante	338.2	A	369.9	A
Almería	207.9	A	220.2	A
Ávila	2,127.2	E	2,018.0	E
Badajoz	767.4	B	692.6	B
Barcelona	655.7	B	728.5	B
Bilbao	819.9	C	852.1	C
Burgos	2,048.4	E	2,005.4	E
Cáceres	1,003.1	C	857.1	C
Cádiz	227.4	A	202.2	A
Castellón	452.4	B	505.5	B
Ciudad Real	1,312.6	D	1,112.3	C
Córdoba	662.7	B	565.5	B
Cuenca	1,828.0	E	1,556.8	D
Gerona	939.3	C	1,077.8	C
Granada	1,041.8	C	1,032.2	C
Guadalajara	1468.6	D	1,438.4	D
Huelva	402.3	B	362.8	B
Huesca	1,350.1	D	1,445.5	D
Jaén	830.4	C	744.1	C
La Coruña	827.5	C	613.4	B
Las Palmas	-	A	0.6	A
León	2,142.6	E	1,905.3	E
Lérida	1,225.7	C	1,172.1	C
Logroño	1,404.9	D	1,270.0	C
Lugo	1,770.9	D	1,472.8	D
Madrid	1,404.9	D	1,281.3	C
Málaga	247.6	A	290.9	A
Murcia	432.5	B	493.9	B
Ourense	967.4	C	946.4	C
Oviedo	1,200.3	C	1,100.3	C
Palencia	1,781.5	D	-	-
Palma de Mallorca	527.4	B	363.5	A
Pamplona	1,534.6	D	1,456.1	D
Pontevedra	891.0	C	761.7	C
Salamanca	1,662.2	D	1,682.2	D
San Sebastián	913.1	C	1,074.9	C
Santa Cruz de	-	A	0.5	A

LOCATION	**NBE-CT 79 CLASSIFICATION BASED ON MEAN ANNUAL DEGREE DAYS BASED AT 15ºC**		**UPDATED CLASSIFICATION BASED ON MEAN ANNUAL DEGREE DAYS BASED AT 15ºC (1981-2010)**	
Tenerife				
Santander	724.1	B	707.3	B
Segovia	1,866.1	E	1,701.9	D
Sevilla	438.4	B	382.8	A
Soria	1,977.6	E	1,964.1	E
Tarragona	625.7	B	-	-
Teruel	1,801.7	E	1,719.5	D
Toledo	1,158.0	C	1,062.6	C
Valencia	515.9	B	368.3	A
Valladolid	1,708.8	D	1,587.0	D
Vitoria	1,599.6	D	1,650.3	D
Zamora	1,501.0	D	1,477.6	D
Zaragoza	1,150.7	C	1,053.5	C

Table 6. Climatic zoning based on mean annual degree days based at 15ºC established in NBE-CT 79 and UNE 2046:1958 and updated classification for the 1981-2010 period for each Spanish provincial capital.

Secondly and in order to gain a better seasonal perspective, heating and cooling degree days were calculated for the 1981-2010 period and compared to those registered within the 1950-1979 period for the eleven Spanish provincial capitals with climate zone shifting (table 7). In all cases, heating degree days have diminished (between 1% in Madrid and 13% in Palma de Mallorca) and cooling degree days have increased (between 24% in Seville and 100% in La Coruña).

LOCATION	**1980-2010**		**1950-1979**	
	HDD	**CDD**	**HDD**	**CDD**
Albacete	1,203.1	479.9	1,326.7	297.4
Ciudad Real	1,178.4	574.2	1,261.0	390.5
Cuenca	1,331.9	291.4	1,388.6	175.3
La Coruña	802.1	37.5	882.0	18.7
Logroño	1,216.2	265.6	1,239.7	195.7
Madrid	1,246.3	430.1	1,258.3	317.1
Palma de Mallorca	699.5	551.3	805.0	361.5
Segovia	1,361.1	216.4	1,418.5	173.9
Sevilla	748.4	802.0	813.1	645.2
Teruel	1,410.5	186.1	-	-
Valencia	701.6	553.7	769.9	410.7

Table 7. Heating and cooling degree days for the eleven Spanish provincial capitals with climate zone shifting.

Finally, long-term trends of heating degree days based at 20ºC and cooling degree days based at 20ºC have been calculated for Madrid, Barcelona and Valencia. Future projections concerning heating degree days based at 20ºC and cooling degree days based at 20ºC were obtained under two IPCC forcing scenarios (A2 and B2) for three different periods (2011-2040, 2041-2070 and 2071–2100). Heating degree days based at 20ºC for Madrid came to 1,235 during the 1950-1979 period and they decreased to 1,177 between 1981 and 2010. During the following period (2011-2040), climate projections indicate a further decrease quantified at 1,097 for A2 scenario and 1,091 for B2 scenario. Similarly, a further decrease in heating degree days based at 20ºC must be expected in the 2041-2070 period, when heating degree days based at 20ºC for Madrid are estimated at 993 (under A2 scenario) and 1,018 (under B2 scenario). Finally, heating degree days based at 20ºC are expected to range between 816 (A2 scenario) and 860 (B2 scenario) by the end of the twenty-first century.

Similar heating degree day trends were found for Barcelona. In this case, heating degree days based at 20ºC amounted to 964 for the 1950-1979 period and 932 for the 1981-2010 period. According to future projections, heating degree days based at 20ºC are expected to diminish to 874 (A2) or 867 (B2) for the following 30 year period. Higher changes are estimated for the 2041-2070 period, when heating degree days based at 20ºC are expected to be 772 (A2 scenario) and 806 (B2 scenario). Finally, future heating degree days based at 20ºC for Barcelona are expected to range from 632 (A2 scenario) to 674 (B2 scenario) by the end of the 21st century. According to calculations, Valencia will also experience a similar trend in heating degree days based at 20ºC. Starting from 770 (registered during the 1950-1979 period), future heating degree days based at 20ºC are expected to range from 488 (A2 scenario) to 532 (B2 scenario) by 2100.

Cooling degree days based at 20ºC for Madrid came to 320 during the 1950-1979 period and they increased to 502 between 1981 and 2010 (figure 4 and 5). During the following period (2041-2070), climate projections indicate a further increase quantified at 619 for A2 scenario (figure 4) and 599 for B2 scenario (figure 5). As shown in figures 4 and 5, a further increase in cooling degree days based at 20ºC must be expected in the 2041-2070 period, when cooling degree days based at 20ºC for Madrid are estimated at 854 (under A2 scenario) and 774 (under B2 scenario). Finally, cooling degree days based at 20ºC are expected to range between 1,271 (A2 scenario) and 1,012 (B2 scenario) by the end of the twenty-first century (figure 4 and 5).

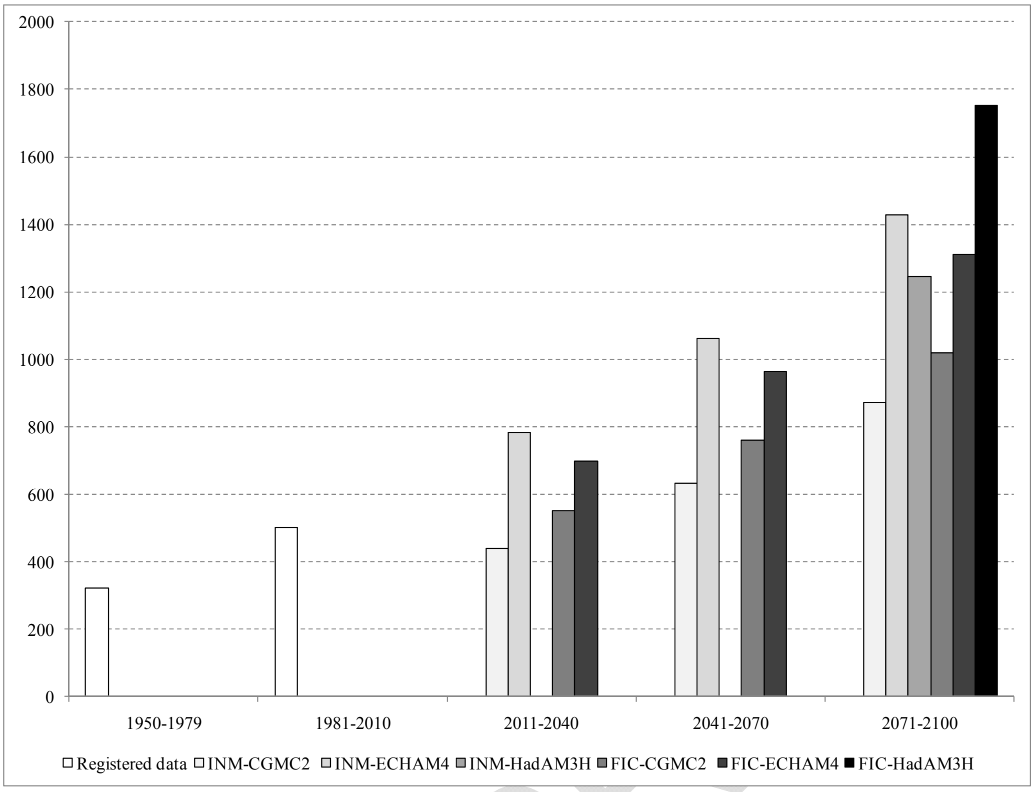


Fig. 4. Long-term trends of cooling degree days from 1950 to 2100 for Madrid under A2 scenario.

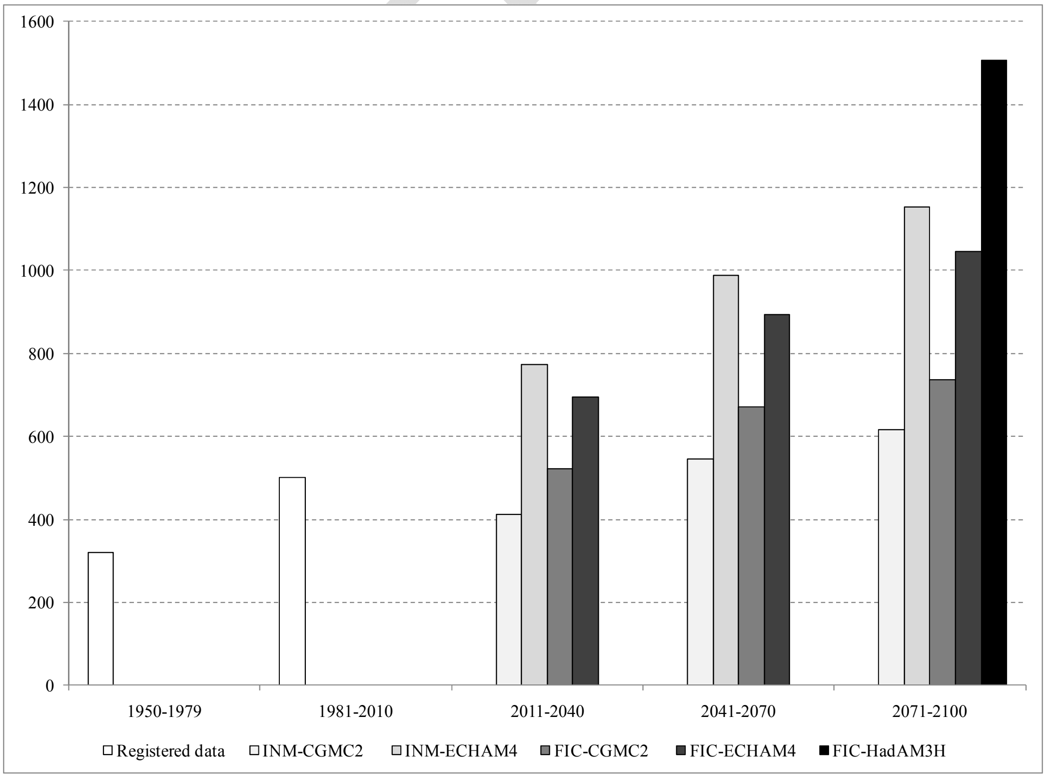


Fig. 5. Long-term trends of cooling degree days from 1950 to 2100 for Madrid under B2 scenario.

Similar cooling degree day trends were found for Barcelona. In this case, cooling degree days based at 20ºC amounted to 241 for the 1950-1979 period and 602 for the 1984-2010 period. According to future projections, cooling degree days based at 20ºC are expected to increase to 839 (A2) or 665 (B2) by the end of the twenty-first century. According to calculations, Valencia will also experience a similar trend in cooling degree days based at 20ºC. Starting from 411 (registered during the 1950-1979 period), future cooling degree days based at 20ºC are expected to range from 1,021 (A2 scenario) to 851 (B2 scenario) by 2100.

3.3. Mean minimum temperatures in January

Mean minimum temperatures in January ranged from 15.5ºC to -4.1ºC in Spain over the 1950-1979 period (prior to NBE-CT 79). The highest mean minimum temperature in January was observed in Santa Cruz de Tenerife (Canary Islands), while the lowest mean minimum temperature in January was observed in Burgos. In the 1981-2010 period, mean minimum temperatures in January ranged from 15.8ºC, registered in Santa Cruz de Tenerife (Canary Islands) and 9.1ºC, registered in Almeria (southeastern coast of mainland Spain) to -3.1ºC, registered in Ávila. Mean minimum temperatures in January were substantially different from station to station, showing broad spatial variability, i.e. mean minimum temperature in January in Seville, a city located in southern Spain was 6.3ºC during the 1981-2010 period and in Burgos, a city located in northern Spain, it was only -2.7ºC during the same period.

Mean minimum temperatures in January for the 1981-2010 period were found to have increased in 31 Spanish provincial capitals in relation to the 1950-1979 period. The highest increase in mean minimum temperatures in January, 2.1ºC, was in Valladolid. Other Spanish provincial capitals experienced lower increases in mean minimum temperatures in January such as Barcelona (2.0ºC), Valencia (0.7ºC) and Madrid (0.3ºC). On average, the increase in mean minimum temperatures in January in Spanish provincial capitals with a warming climate is 0.8ºC.

In relation to the climate zoning stated in NBE-CT 79, eight Spanish provincial capitals should be classified in a warmer category. Albacete and Cuenca were initially classified in a Z zone by Spanish thermal regulation NBE-CT 79. However, mean minimum temperatures in January calculations based on the 1981-2010 period suggest that these locations should now be classified in a Y zone. Similarly and according to mean minimum temperatures in January, Badajoz and Córdoba were initially classified in an X zone. Updated calculations suggest a W classification for these Spanish provincial capitals and their surrounding areas. Finally, calculations for Almería, Cádiz, Málaga, and Palma de Mallorca also indicate an increase in their mean minimum temperatures in January and therefore, the initial classification in a W zone needs to be updated to a V zone. No changes in mean minimum temperatures in January were found in 3 Spanish provincial capitals (Castellón, Córdoba and León). Mean minimum temperatures in January were found to have decreased in nine Spanish provincial capitals. However, the average decrease in mean minimum temperatures in January in these Spanish provincial capitals is -0.5ºC.

According to climate projections, mean minimum temperatures in January are expected to significantly increase in three representative Spanish provincial capitals. Madrid had a mean minimum temperature in January of 0.6ºC during the 1981-2010 period. Future climate projections for Madrid indicate a mean minimum temperature in January between 4.3 ºC (B2 scenario) and 4.1ºC (A2 scenario) by 2011-2040. This variable is expected to increase to 5.6ºC (B2 scenario) and 5.7ºC (A2 scenario) during the 2041-2070 period. Trends are emphasised in 2071-2100, when mean minimum temperatures in January are expected to be 6.7ºC, under A2 scenario, or 5.9ºC under B2 scenario. For Barcelona, mean minimum temperature in January has been estimated at 4.5ºC and it is predicted to be 7.0 ºC and 7.4 ºC for A2 and B2 scenarios, respectively, during the 2011-2041 period. By the end of the twenty-first century it could increase to 8.9 ºC (B2 scenario) and 9.5 ºC (A2 scenario). Finally, regionalised climate projections for Valencia indicate a future mean minimum temperature in January between 8.8 ºC (under B2 scenario) and 8.3ºC (under A2 scenario) during the 2011-2040 period. They are expected to increase to 10.9 ºC and 10.3 ºC for A2 and B2 scenarios, respectively, by 2100.

4. DISCUSSION

According to mean annual degree day calculations based on the 1981-2010 period (table 6), climate change due to global warming has already substantially modified climate conditions of approximately 10% of Spanish buildings (0.8% from E to D, 4.3% from D to C zone, 0.8% from C to B and 4.2% from B to A) (figure 6).

A thorough analysis of recent trends in mean minimum temperatures in January leads to the conclusion that approximately 8% of the buildings changed to a warmer zone (0.7% from Z to Y, 1.2% from Y to X, 1.7% from X to W and 4.8% from W to V) and approximately 4% of the buildings have changed to an area with a lower mean minimum temperature (1.1% from W to X, 0.9% from Y to Z and 2.5% from X to Y). Taking into account that 59% of existing residential building stock in Spain in 2010 was built before NBE-CT 79, almost 72% of current residential building stock in Spain is thermally unprotected according to current climate conditions. More than seven million Spanish residential buildings are suitable candidates for energy related refurbishment of their fabric (figure 7).

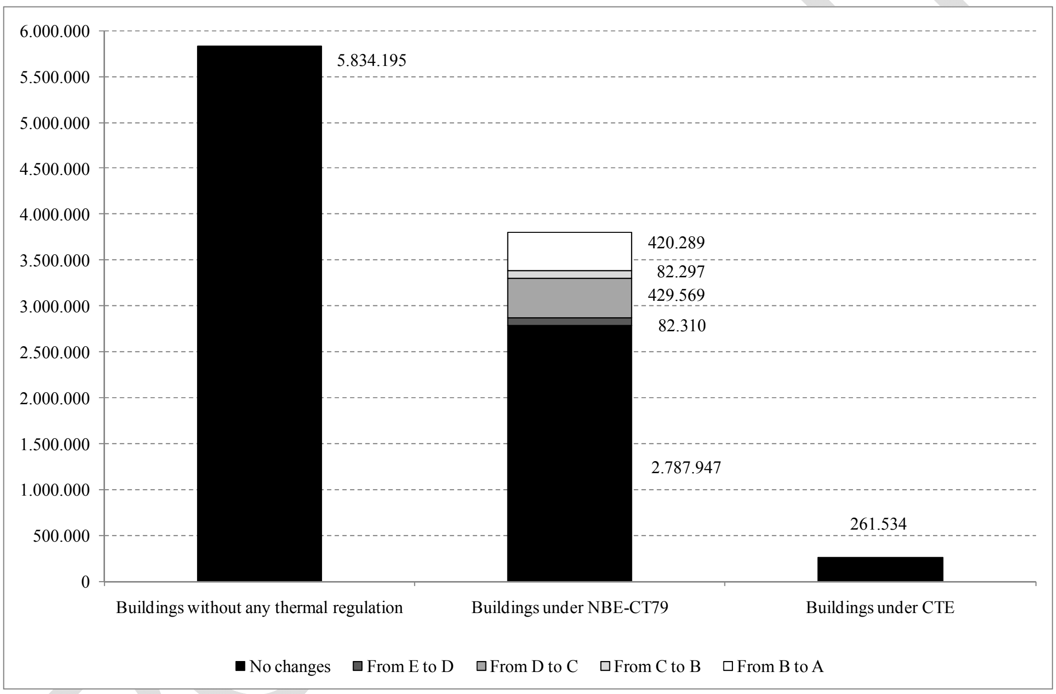


Fig. 6. Existing residential building stock in Spain according to building thermal regualtions and climate zoning based on mean annual degree days based at 15ºC (2010).

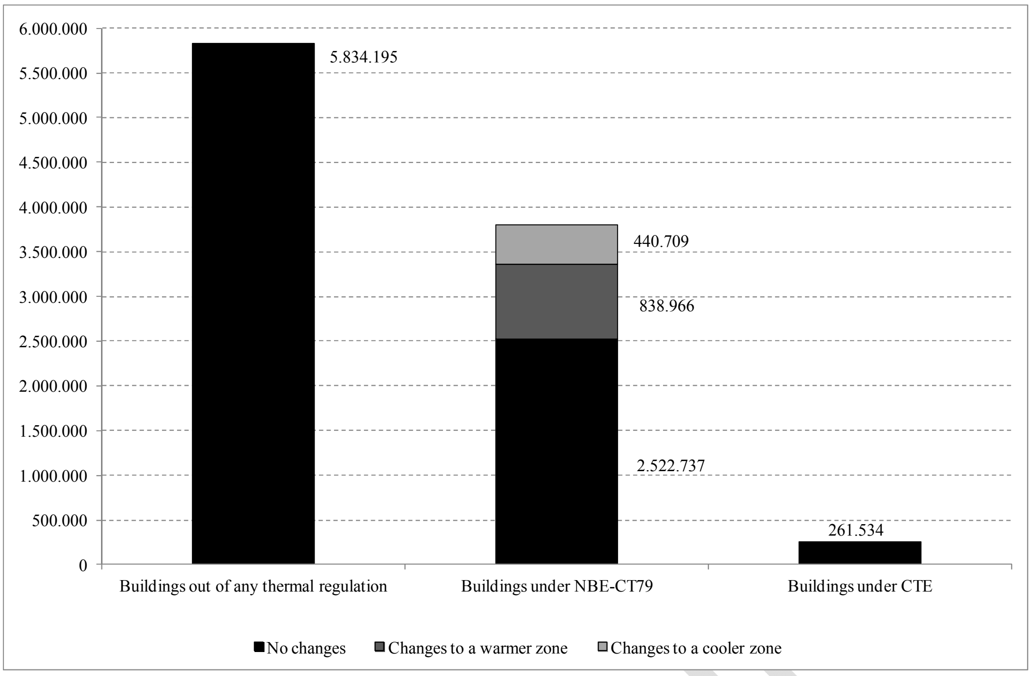


Fig. 7. Existing residential building stock in Spain according to building thermal regulation and climate zoning based on mean minimum temperatures in January (2010).

This research has demonstrated that predicted future climate will reduce energy demand for space heating in buildings during winter. Accordingly, calculations for Madrid indicate an expected decrease in heating degree days of around 11.5% for the 2011-2040 period regarding meteorological data used as the basis for NBE-CT 79 (1950-1979 period). During the following period (2041-2070), decrease in heating degree days is estimated at approximately 20% for A2 scenario and 18% for B2 scenario. Finally, heating degree days are expected to decrease by 34% under A2 scenario and 30% under B2 scenario during the 2071-2100 period. Similar figures were also found for Barcelona and Valencia. By the end of the twenty-first century, maximum decreases in heating degree days are expected under A2 scenario and they reach 37% for Valencia and 34% for Barcelona. A thorough analysis of expected trends in mean minimum temperatures in January also corroborates these findings. Thus, results show that the energy demand for heating the building sector in Spain could decrease between 30% (Barcelona, B2 scenario) and 36% (Valencia, A2 scenario) by 2100.

However, higher summer temperatures are expected to have implications for human comfort, from irritability to more severe consequences, even death. Salagnac (2007) demonstrated a correlation between the increase of the French death rate and temperature curves during the 2003 extreme heat wave. Temperature trends observed between 1950 and 2010 and future projections for 2011 to 2100 indicate a significant increase in cooling degree days. Regarding Madrid, cooling degree days are expected to rise from 87% (B2) (figure 5) to 93% (A2) (figure 6) during the 2011-2040 period in relation to the 1950-1979 period. These rates are estimated to further increase to 166% (A2) and 142% (B2) in the following period (2041-2070) (figures 5 and 6). Again, the maximum increase in cooling degree days is expected for the 2071-2100 period under A2 scenario (296%), whereas this rate is expected to be 216% under B2 scenario (figure 5 and 6). Similar results were found for Valencia and Barcelona. In relation to the 1950-1979 period, increases in Valencia are likely to stay at 149% under A2 scenario and 107% under B2 scenario by the 2071-2100 period. According to the simulations, Barcelona is likely to experience higher increases in cooling degree days by the end of the twenty-first century. The lowest prediction is for B2 scenario, with an estimated increase of 176%, whereas the highest prediction is for A2 scenario, with an expected increase of 248 %. Thus, results show that the energy demand for cooling could increase between 107% (Valencia, B2 scenario) and 296% (Madrid, A2 scenario) by 2100.

In light of the abovementioned figures and in order to achieve a real and effective adaptation of the current and future built environment, adaptation will need to include future building codes and standards. Options for policy-makers to revise the current building codes and standards are discussed below.

Update climatic design values in codes and standards.

In order to improve the future adaptation potential of buildings, it is important to consider recent climate change impacts when updating building codes and standards (Lisø et al., 2003). Current building regulations have been developed using historical climate data, and are based on the assumption that climate norms will continue over the whole lifespan of the building. However due to climate change, this assumption is no longer valid. Both the recently observed trends in temperature and the global warming predicted by climate models for the twenty-first century pose a major threat for indoor comfort and energy efficiency of buildings. Meteorological data currently used in building thermal regulations may compromise future indoor thermal comfort levels. Within a changing climate context, it will be necessary to anticipate medium and long term climate variations. A periodic updating of weather data used for building design is required in order to avoid uncomfortable indoor conditions and prevent an underestimation of cooling energy demands. The challenge is for the design of new buildings to be sufficiently flexible to adjust to changing conditions in the coming decades.

Methodologies to incorporate climate change scenarios into climate zoning should also be developed. The use of a climatic correction factor could facilitate the adoption of an adaptation approach in building codes and standards. This could assist with the updating of climatic design values based on recent observed trends. In this sense, ensuring weather data quality and long-term records of climate observation networks is of vital importance. In addition, this correction factor could incorporate future expected climate trends derived from regionalised climate change projections. Alternatively, uncertainties can be accommodated by using ranges of values (minimum, average, maximum). Embedding a long term horizon in building codes and standards is an appropriate strategy to enhance buildings' adaptive capacity. However, the reduction of uncertainty in regionalised climate change projections is an essential prerequisite.

Expand codes for summer climates

Recently observed trends in temperature and global warming predicted by climate models for the 21st century recommend inclusion of summer situations in building codes in warmer climates. The analysis of maximum summer temperatures is highly relevant as it would indicate whether the building fabric and cooling equipment are appropriate for increasing temperatures. It could promote passive approaches to indoor thermal comfort.

Although the Spanish Technical Building Code (Spain, 2006), enacted in 2006 accounts for both winter and summer situations, U-value requirements in façades and roofs are not subject to summer situational conditions. Thermal insulation thicknesses based only on heating degree days may be insufficient during the cooling period. For the cooling season, limitations are only placed on fenestration solar factor according to internal heat loads, and building orientation. Recently observed trends and future projections in cooling degree days suggest there is a need to provide new U-value requirements for summer situations in future revisions of building codes and standards. This applies especially to southern European climates where annual cooling requirements are becoming equal or dominant compared to annual heating requirements. Better insulation in roofs is especially important since the roof is heated by both outdoor ambient temperature and direct solar radiation. Thus, ensuring effective thermal insulation in regions where cooling demands are likely to rise is a significant adaptation issue.

Redefine base temperatures

The definition of comfort level plays an important role in adapting buildings to predicted warming through building codes. Both heating and cooling degree days are defined in the Spanish Technical Building Code using a base temperature of 20ºC. Base temperatures represent the temperature where energy consumption is at its minimum. Recent research has shown that human thermal comfort extends over a wider temperature range which allows for flexibility in the establishment of set point temperatures (Nicol, 2011; Cole et al 2008). By increasing the base temperatures (without exceeding thresholds for indoor thermal comfort), cooling degree days decrease significantly. Therefore, keeping base temperatures high contributes to potential savings in cooling energy, particularly in buildings located in warm zones. However, it must be taken into account that increasing base temperatures will have a direct linear effect on heating degree day values. Thus, the use of different base temperature for calculating heating and cooling degree days is recommended.

Include other climatic variables

Climatic zoning in the old Spanish building thermal regulation was based on mean yearly degree days. Besides including a seasonal perspective, the new Spanish Technical Building Code also introduced the solar radiation (or the number of sun hours), which also has an important impact on cooling and heating energy demands in buildings. These variables are included in the concepts of winter climatic severity and summer climatic severity. It is assumed that two similar buildings located in two different zones but with the same winter climatic severity will have similar energy heating demands. Correspondingly, two similar buildings located in two different zones but with the same summer climatic severity will have a comparable energy cooling demand. However, the inclusion of other commonly available climatic variables (such as daily amplitude of temperatures, average relative humidity, number of days with precipitation, wind speed, etc.) for a more detailed climatic zoning should also be discussed. By way of example, Erell et al. (2003) proposed a methodology for better mapping climate regions in Israel. Their summer zoning approach included mean daily temperature, daily amplitude of temperatures, solar radiation, and average relative humidity while the winter zoning approach considered mean daily temperature during the coldest month, amplitude of temperatures, solar radiation, and the number of rain-days (Erell et al., 2003).

Define local climatic zones

According to the Spanish Technical Building Code, all locations in a province belong to the same climatic zone as its capital. Instead of dividing the country into several zones, winter and summer climatic severities should be specifically calculated for each location. Building codes and standards based on appropriate climatic zoning may serve a valuable role. As suggested by Lisø et al. (2006), Lisø et al. (2007) and Almås et al. (2011), Geographical Information System (GIS) can be a useful tool for that purpose. The appropriate climate zone for each locality should be determined based its own climatic records. If climatic records are unavailable for a particular location, then climate characteristics of nearby locations could be used, but adjusted for altitude differences, etc.

Apply the adaptive model of thermal comfort

The rationale of most building codes and standards is derived from static thermal models, which view occupants as passive recipients of thermal stimuli. In static models, optimum indoor thermal comfort is achieved within a relatively constant narrow band of temperature. However and according to the point of view of adaptive thermal models, the perception of comfort is not a fixed condition (Nicol, 2011) as humans can adapt and tolerate different temperatures with behavioural, physiological and psychological adjustments. Widening the acceptable range of thermal comfort offers great potential for conserving energy in buildings (Kwok and Rajkovich, 2010). Adaptive thermal comfort can also be used by building designers to make buildings more resilient towards climate change (Cole et al. 2008). In order to incorporate adaptive thermal comfort approaches into national standards and building codes, guidance provided in European adaptive standard EN 15251:2007 (CEN, 2007) may be useful.

Include minimum thermal requirements for major building renovations.

Given that first regulations containing specific energy requirements for new buildings were issued in some countries such as Spain or Italy (Sivestrini and D'Apote, 2006) at the end of the 1970s, the majority of current building stock has poor thermal characteristics. Due to the longevity and renovation cycle of existing buildings, there is significant scope for existing buildings to be thermally upgraded. This could be achieved through a regulatory requirement for compliance with current thermal codes and standards when major renovations occur. Although current building regulations and other instruments are mainly focused in newly built buildings (Meijer et al. 2009), future codes should address major renovations in existing buildings by including requirements for minimum levels of performance. Standards including maintenance practices should also be developed in order to minimize changes in buildings' internal environment.

Reduce vulnerability to increased temperatures
In addition to improved insulation values in existing residential buildings, other strategies to minimise indoor overheating can be promoted by future building codes and standards. Adaptation efforts will mainly depend on technological and financial limits. Within this context, different approaches involving different intervention levels can be adopted:

- Minimum interventions may include insulation of cavity walls, increasing existing insulation thicknesses or replacing the existing insulation material by another one with higher thermal performance.
- The provision of transient or permanent shading using vegetation, curtains, blinds, shutters, awnings and other shading devices in south and west facing windows also helps to reduce the vulnerability of the existing built environment to increased temperatures. Low emissivity paints will also reduce heat transfer rate through building structures.
- Other refurbishment actions involve more invasive works such as adding extra insulation to building facades. Internal insulation involves fixing insulation to inner surfaces of external walls whereas external insulation involves fixing insulation materials to the outer surface of wallsInternal insulationwill slightly reduce net usable area and its installation will cause disruption to inhabitants. Retrofitting of existing facades (regardless of whether external or internal insulation is chosen) requires technical expertise and contractors' attention to detail, as well as careful consideration of the context, especially in cases of dense urban fabrics. Other strategies for adapting the urban environment to unavoidable increased temperatures also include window replacement, which is currently being funded by the Spanish government. The use of high performance glazing is also an effective way to reduce internal temperature variation. Refurbishment actions for improving thermal performance of roofs vary depending on the roof typology.
- Higher intervention levels may involve substantial changes in the existing buildings. Highly invasive actions include upgrading windows to a design allowing better air movement.

The transmission of internal heat loads occur much less through a highly insulted envelope than a lower insulated envelope. As a result, in cases of extended hot periods, heat may remain trapped inside buildings. Approaches to dissipate the internal heat load and cool internal spaces must include passive measures such as night cross-ventilation in order to avoid the need for air conditioning. Concurrent mixed-mode operation of operable windows and high efficient mechanical systems can also help reduce summer overheating. Similarly, reducing internal loads due to appliances and lighting also diminishes uncomfortable indoor overheating conditions. In any case, thermal insulation plays a considerable role as a risk-reduction factor in case of heat waves. According to Salagnac (2007), the odds ratio is decreased by a factor of 5 between non-insulated and insulated dwellings. Given that external climate conditions determine cooling demands to a large extent, promoting cost-efficient refurbishment measures will also allow an important reduction in energy consumption and related GHG emissions in residential buildings. This is highly relevant because improvements alone on new buildings (those affected by the Spanish Technical Building Code) are insufficient to reduce energy consumption in the building sector and the corresponding GHG emissions. This will slow down increases in both energy consumption and GHG emissions, but it will not decrease them.

5. CONCLUSIONS

Results from this research presents evidence, for the first time, of the Spanish building stock's vulnerability to summer overheating. This is due to the existing climate zone shifting (becoming warmer in both the winter and summer) and the the age, the typology and physical quality of the existing Spanish residential stock.

Detailed analysis of historical weather data confirms significant warming trends for both winter and summer temperatures across Spain's different climatic zones. Based on heating degree days, the energy demand by 2100 for winter heating is expected to decline by 30% for Barcelona, 34% for Madrid and 36% for Valencia (compared to 1950-79) but cooling degree days are expected to increase dramatically (216-296% for Madrid, 176-248% for Barcelona). This has several implications:

- the current regulations are based on inaccurate weather data and therefore are inappropriate particularly for current conditions
- the warming trend will have significant impacts for cooling on both existing and new buildings over the next 100 years
- building regulations based on static, historical climate data cannot reflect the conditions over the whole lifespan of the building
- a periodic updating of weather data used for building design and regulatory requirements is needed

Detailed recommendations are provided for Spain's climate adaptation policies to reduce vulnerability in its building stock:

- expansion of regulatory codes to address summer climates
- redefine base temperatures for flexibility and adaptive comfort
- include a wider range of climate variables
- provide more local climate data and require conformance to local conditions
- require minimum thermal standards for existing buildings
- promote specific passive measures to reduce the need for cooling

The results provide valuable information for energy policy and planning in Spain. Based on the analysis of future trends in heating and cooling degree days for Spain.
Regulatory instruments hold the potential to prevent or reduce adverse effects derived from increased temperatures. By including adaption measures in present building codes and standards, it will enhance future resilience to cope with a changing climate from the very beginning (design stage) and thus, the adaptation costs are significantly minimized. Updating thermal standards for buildings will reduce the sensitivity of the internal environment to a warming climate and therefore reduce occupant vulnerability. particularly by reducing extreme peak internal temperatures. It will also improve energy performance of buildings in warm climates by reducing cooling energy demand and assist with meeting the carbon emission reduction targets. However, next-generation building codes and standards must be enough flexible to allow for innovations contributing to building stock resilience, by enhancing the new concept of Climate Impacts Prevention through Design (CIPtD), in which engineers and architects explicitly consider, during the design process, potential climate change impacts on buildings.

Strategies for adapting future buildings to climate change through building codes have been suggested using a top-down approach. Updating U-value requirements according to summer situations in future revisions of building codes and standards is indispensable especially for southern European climates. Building codes and standards based on appropriate climatic zoning may serve a valuable role in adapting future buildings to a changing climate. Results obtained in this investigation recommend updating the historical climatic design information with observed trends and uncertainties of future projected climate changes in building codes and standards. A more detailed climatic zoning could be achieved by using other climatic variables in addition to temperature and solar radiation.

In order to reduce the vulnerability of the existing built environment to increased temperatures, future building codes and standards should promote improving insulation levels in existing residential building envelopes while including requirements for minimum levels of performance of retrofit components.

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Endnotes

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[1] AEMET is the authority responsible for compilation of meteorological data in Spain. Founded in 1887, the AEMET observation network currently includes 90 staffed observatories and 700 automatic weather observation stations.

[2] Unfortunately, no long term series of registered climatic variables are available for Tarragona, one of the 50 Spanish provincial capitals.

[3] This number includes both single-family houses and blocks of flats.

[4] Walls were often comprised of limestone or granite. In some cases, load-bearing walls were made of single-brick (coated or uncoated). Occasionally there is a secondary interior brick skin wall.