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TECHNICAL PAPER

The impact of building energy codes evolution on the residential thermal demand

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Abstract

The building stock decarbonization by 2050 requires the implementation of an energy transition strategy. Building energy codes must be considered to minimize the energy consumption of the residential sector. This paper aims to evaluate the evolution of the building energy codes of Spain based on energy simulation. A quantitative assessment of the residential thermal demand according to the new energy efficiency requirements introduced in national regulations over the years was performed. Heating, cooling, and domestic hot water demands were assessed for 60 cases modeled in DesignBuilder, combining different building geometric typologies, energy codes, and climate zones. Heating presented the largest contribution to the total energy demand reaching up to 75%. The codes' evolution led to a significant reduction in heating and a slighter decrease in cooling. The results showed an average energy demand improvement of 50% from the first regulatory release to the latest one.

Keywords Energy simulation · Energy efficiency · Building energy codes · Thermal demand · Residential sector

1 Introduction

The residential sector accounts for 28% of global carbon dioxide emissions and 30% of global final energy consumption, figures that rise to 38% and 35%, respectively, if the contribution of the construction industry is also accounted for. In 2019, these percentages presented an energy consumption of 151 EJ and an emission of 10 $GtCO_2$ due to buildings' direct and indirect impact [1, 2]. Moreover, buildings accounted for 57% of final energy consumption and 32% of CO_2 emissions in Africa, 26% of final energy consumption and 24% of CO_2 emissions in Southeast Asia, and 24% and 21% of energy consumption and emissions, respectively, in Central and South America. In Europe, buildings were responsible for 40% of energy consumption and 36% of CO_2 emissions, with similar figures in the USA [3]. Although the building impact varies according to the geographical region considered, its contribution is relevant worldwide.

The decarbonization of the building stock by 2050 requires the development of roadmaps and the implementation of energy transition strategies that include regulatory changes and support for investments in energy efficiency for existing buildings. Therefore, building energy codes (BECs) come out as an essential instrument to reduce building energy consumption, especially if they are mandatory and enforced by the local government [4]. Energy codes use energy standards as the technical basis for specifying how buildings must be constructed or performed in order to save energy effectively, with some variations according to the regional climate [5]. Furthermore, using renewable energy sources, such as solar energy [6] and biomass [7], is another way to move forward decarbonization since they are replenished by nature and emit little to no greenhouse gases.

Focusing on the European level, in 2002, the first Directive on Energy Performance of Buildings was enacted —Directive 2002/91/CE— [8], later modified first by Directive 2010/31/EU [9] and then by Directive (EU) 2018/844 [10]. This Directive led to a progressive tightening of regulations regarding the thermal envelope of buildings in the EU countries. Therefore, all EU countries approved regulatory changes to achieve nearly zero energy buildings (NZEBs) for all-new residential, office, and service buildings by 2020. NZEB is defined as a building with a very high-energy

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performance, where a very low-amount of energy required should be covered as much as possible by renewable energy sources [11]. Nevertheless, the design of sustainable buildings is not a simple task, as it must achieve such high levels of performance [12]. Thus, higher efforts on new policies must be made over the next years to reach a building stock (new and existing) decarbonized by 2050. To achieve this goal, thermal demand reduction is a key point, which can be achieved by improving the thermal envelope established on the BECs [13].

Previous studies have analyzed the effect of new BECs on building energy efficiency in different countries, such as India [14], several states of the USA [15], and other comparative studies in neighboring countries with similar climate conditions [16, 17]. In particular, Bianco and Marmori [18] presented a novel bottom-up model, based on the definition of building archetypes to estimate energy consumption evolution in the Italian residential sector according to four different energy efficiency scenarios. Merini et al. (2020) [19] examined the thermal demands in a single reference building by comparing the current regulations of Morocco and Spain in a single climate zone (similar in both countries) using DesignBuilder as a simulation tool. Monzón-Chavarrías et al. [20] used the official national tools to quantify the reduction obtained in demand, energy consumption, and CO_2 emissions by implementing different refurbishment solutions in an old housing block to comply with current Spanish and Portuguese regulations, considering two different climate zones in each country. Gangolells et al. [21] made an energy mapping of the Spanish building stock, analyzing nearly 130,000 energy performance certificates collected from a specific Spanish Region (Catalonia). Additionally, Cerezo-Narváez et al. [22] used the TRNSYS simulation tool to quantify energy savings achieved by upgrading an old single-family house in Andalusia (south of Spain) to the latest national building energy code. Likewise, Gesteira et al. [23] performed a simulation in TRNSYS to estimate the demand of a single-family townhouse located in Almeria, on the Mediterranean coast of Spain, meeting the national BEC requirements.

Other studies have investigated innovative solutions for promoting building energy savings. In this framework, Ebrahimi-Moghadam et al. [24] proposed five types of light shelves as a passive-enhancement method for building energy saving. The results revealed that the light shelves caused an annual average improvement of 18%, 11%, and 7% in the building demand for heating, cooling, and electricity, respectively. Gasparin et al. [25] developed an innovative non-uniform adaptive method to determine the optimal insulation thickness of external walls as thermal insulation can reduce energy consumption associated with heating or cooling in buildings. The method improved in 25% the building's thermal efficiency. Sadripour et al. [26] used a ceiling fan with a central heating system during the winter to save energy inside a building. The effective room temperature increased by 0.35 °C, which could be used to reduce the radiators' temperature, thereby reducing 37% of energy consumption. Vaishnani et al. [27] computationally modeled a cross-ventilation system with asymmetric openings positions to examine the effects of natural ventilation in a wind-driven system. The provision of natural ventilation in buildings is associated with reductions in energy consumption with HVAC systems by the circulation of air within the building, without the help of any mechanical systems.

Over the past years, new BECs have been launched worldwide. They establish minimum energy-efficient design and construction requirements and outline uniform requirements for new buildings as well as additions and renovations. Furthermore, the BECs drive the innovation of new energy-efficient solutions forward. In this work, a significant number of building types, climate zones, and BECs from the last 50 years in Spain were computationally simulated. Despite their importance, to date, previous studies have not assessed the evolution of BECs applied to residential buildings over such a long period. In fact, they considered only regulatory changes in recent years.

This paper aims to propose a procedure based on an energy simulation tool (DesignBuilder) to assess heating, cooling, and domestic hot water thermal demand of residential buildings according to the evolution of the national building energy code requirements. To this end, the following specific objectives are proposed:

- Propose a procedure that can be easily replicated in any country.
- Apply the proposed procedure to a case study (Spain), selecting a comprehensive set of building types and climate zones.
- Model a set of representative buildings using an energy simulation tool commonly used in the architecture field to estimate the demands.
- Analyze the building thermal demands for heating, cooling, and domestic hot water (DHW) broken down by building type, climate zone, and BECs in the last 50 years.
- Assess whether the BECs contribute to achieving thermal demand reduction.

2 Materials and methods

This section describes the procedure proposed to assess the residential thermal demand according to the national BEC evolution. The procedure can be summarized in the following steps:

1. Selecting representative climate zones and climate data.
2. Setting the period to be analyzed and the corresponding BECs.
3. Defining the building clusters.
4. Assigning constructive solutions.
5. Defining the usage profile.
6. Estimating the air renewal rate.
7. Modeling, simulating and analyzing the results.

First, it is necessary to identify the most representative climate zones of the country. The zone selection can be based on criteria such as the area covered or the local population. In case of official climate zoning lack, the Köppen–Geiger [28] climate classification can be used as a reference. This classification sets five climate types subdivided into thirty types depending on outside temperatures, rainfall, and local vegetation. The climate data are based on the synthesis of weather data collected over long periods (usually between 10 and 30 years). The main climate variables of a typical year for each zone can be obtained by a variety of free or paid databases, such as EnergyPlus weather data [29], NOAA's National Centers for Environmental Information (NCEI) climate data [30], and Meteonorm [31]. In general, the energy simulation tools require input temperature, humidity, solar radiation, and wind parameters on an hourly basis for an entire year.

The next step is defining the period to be analyzed and the BECs under effect during this time. It must consider the regulatory updates that directly or indirectly affect the building energy efficiency. BECs cover the building itself, for instance, the walls, floors, ceiling insulation, windows, and air leakage. However, some regulatory changes regarding accessibility, building structure, fire safety, etc., can be ignored during this analysis.

The definition of the representative building stock can be done through the population and home census. Besides, it is possible to find international data hubs, including information about thermal quality, size, age, and type of buildings from different countries [32], such as the ENTRANZE [33] and ODYSSEE [34] databases. The building stock is divided into different typological clusters considering each constructive characteristic: building conditioned surfaces, number of dwellings per building, number of people per dwelling, number of floors, the height of each floor, the orientation of the main façade, the surface area of each element of the thermal envelope (façades, floors, roofs, and openings), etc. It allows the geometric modeling of the representative building of each cluster.

Based on the BECs already selected and the building typology considered, constructive solutions can be assigned to each building. In particular, the main constructive solutions are: materials (layer by layer), thermal transmittance value (U-value) for each element of the building's thermal envelope, window transmittance to solar energy, commonly known as a solar factor (g-value), as well as the window-to-wall ratio on each façade. All these data determine the building's one-dimensional thermal losses. Additionally, to calculate two- or three-dimensional losses, it is necessary to set the linear thermal transmittance value (ψ) of the thermal bridges for each BEC and building type.

The next step is defining the usage profile. It is based on ordinary operating and occupancy conditions. At this point, it is necessary to set the working hours and temperature setpoints for heating and cooling, as well as the internal loads (W/m^2) related to occupancy, lighting, and other equipment. In addition, a daily reference demand (l/day) and an hourly profile for the domestic hot water service must be established. All these data related to the user profile can be obtained from the literature or national standards and regulations.

Another relevant input data for the building energy modeling are the air renewal rate due to ventilation and infiltration. Ventilation is the controlled air renewal to ensure indoor air quality, while infiltration is the uncontrolled air renewal depending on the thermal and pressure gradient between the inside and outside of the building and the air permeability of the opening elements (windows and doors) of the thermal envelope. The air renewal data can be obtained from the literature or national regulations. It is presented as the number of air changes per hour (ach) or airflow (m^3/h or $m^3/h\cdot m^2$).

Finally, the total number of simulations can be obtained through the number of building types, BECs, and climate zones. In order to organize the simulation process and the result´s analysis, it is convenient to establish a unique code for each simulation case using a set of alphanumeric characters. Several simulation tools can be chosen to estimate the building thermal demand. Most simulation tools calculate the heating and cooling demands through a heat balance considering:

- Thermal losses or gains through the walls, glazing, roof, floor, and thermal bridges.
- Thermal losses or gains associated with ventilation and infiltration.
- Solar gains through glazing and internal gains due to lighting, equipment, and occupancy.

Different calculation methods [35, 36] and modeling and simulation tools [37–39] have been developed and adopted for building energy modeling (BEM). Although they differ in their engine (data modeling, algorithms, hypothesis, etc.), their results are consistent and reliable even if they present some variations among them. Some authors have widely explained these issues [40–46]. Table 1 presents the main features of the most commonly used energy simulation tools

Table 1 List of energy simulation tools for buildings worldwide

Software	Developer	Country	Overview	Type	Engine	References
EnergyPlus	NREL, various DOE national laboratories, academic institutions, and private firms	US	Modeling energy consumption, lighting, plug and process loads, and water use in buildings, including plant integration with heat balance-based zone simulation, multizone air flow, thermal comfort, and photovoltaic systems	Free	DOE-2 and BLAST	[47, 48]
eQUEST	DOE	US	Detailed comparative analysis of building designs and technologies, including energy cost estimating, daylighting and lighting system control, and automatic implementation of energy efficiency measures	Free	DOE-2	[49, 50]
ECOTECT	Autodesk	US	Visual architectural design and analysis tool covering thermal, energy, lighting, shading, acoustics, and cost aspects	Paid discontinued	Self	[51, 52]
TRNSYS/ TRNBuild	University of Wisconsin	US	Detailed multi-zone building model and components for HVAC systems and renewable energy systems. Building input data entered through a dedicated visual interface (TRNBuild)	Paid	Self	[53, 54]
HEED	University of California	US	Easy to use tool that quickly compares multiple design alternatives with few input data, displaying a wide array of graphic outputs	Free	Self	[55]
SUNREL	NREL	US	Hourly building energy simulation program that aids in designing small energy-efficient buildings	Free discontinued	Self	[56]
HAP	Carrier	US	Designing systems and sizing system components as well as modeling annual energy performance and energy costs	Paid	Self	[57]
ESP-r	University of Strathclyde	Scotland	Modeling heat, air, moisture light, and electrical power flow at user-specified spatial and temporal resolution	Free	Self	[58, 59]
BSIM	University of Aalborg	Denmark	Simulating and calculating thermal indoor climate, energy consumption, daylight conditions, synchronous simulation of moisture and energy transport in constructions and spaces. Calculation of natural ventilation and electrical yield from building integrated photovoltaic systems	Paid	Self	[60, 61]
IDA-ICE	EQUA Simulation AB	Sweden	Detailed and dynamic multi-zone simulation application for the study of indoor thermal climate as well as the energy consumption of the entire building	Paid	Modelica based	[62, 63]
IES-VE	IES	Scotland	Analysis tools for the design and retrofit of buildings. It provides building and system designs, allowing them to be optimized concerning comfort criteria and energy use	Paid	Self	[64, 65]

for buildings worldwide. It also includes references to some studies where these tools have been used.

The thermal demand results obtained for each typology, BEC, and climate zone are analyzed and compared. Considering the size difference among the buildings analyzed, the ratio between the thermal demand and the building area can be used to levelize the results. The breakdown of the thermal balance can also be studied to identify possible improvements for the future.

3 Case study

In this section, the proposed procedure is applied to the case study of Spain, which was selected due to its variety of climate zones and relevant regulatory updates in the past 50 years.

3.1 Climate zones and data

The climate zones were selected from the basic document of energy saving of the Spanish technical building code: DB-HE [66]. In Spain, there are 15 climate zones classified according to winter and summer climate severities, calculated based on degree-day patterns and solar radiation. Winter climate severity is divided into five ranges coded from A to E, being A the lowest and E the highest severity. In comparison, summer climate severity is divided into four ranges, from 1 to 4, the first is the lowest and the fourth is the highest severity [67, 68]. In this work, five cities located in five different climate zones were selected following the criteria of area and population. Additionally, all winter climate severities were included as heating demand is much higher than cooling in the Spanish residential buildings [69].

Therefore, the climate zones selected were Z1 (Almeria—A4), Z2 (Valencia—B3), Z3 (Santander—C1), Z4 (Zaragoza—D3), and Z5 (Burgos—E1). Table 2 shows a description of each climate zone. The hourly climate data were taken from the Meteonorm database for the energy simulation. These data are measured from meteorological stations in each selected city [31]. Furthermore, the average monthly temperature of the tap water for each city was also taken from the Spanish regulation [70] to calculate the domestic hot water demand.

3.2 Time period and BECs

In Spain, the national building energy codes have evolved in the past 50 years. During this period, five new milestones were launched proposing the improvement of the thermal envelope quality. In 1979, the first building standard was approved, reported on the NBE-CT-79 [71], which for the first time limited the heat losses through the building thermal envelope depending on the location. This regulation forced the introduction of minimum thermal insulation in new building envelopes. Twenty-seven years later, the previous building standard was replaced by the Spanish Technical Building Code [72] to comply with the first Directive on Building Energy Performance (Directive 2002/91/CE [8]). The amendments introduced by the Directive 2010/31/EU [9] led to the release of the Basic Document of Energy Saving of the Spanish Technical Building Code in 2013 [73]. In 2019, this document was updated [66], including the new requirements established in the Directive (EU) 2018/844 [10].

This paper considered four of five milestones, neglecting the last update as the BECs chosen were enough to analyze its evolution. Therefore, as shown in Table 3, the BECs were classified as S1 (before 1979), S2 (from 1979 to 2006), S3 (from 2007 to 2013), and S4 (from 2014 to 2019).

3.3 Building clusters and constructive solutions

The typological clusters definition regarding the residential building stock in Spain was based on the data collected from the Population and Housing Census [74]. Three building types were considered, T1 for a single-family semi-detached house, T2 for a small block of flats between party walls, and T3 for a medium/large block of flats. The main geometric characteristics for each case are detailed in Table 4.

The following figures present a 3D view (Fig. 1) and the floor plans (Fig. 2) of the building types considered.

Table 2 Description of the main climate conditions of the selected cities. *Source*: [31, 66, 70]

Zone	Z1	Z2	Z3	Z4	Z5
Location (climate zone)	Almeria (A4)	Valencia (B3)	Santander (C1)	Zaragoza (D3)	Burgos (E1)
Latitude	36°50′ N	39°28′ N	43°27′ N	41°39′ N	42°21′ N
Altitude above sea level (m)	0	8	1	207	861
Annual average outdoor temperature (ºC)	18.4	17.6	14.6	15.2	12.1
Horizontal global solar radiation (kWh/year)	1829	1615	1279	1656	1549
Average annual wind speed (m/s)	4.1	3.1	5	4.5	4.8
Average annual temperature of tap water (ºC)	15.7	14.6	12.8	13.3	10.1

Table 3 Period and national building energy code considered

BEC	S1	S2	S3	S4
Period	Before 1979	1979—2006	2007—2013	2014—2019
Regulation	No energy efficiency requirements	Basic Building Norm: NBE-CT 79 [71]	Technical Building Code: CTE-DB-HE 2006 [72]	Technical Building Code: CTE-DB-HE 2013 [73]

Table 4 Geometric characteristics of the three building types considered

Building type	T1	T2	T3
Type	Single-family semi-detached house	Small block of flats between party walls	Medium/large block of flats
No. of homes	1	12	80
Total number of people	4	48	240
Useful surface per dwelling (m^2)	110	100	70
Total conditioned area (m^2)	110	1200	5600
Total area (m^2)	165	1583	7190
Height per plant (m)	3	3	3
Total volume (m^3)	371.3	4750.2	21,568.8
No. of floors above ground	3 (2 + attic floor)	7 (6 + ground floor)	11 (10 + ground floor)
No. of floors below ground	0	0	0
Total building height (m)	7.5	21	33
No. of bedrooms per home	4	4	2
Orientation	North–South	North–South	North–South
Roof type	Pitched roof	Flat roof	Flat roof
Window-to-wall ratio, north façade (%)	10	10	10
Window-to-wall ratio, south façade (%)	15	15	15
Thermal envelope area (m^2)	178.4	1183.2	6191.2
Compactness[a] (m)	2.08	4.02	3.48
External shades	No	No	No

[a] *Compactness* is the ratio between the volume (m^3) enclosed by the thermal envelope of a building and the sum of the thermal exchange surfaces (m^2) of that envelope in contact with the outside air or the ground. It is expressed in m. The compactness of a building is a design variable that affects heat exchange through the thermal envelope, so the greater the compactness, the lower the heat loss through the envelope

The building types were modeled according to the requirements established in each BEC for each climate zone. As shown in Table 5, different U-values were considered for the thermal envelope elements based on the BECs and climate zones.

Additionally, the thickness of the thermal insulation and the window type for each climate zone was defined depending on the building age. Regarding the doors, only the outside doors were modeled, so for the internal doors, the same composition of the internal partitions was assumed. It is worth noting that the convective coefficients of inside and outside surfaces for each enclosure were calculated through the simulation tool algorithm.

Thermal bridges were also estimated through the linear thermal transmittance (ψi) based on the internal dimensions of the building types. The values of ψ_i were taken from the atlas of thermal bridges of the Spanish Technical Building Code [75] and the user manual of the energy certification software for existing buildings CE3x [76]. Table 6 shows the thermal bridge values according to the BECs.

In this study, the thermal demand of a set of 60 buildings was assessed due to the combination of three building types, four BECs, and five climate zones. Each case was coded using six characters: *TiSjZk*; being *i*, *j*, and *k* numerical values (1, 2, 3, etc.). *T*, *S*, and *Z* correspond to the building types, standards, and climate zones, respectively.

3.4 Usage profile

The usage profile considered is included in the Spanish regulation [66] and consists of the following aspects:

- Heating is available from January to May and from October to December, with a setpoint of 20 °C from 8:00 a.m. to 11:59 p.m., and 17 °C from 0:00 a.m. to 7:59 a.m.

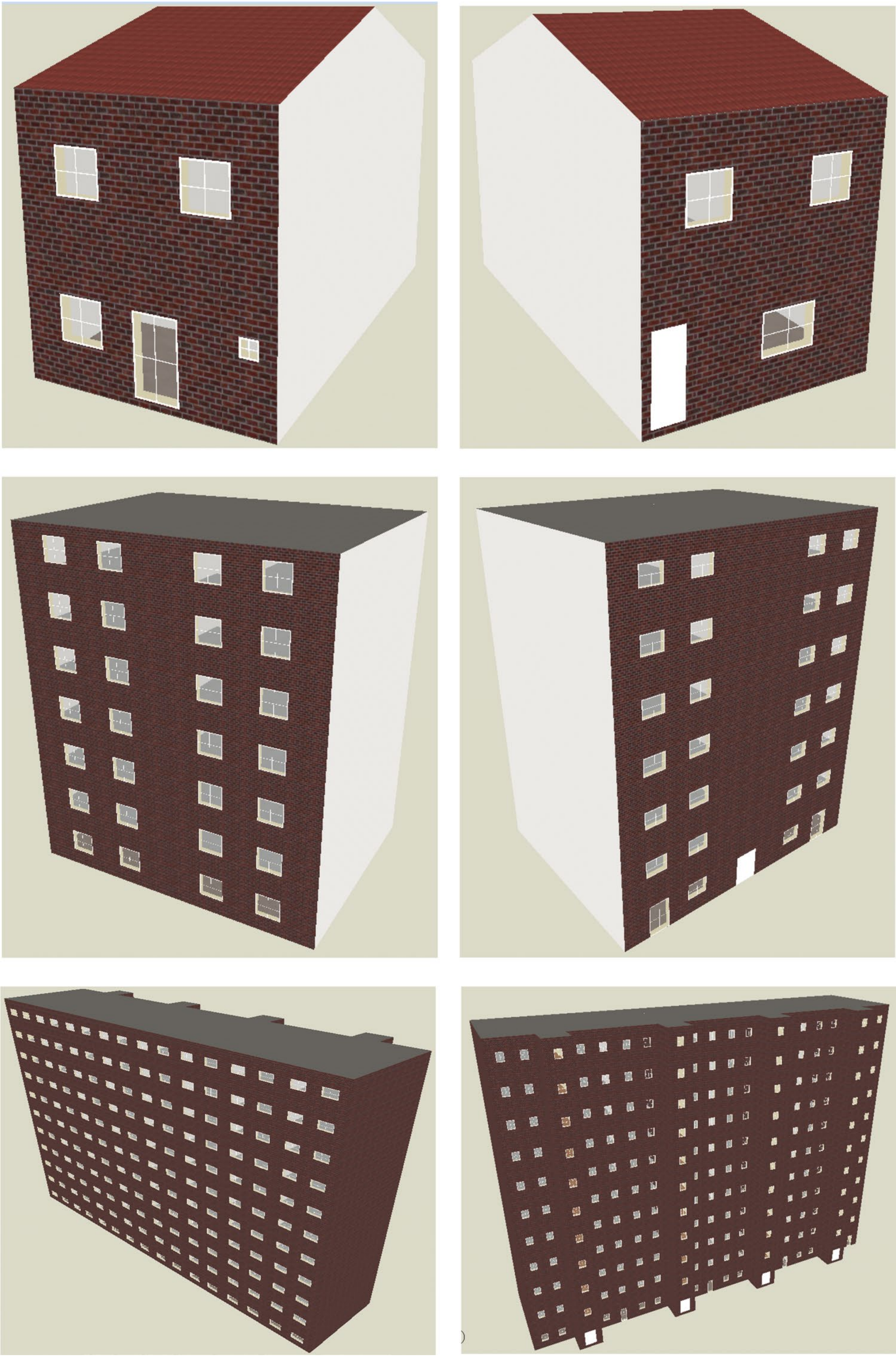

Fig. 1 3D view of the South façade (left) and the North façade (right) of the building types T1 (top), T2 (center), and T3 (bottom)

- Cooling is available from June to September, with a setpoint of 25 °C from 4:00 p.m. to 11:59 p.m. and 27 °C from 0:00 a.m. to 7:59 a.m. From 8:00 a.m. to 3:59 p.m., cooling is not available.
- A metabolic rate of 117.21 W/person and an occupancy density of 0.03 people/m^2 resulted in a thermal load per person of 3.51 W/m^2. The hourly distribution on working days is 100% from 0:00 a.m. to 7:59 a.m., 25% from 8:00 a.m. to 3:59 p.m. and 50% from 4:00 p.m. to 11:59 p.m. A 100% occupancy is considered 24 h a day on Saturdays and holidays. 61% of the occupancy load is sensitive, while 39% corresponds to latent load.
- Internal heat gains from equipment and lighting of 4.40 W/m^2 in both cases, according to the following

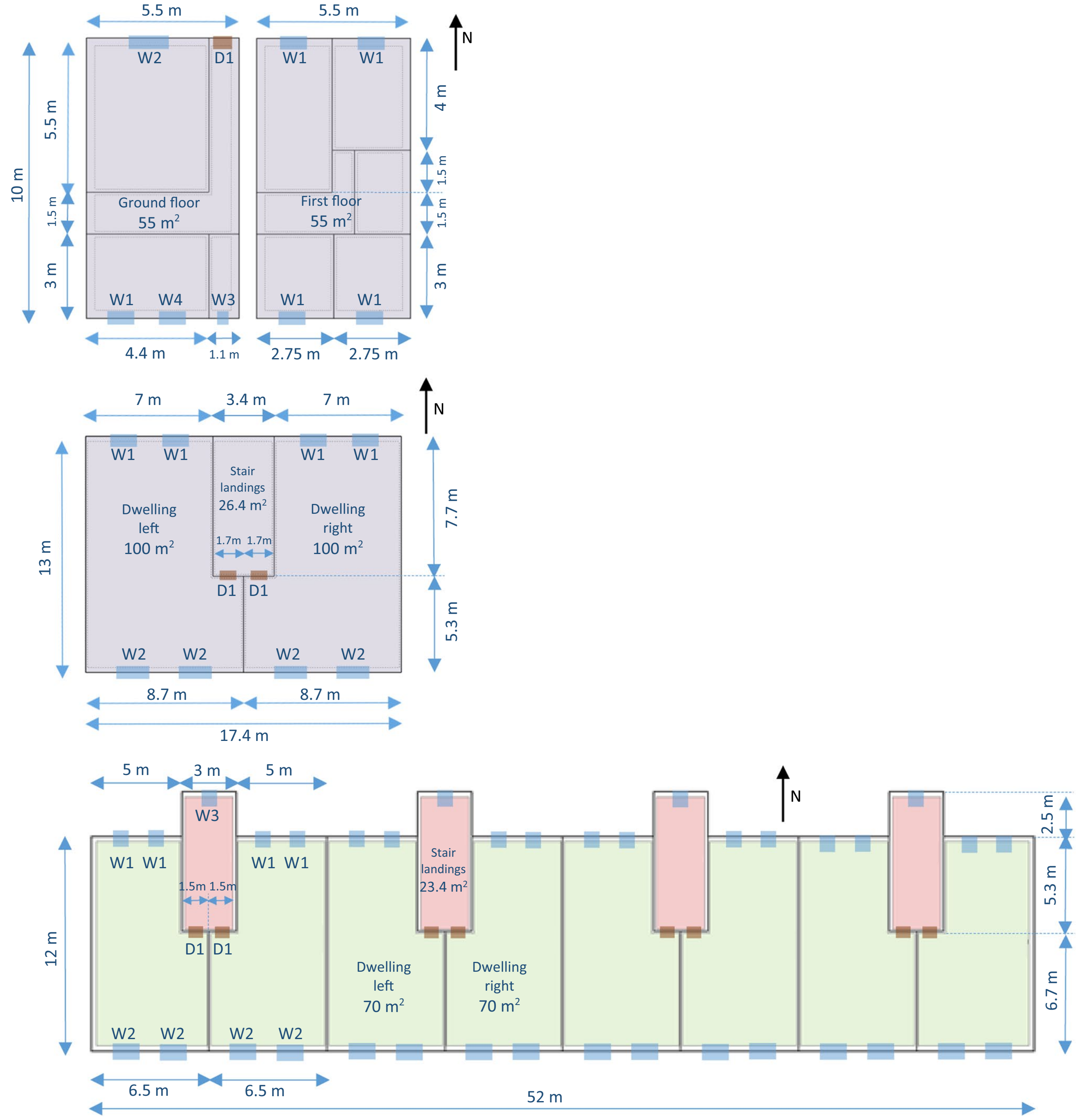

Fig. 2 Ground floor plan (left) and first-floor plan (right) of the building type T1[a] (above) and typical floor plan of the building types T2[b] (center) and T3.[c] (below). [a]Height from the floor of the plant (z) and windows dimensions (width × height) in T1: W1: z = 1 m, 1 m × 1 m; W2: z = 1 m, 1.3 m × 1 m; W3: z = 1.5 m, 0.4 m × 0.4 m; W4: z = 0 m, 1 m × 1.8 m. Doors dimensions (width × height) in T1: D1: 0.8 m × 2 m. [b]Height from the floor of the plant (z) and windows dimensions (width × height) in T2: W1: z = 1 m, 1.3 m × 1 m; W2: z = 1 m, 1.4 m × 1.4 m. Doors dimensions (width × height) in T2: D1: 0.8 m × 2 m. The ground floor in T2 consists of two premises instead of two dwellings, in addition to an entrance door (1.5 m × 2 m) to the portal-stairs and two doors (1.3 m × 2 m) for the entrance to the two premises. [c]Height from the floor of the plant (z) and windows dimensions (width × height) in T3: W1: z = 1 m, 0.8 m × 1 m; W2: z = 1 m, 1.46 m × 1 m; W3: z = 1 m, 0.7 m × 1 m. Doors dimensions (width × height) in T3: D1: 0.8 m × 2 m. The ground floor in T3 consists of four premises instead of eight dwellings, in addition to four entrance doors (1.4 m × 2 m) to the four portals-stairs and four doors (0.8 m × 2 m) for the entrance to the four premises

Table 5 Characteristic U-values (W/m^{2}K) of the thermal envelope of buildings depending on the climate zone and the BEC. *Source*: Author elaboration based on [71–73]

Element	S1	S2	S3	S4
External wall	Z1-Z5: 2.5	Z1: 1.8 Z2: 1.8 Z3: 1.6 Z4: 1.4 Z5: 1.4	Z1: 0.94 Z2: 0.82 Z3: 0.73 Z4: 0.66 Z5: 0.57	Z1: 0.50 Z2: 0.38 Z3: 0.29 Z4: 0.27 Z5: 0.25
Roof	Z1-Z5: 2.5	Z1: 1.4 Z2: 1.4 Z3: 1.2 Z4: 0.9 Z5: 0.7	Z1: 0.50 Z2: 0.45 Z3: 0.41 Z4: 0.38 Z5: 0.35	Z1: 0.47 Z2: 0.33 Z3: 0.23 Z4: 0.22 Z5: 0.19
Party walls and horizontal/vertical internal partitions between zones with different uses	Z1-Z5: 2.5	Z1-Z5: 1.94	Z1: 1.22 Z2: 1.07 Z3: 0.95 Z4: 0.86 Z5: 0.74	Z1: 1.25 Z2: 1.10 Z3: 0.95 Z4: 0.85 Z5: 0.70
Horizontal internal partitions between zones with the same use	Z1-Z5: 2.5	Z1-Z5: 1.6	Z1-Z5: 1.2	Z1: 1.80 Z2: 1.55 Z3: 1.35 Z4: 1.20 Z5: 1.00
Vertical internal partitions between zones with the same use	Z1-Z5: 2.5	Z1-Z5: 1.94	Z1-Z5: 1.2	Z1: 1.4 Z2: 1.2 Z3: 1.2 Z4: 1.2 Z5: 1.0
Ground floor	Z1-Z5: 2.35	Z1: 1.4 Z2: 1.4 Z3: 1.2 Z4: 0.9 Z5: 0.7	Z1: 0.94 Z2: 0.82 Z3: 0.73 Z4: 0.66 Z5: 0.57	Z1: 0.50 Z2: 0.38 Z3: 0.29 Z4: 0.27 Z5: 0.25
South-facing windows without obstacles (high solar gain) considering the window-to-wall ratio of 15%	Z1-Z5: 5.7	Z1-Z5: 5.7	Z1: 5.7 Z2: 5.7 Z3: 4.4 Z4: 3.5 Z5: 3.1	Z1: 2.6 Z2: 2.1 Z3: 1.9 Z4: 1.8 Z5: 1.9
North-facing windows without obstacles (low solar gain) considering the window-to-wall ratio of 10%	Z1-Z5: 5.7	Z1-Z5: 5.7	Z1: 5.7 Z2: 5.4 Z3: 4.4 Z4: 3.5 Z5: 3.1	Z1: 2.6 Z2: 2.0 Z3: 1.6 Z4: 1.4 Z5: 1.3

Table 6 Characteristic values of the linear thermal transmittance ψ_i (W/mK) of thermal bridges for the buildings according to the BECs. *Source*: Author elaboration based on [75, 76]

Thermal bridge	S1 & S2	S3 & S4
Junction Roof-Wall	0.44	0.25
Junction Wall-Ground floor	0.20	0.20
Junction Wall-Internal floor	0.60	0.20
The lintel above the window or door	0.80	0.1
Sill below window	0.50	0.1
Jamb at window or door	0.50	0.05

schedule: 10% from 1:00 a.m. to 7:59 a.m., 30% from 8:00 a.m. to 6:59 p.m., 50% from 7:00 p.m. to 7:59 p.m., 100% from 8:00 p.m. to 11:59 p.m. and 50% from 0:00 a.m. to 0:59 a.m. 90% of equipment load is sensitive, while 10% is latent. Regarding the sensitive part, 70% is transmitted by convection and 30% by radiation. On the other hand, lighting load is 50% transmitted by convection, 30% by long-wave radiation (thermal), and 20% by short-wave radiation (visible).

- A specific domestic hot water (DHW) demand of 28 l/person·day with a setpoint temperature of 60 °C.
- Same hourly profile of the DHW demand per day (see Fig. 3).

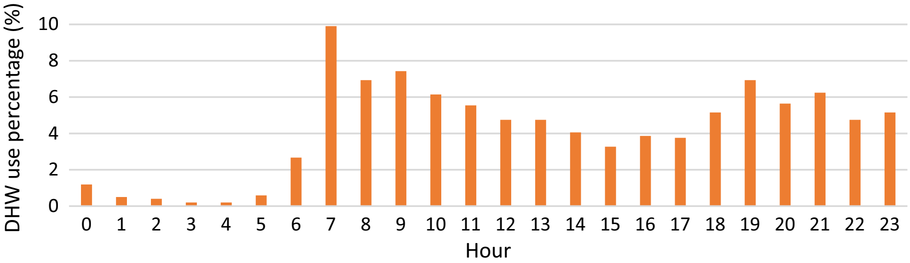

Fig. 3 Hourly profile of the daily DHW demand. *Source*: Author elaboration based on [76]

Table 7 Building ventilation rate (ach) considered based on the period and the building construction age. *Source*: Author elaboration based on [77–79]

Building type	S1	S2	S3	S4
June to September, 01:00 a.m.—08:59 a.m				
T1, T2 and T3	4	4	4	4
June to September, 09:00 a.m.—00:59 a.m. and October to May, 00:00 a.m.—23:59 p.m				
T1	0.63	0.63	0.69	0.40
T2	0.63	0.63	0.73	0.44
T3	0.63	0.63	0.67	0.46

The method reported in the Spanish regulation [66] was used to estimate the daily DHW demand for each building. It consists of multiplying the specific DHW demand by the number of people in each dwelling. In the case of housing blocks, this result can be corrected by a factor based on the number of houses in the block. Thus, for the T1 building, the daily DHW demand was 140 l/day = 28 l/person·day · 5 people (4 bedrooms). For the T2 case, the demand was 1,512 l/day = 28 l/person·day · 5 people/dwelling · 12 dwellings · 0.9 (simultaneity factor). For T3, the demand was 5,040 l/day = 28 l/person·day · 3 people/dwelling (2 bedrooms) · 80 dwellings · 0.75 (simultaneity factor).

3.5 Air renewal (ventilation and infiltration)

As shown in Table 7, the ventilation rate considered for all cases during the summer nights (from June to September) is 4 ach, which is associated with windows opening [77]. During all other seasons, the ventilation rate varies depending on the building's age and type. The ventilation rate for the S4 was based on the last update of the Basic Document on Salubrity of the Spanish Technical Building Code [78]. Regarding the S3, the first version of the Basic Document on Salubrity of the Spanish Technical Building Code [79] was considered. For the S1 and S2, a default value of 0.63 ach [77] was assumed for all building types, as there was no specific regulation regarding air renewal in these BECs' periods.

Regarding uncontrolled ventilation, known as infiltration, Table 8 shows the air permeability through the windows and doors reported by the BECs for each period considered. Infiltration depends on the thermal and pressure gradient, the wind, and the air permeability of all thermal envelope elements. For the sake of simplicity, an annual mean infiltration rate was considered as a function of the air permeability of the windows. Thus, as shown in Table 9, three possible constant infiltration rates were established based on the results reported by Rodríguez Trejo [80]. Infiltration rate of 0.3 ach for enclosures with very high airtightness (27 m^3/hm^2), 0.45 ach for enclosures with medium airtightness (50

Table 9 Infiltration rates (ach) considered based on the climate zone and the building construction age. *Source*: Author elaboration based on [80]

	S1	S2	S3	S4
Infiltration rate (ach)	0.60	Z1: 0.45 Z2: 0.45 Z3: 0.30 Z4: 0.30 Z5: 0.30	Z1: 0.45 Z2: 0.45 Z3: 0.30 Z4: 0.30 Z5: 0.30	Z1: 0.45 Z2: 0.45 Z3: 0.30 Z4: 0.30 Z5: 0.30

Table 8 Air permeability of windows and doors (m^3/hm^2) in residential buildings depending on the climate zone and the building construction age. *Source*: Author elaboration based on [71–73]

	S1	S2	S3	S4
Air permeability of windows and doors ($m^3/h{\cdot}m^2$)	100	Z1: 50 Z2: 50 Z3: 27 Z4: 27 Z5: 27	Z1: 50 Z2: 50 Z3: 27 Z4: 27 Z5: 27	Z1: 50 Z2: 50 Z3: 27 Z4: 27 Z5: 27

m^3/hm^2), and 0.6 ach for enclosures with low airtightness (100 m^3/hm^2).

3.6 Energy model and simulation

The DesignBuilder simulation tool, based on the EnergyPlus engine, was used to model and simulate the set of 60 buildings. This engine was selected due to its wide international recognition and also because it is one of the calculation engines commonly used in Spain for issuing energy performance certificates. The buildings were modeled, and the thermal demands of heating, cooling, and DHW were estimated. All data were generated on an hourly basis.

4 Results and discussion

The thermal demand results of the 60 building cases performed by DesignBuilder are presented and analyzed in this section. Considering the size difference among the building types, the comparison was based on the ratio between the thermal demand and the building area to levelize the results.

Figure 4 shows the energy demand results broken down into heating, cooling, domestic hot water, and electricity (lighting and equipment). The average energy demand of the 60 building cases was 106.2 kWh/m^2year. Focusing on the BECs, the average energy demand per standard ranged from 144.4 kWh/m^2year for S1 to 73.4 kWh/m^2year for S4. Thus, the improvement achieved by the release of each regulatory update was around 17%, and the total improvement reached up to 50% for the whole time considered. The higher energy demands were found for the TiS1Z5 cases, due to the worse constructive solutions among the standards and the greater heating demand in Burgos. On the contrary, lower energy demands were found for the TiS4Z3 cases, in accordance with the better constructive solutions established in S4 and the lower cooling demand of Santander. It is important to note that DHW demand decreases from T1 to T3 due to the simultaneity factor. Electricity demand, obtained from the internal loads, presents the same value in terms of kWh/m^2year for all cases.

Considering the average energy demand for all building cases, as shown in Fig. 5, heating presented the largest contribution (41%), followed by electricity demand (30%). DHW and cooling accounted for 17% and 12%, respectively. The heating contribution to the total energy demand can significantly vary from 6% (T2S4Z1) to 75% (T3S1Z5) due to the winter climate severity and the thermal envelope quality. On the other hand, the cooling contribution can be negligible in some cases (0.6–3% for TiSjZ3) or reach up to 24% (TiSjZ1) in other cases due to the summer severity of the climate zones. Regarding the DHW and electricity demands, their contribution to the energy demand depends on the other demands. Therefore, lower percentages were found for higher heating and cooling demands (10% and 15% for TiS1Z5, respectively) and higher percentages for lower heating and cooling demands (30% and 45% for TiS4Z3).

Focusing on the heating demand (Table 10), a substantial decrease (50%) is observed between S3 and S4, and notable reductions, although somewhat lower, between S2 and S3 (40%) and the S1 and S2 (30%). These improvements are mostly associated with the better U-values of the thermal envelope and the ventilation rate reduction defined by each BEC. If the analysis is performed with the climate zones, a clear correlation is observed for all buildings and BECs; the higher winter climate severity, the higher the heating demand. On the other hand, comparing the building types, the heating demand is lower for the blocks of flats (T2 and T3) than for the single-family house (T1) because of T1's lower compactness. In addition, the heating demand of T2 is lower than T3 because T2 is between party walls.

Regarding the cooling demand, as shown in Table 11, the higher demands are found in zones with higher summer climate severity (Z1, Z2, and Z4). Conversely, much lower or even negligible values are achieved in zones with lower summer severity (Z5 and Z3). The highest cooling demand does not occur in the highest summer severity zone (Z1). It happens because the climate zones are defined by the Spanish Weather for Energy Calculations [29] for an area instead of a city. Nevertheless, real measured climate data from Meteonorm [31] for each city were considered in the simulation. Thus, Valencia presents the highest cooling demand instead of Almeria.

The cooling results showed a decrease of 11% between S1 and S2, 4% from S2 to S3, and also 4% between S3 and S4. This slight decrease is due to the lack of solar control elements (awnings, shutters, blinds, etc.) for the windows in the BECs requirements. The solar control elements are considered essential to reduce the cooling demand. In fact, this update came up only in the new regulation launched in 2019 [66], which was not considered in this study. The minor differences in the cooling demand between the building types can be explained by their compactness. The building blocks present higher compactness, thus, lower heat losses compared with the single-family house. Therefore, T3 presents the highest cooling demand, followed by T2 and T1, respectively.

Analyzing the heating and cooling thermal balance, it was observed that the heat loss through the thermal envelope and by the air renewal (ventilation and infiltrations) comprised 50% of the total annual thermal loss. However, the relevance of each term in the thermal balance depends on the BEC. Thus, in S1, the thermal envelope was more relevant due to the higher U-values found, while in S4, the air renewal rate had a higher contribution.

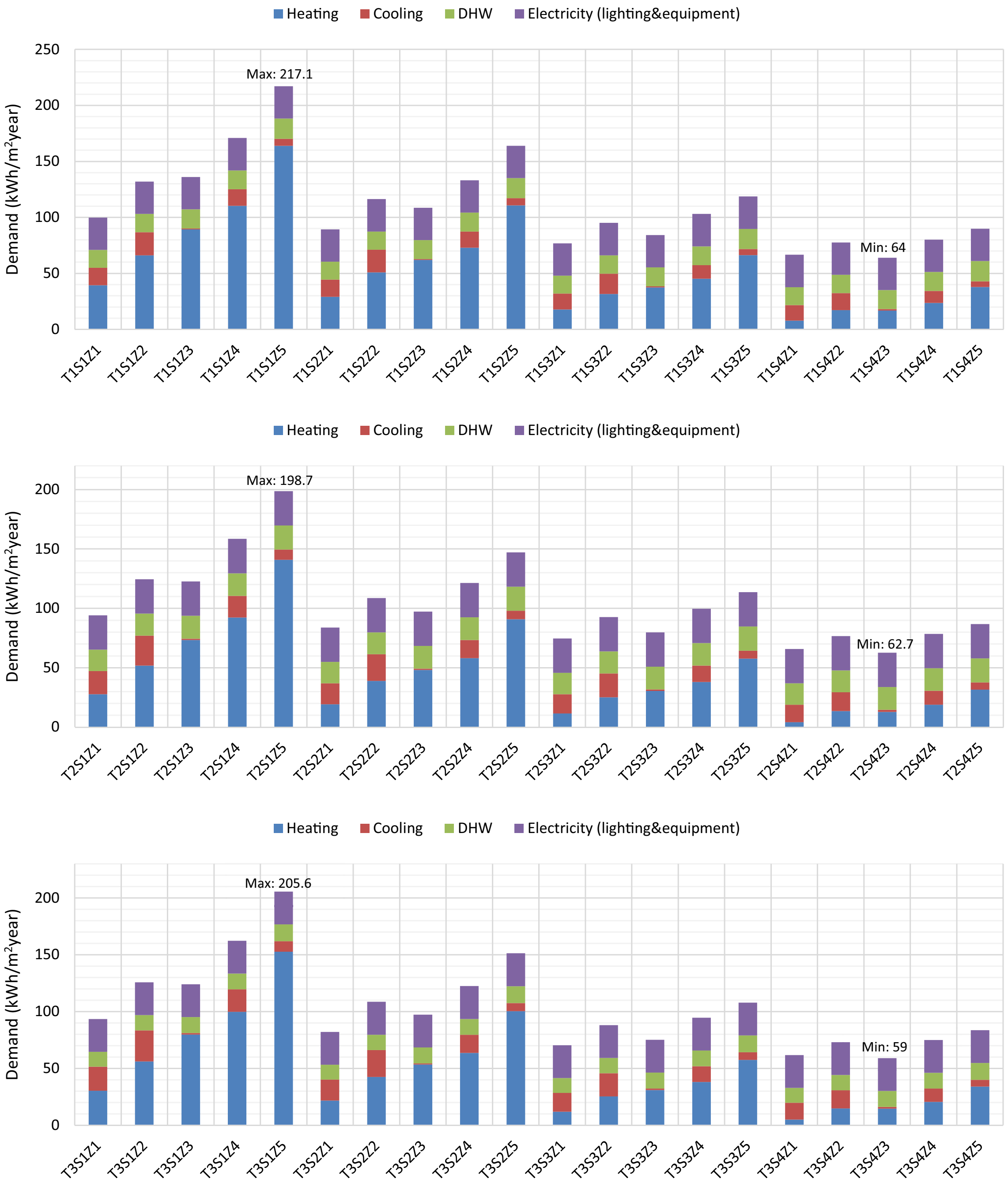

Fig. 4 Energy demand (kWh/m^{2}year) depending on building type, BEC, and climate zone

Regarding the thermal envelope loss breakdown, the walls (including the corresponding thermal bridges) were the most relevant, accounting for 39% of the total annual thermal loss, while glazing accounted for 26%. It is worth noting that the heat losses through the ground were more significant for T1, since T2 and T3 have an unconditioned ground floor behaving as a thermal insulating space. Moreover, focusing on the air renewal losses, ventilation accounted for 64%, and 36% corresponded to infiltration. Concerning the heat gains, the internal gains (occupancy, lighting, and equipment) accounted for 54% of the total annual thermal gain, while solar gain accounted for 46%. A higher solar contribution was found for climate zones with higher solar radiation (Z1 and Z2) and higher g-value of the windows (S1, S2, and S3).

The DHW demand, as shown in Table 12, is not dependent on the BEC. It is affected solely by the building type and climate zone. The DHW demand is higher in zones with a

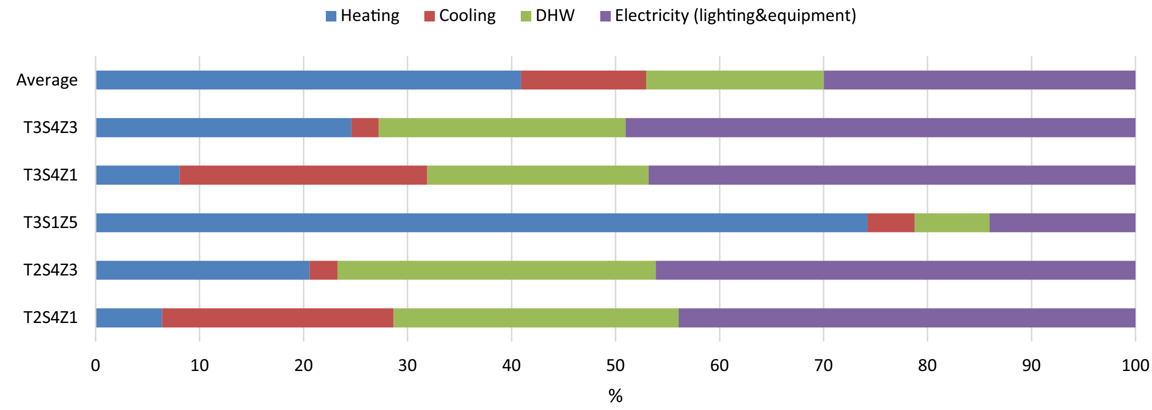

Fig. 5 Breakdown of energy demand (%) in some representative cases

Table 10 Heating demand (kWh/m^{2}year) depending on building type, BEC, and climate zone

Building type	S1	S2	S3	S4
T1	Z1: 39.44 Z2: 66.03 Z3: 89.36 Z4: 110.39 Z5: 163.88	Z1: 29.01 Z2: 50.94 Z3: 62.04 Z4: 73.02 Z5: 110.78	Z1: 17.83 Z2: 31.65 Z3: 37.47 Z4: 45.24 Z5: 66.26	Z1: 7.88 Z2: 17.30 Z3: 16.89 Z4: 23.55 Z5: 37.88
T2	Z1: 27.62 Z2: 51.80 Z3: 73.39 Z4: 92.26 Z5: 140.95	Z1: 19.31 Z2: 38.92 Z3: 48.11 Z4: 58.01 Z5: 90.86	Z1: 11.52 Z2: 25.17 Z3: 30.45 Z4: 38.10 Z5: 57.53	Z1: 4.22 Z2: 13.47 Z3: 12.89 Z4: 18.84 Z5: 31.59
T3	Z1: 30.33 Z2: 56.08 Z3: 79.83 Z4: 99.69 Z5: 152.60	Z1: 21.60 Z2: 42.51 Z3: 53.32 Z4: 63.67 Z5: 100.29	Z1: 11.87 Z2: 25.39 Z3: 30.99 Z4: 38.10 Z5: 57.72	Z1: 5.00 Z2: 14.70 Z3: 14.49 Z4: 20.45 Z5: 33.95

Table 11 Cooling demand (kWh/m^{2}year) depends on the building type, BEC, and the climate zone

Building type	S1	S2	S3	S4
T1	Z1: 15.55 Z2: 20.78 Z3: 0.80 Z4: 14.76 Z5: 6.34	Z1: 15.43 Z2: 20.16 Z3: 0.69 Z4: 14.43 Z5: 6.35	Z1: 14.16 Z2: 18.18 Z3: 0.92 Z4: 12.11 Z5: 5.53	Z1: 13.87 Z2: 15.09 Z3: 1.23 Z4: 10.83 Z5: 5.15
T2	Z1: 19.59 Z2: 25.31 Z3: 1.12 Z4: 18.28 Z5: 8.52	Z1: 17.57 Z2: 22.41 Z3: 1.07 Z4: 15.37 Z5: 7.09	Z1: 16.15 Z2: 20.05 Z3: 1.23 Z4: 13.67 Z5: 6.69	Z1: 14.64 Z2: 15.81 Z3: 1.69 Z4: 11.79 Z5: 6.06
T3	Z1: 21.06 Z2: 27.24 Z3: 1.27 Z4: 19.85 Z5: 9.28	Z1: 18.50 Z2: 23.65 Z3: 1.07 Z4: 15.96 Z5: 7.23	Z1: 16.48 Z2: 20.33 Z3: 1.25 Z4: 13.72 Z5: 6.62	Z1: 14.69 Z2: 15.94 Z3: 1.56 Z4: 11.71 Z5: 5.93

Table 12 DHW demand (kWh/m^{2}year) depending on building type and climate zone

BEC	T1	T2	T3
S1-S4	Z1: 15.96 Z2: 16.35 Z3: 16.99 Z4: 16.83 Z5: 17.97	Z1: 18.03 Z2: 18.47 Z3: 19.19 Z4: 19.01 Z5: 20.30	Z1: 13.15 Z2: 13.48 Z3: 14.00 Z4: 13.87 Z5: 14.81

lower mains water temperature. The differences among the building types are due to the simultaneity factor (1, 0.9, and 0.75 for T1, T2, and T3, respectively) and the occupancy (five people per dwelling in T1 and T2 and three people per dwelling in T3). Thus, the higher demand is found in T2 and the lower in T3.

5 Conclusions

A procedure based on energy simulation was proposed to evaluate the improvement in energy efficiency achieved by the changes introduced in the building energy codes. The procedure was applied to the Spanish residential sector, focusing on heating, cooling, and DHW demands. DesignBuilder simulation tool was used to model and simulate 60 different cases, combining three representative building types, four national building energy codes, and five selected climate zones.

The analysis of the thermal demands showed a remarkable decrease in heating, particularly, between S3 and S4 standards. The reduction was mostly impacted by the U-values, and ventilation and infiltration rates required by each BEC. The decrease achieved in cooling was substantial, but it was much lower than in heating. Further improvements regarding the thermal energy demands should consider higher building compactness, better construction solutions, lower infiltration rate, and new ventilation systems (e.g., with energy recovery).

The DHW demand is not dependent on the BEC. However, it is important to mention that the S3 standard introduced the obligation to cover 30–50% of the DHW demand using renewable or residual energy sources or combined heat and power systems.

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Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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