Energy & Buildings 287 (2023) 112986

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Cost-effectiveness and minimum requirements of nZEB for residential buildings under the new Spanish Technical Building Code

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ARTICLE INFO

Article history:
Received 2 November 2022
Revised 6 March 2023
Accepted 9 March 2023
Available online 15 March 2023

Keywords:
Spanish Technical Building Code
nZEB
Cost-optimality
Building energy simulation
DesignBuilder

ABSTRACT

This paper evaluates a parametric analysis towards compliance with the nZEB standard, which in Spain is defined by the latest update of the Technical Building Code. This regulation is critically assessed regarding its ability to promote the concept of cost optimization, promote renewable energy sources and minimize primary energy consumption in the residential sector. To this end, a virtual building was defined and multiple designs were evaluated using DesignBuilder software. A set of 170 alternative scenarios was established and parametrically evaluated for five cities representing the five climatic zones of inland Spain (Bilbao, Burgos, Seville, Madrid and Almeria). The results were evaluated focusing on cost-cost effectiveness and primary energy consumption values for the different scenarios, evaluating them in relation to the minimum requirements set by the regulation. The great potential of photovoltaic energy is highlighted, which allows negative values to be obtained for the two Equivalent Uniform Annual Costs due to the cost avoided through self-consumption. This fact makes the optimal designs tend to electrification, specifically through air and ground source heat pumps. It is worth mentioning that the new Code has only established a minimum target for renewable self-consumption in the residential sector, which should be reinforced in future updates.

1. Introduction

In recent decades, a consensus has emerged on the need to decarbonize human activities. It is well known that over 40 % of global energy consumption and 30 % of greenhouse gas (GHG) emissions are related to the building sector [1]. Already in 2007, the Intergovernmental Panel on Climate Change synthesis report identified that the building sector was the sector with the main economic mitigation potentials, using technologies and practices expected to be available in 2030 [2]. In this context, in 2007, the European Union (EU) adopted the "2020 Climate and Energy Package" [3] and the roadmap was updated in October 2014 with the definition of the "2030 Climate & Energy Framework" [4]. As far as the building sector is concerned, the EU, through the Directive 2010/30/EC (EPBD), from January 2019, obliges Member States to ensure that all newly constructed public buildings must be nearly Zero Energy Buildings (nZEB) [5].

EPBD states that an nZEB is a building that has a very high energy performance, where the nearly zero or very low amount of energy required should be covered, to a very significant extent, by renewable sources, including sources produced on-site or nearby. Specifically, the minimum energy performance is limited in terms of primary energy consumption in a relation of cost-optimal levels for a set of reference buildings.

The cost-optimal level is found in the lower part of the graph that reports the global costs and primary energy consumption of each potential building configuration, including the passive and active elements, as well as the renewable energy production [6]. Therefore, there is an implicit need to optimize building design that combines passive solutions or Energy Saving Measures (ESM), active solutions or Energy Supply Systems (ESS) and on-site or nearby Renewable Energy Sources (RES), in order to meet a certain level of primary energy consumption at minimum cost [7].

Several authors have made their proposals to find these optimal designs using different approaches. Of these, most addressed this kind of optimization problem by (i) parametric assessment [8–10], (ii) mathematical optimization [11–13], or (iii) other more

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https://doi.org/10.1016/j.enbuild.2023.112986
0378-7788/

sophisticated optimization routines, such as genetic algorithms or machine learning techniques [14–16]. All these approaches present advantages and disadvantages and the final selection of the optimization method strongly depends on the specific optimization problem. The computational cost of building energy simulations has traditionally been a constraint, but this has been overcome by reducing the mathematical model to a set of linear equations, enabling the use of mathematical programming-based optimization methods. The large number of evaluations required by parametric assessments can be overcome by sophisticated optimization routines, especially when the operation optimization is also sought.

EPBD does not establish a uniform approach for implementing nZEB. The specific definition of nZEB should be completed by the quantitative definition of the primary energy consumption limits, which corresponds to each Member State in compliance with a comparative methodology framework [17], and should be in line with national, regional or local conditions, including a numerical indicator of primary energy use (in kWh/m^{2}y). Furthermore, Member States have to implement targeted policies and provide financing to foster the transition to nZEBs, progressively increasing the number of nZEBs with differentiated targets for building categories.

On this premise, D'Agostino and Parker determined the cost-optimal design of a new residential building under different European climates [18]. Likewise, Vujnović and Dović presented a similar analysis for a new hotel building [19], making it clear that measures strongly depend on local weather conditions. To date, almost all Member States have defined their specific nZEB definition [20] and, in connection with this, D'Agostino and Parker also compare the finally approved nZEB requirements by the Member States with the established European benchmark and cost-optimal levels, concluding that nZEB requirements are 50 % lower than cost-optimal levels in terms of primary energy consumption [21]. Since then, some authors have compared these requirements with the cost-optimal solutions for specific case-studies. For instance, Kurnitski et al. assessed the energy performance of cost-optimal and nZEB buildings in Estonia, showing that the cost optimal energy performance level of an Estonian reference detached house was significantly lower than the current minimum requirement regarding primary energy consumption [22]. Similarly, Buso et al. carried out a cost-optimal analysis for a reference hotel in Italy, where the primary energy consumption of the optimal-cost was found to be slightly below that of the Italian nZEB target [23]. On the other hand, De Luca et al., for the case of social housing also located in Italy, determined that the cost-optimal energy efficiency measures did not comply with the legal primary energy consumption requirements [24].

In the case of Spain, nZEB is defined in the last update of the Spanish Technical Building Code (CTE, by its acronym in Spanish), approved by the Royal Decree 732/2019, and coming into force in July 2020 [25]. Specifically, nZEB in Spain is defined as any building that complies with the new Technical Building Code, which currently combines a prescriptive-based approach (for setting limits to building energy demand, fixing maximum transmittance values for the different building elements) with a performance-based approach (for setting a maximum limit of primary energy consumption). Additionally, some new modifications have recently been introduced by the RD 450/2022 [26], such as considering the implementation of charging infrastructure for electric vehicles or a minimum target of RES generation for electricity. A detailed analysis of the evolution over the years of the Spanish building energy Code was presented by Monzón-Chavarrías et al [27]. Cerezo-Narvaez et al. carried out a detailed analysis of its energy, emissions and economic impact on the climatic objectives for the case of Andalucía (southern Spain) [28]. However, instead of optimizing the energy design, a single standard solution for the analysed buildings was selected in advance as a single option, not considering the energy reduction potential of other solutions. This article aims to evaluate the minimum requirements established by the Spanish regulations for new buildings to be nZEB in relation to the cost-effectiveness of potential solutions, identifying the extent to which these requirements could be stricter without significantly affecting the economic feasibility of the required solutions. Additionally, it also focuses on providing a systematic analysis of how the combination of ESM and ESS can contribute to meeting the new nZEB standard in Spain. The approach studied here presents several novelties with respect to other existing works in the literature. The technical assessment is done through the joint simulation of a complete combination of both building envelopes and energy systems. Design Builder software was used for modelling and simulating all possible solutions usually implemented in residential buildings, by applying a detailed HVAC simulation approach, which allows a dynamic performance and the interaction between all the specific devices that make up the energy supply, distribution and delivery subsystems in a building. On the other hand, for the first time, a critical assessment of the new Spanish Technical Building Code is carried out, considering the main climate zones identified by the CTE, and the specific limitations established for each of them. To the best knowledge of the authors, there are no similar works in the literature.

The interaction between ESM and ESS, as well as the integration of RES, is essential to reflect the actual functioning of nZEBs. Therefore, to explore the synergies between these three strategies, as well as the combined effect of these solutions, ESM (4 sets of actions), ESS (12 technologies and 52 scenarios) and RES solutions were combined, resulting in 170 scenarios. It should be noted that some scenarios were not considered due to incompatibility between some solutions, e.g. 100 % photovoltaic and 100 % solar thermal solutions cannot be considered under the same scenario. The 170 scenarios cover the state of the art of the solutions currently applied in the Spanish building market. These scenarios were evaluated for the 5 climatic zones mentioned, obtaining a set of 830 simulations that allow the most competitive solutions that meet the primary energy consumption requirements, under different constraints, to be identified. Additionally, the "ambitiousness" of the Technical Building Code in terms of PE reduction in relation to the cost efficiency of potential solutions to be implemented is also addressed in this study.

One of the limitations of this work is that it is restricted to densely built, urban, multifamily buildings with thermal heating loads (space heating and DHW), neglecting cooling needs. However, the vast majority of new residential buildings fall into this category and amongst these, unlike tertiary buildings, there are still few residential buildings that include cooling systems in their HVAC system. In fact, in the case of Spain, and according to a study published by the Spanish Institute for Energy Diversification and Saving, IDAE, cooling consumption represents 0.8 % of the total energy consumption in residential buildings in Spain (the lowest consumption by use; heating consumption or DHW represent 47 % and almost 20 %, respectively) [29]. Even when values are disaggregated by climate areas, cooling consumption also presents the lowest share of energy consumption in the Mediterranean area (the most unfavourable area in terms of cooling load).

The rest of the paper is organized in five sections, as follows: Section 2 introduces the Spanish Technical Building Code, summarizing its main specifications for residential buildings; the main characteristics of the reference building, and the scenarios under evaluation, as well as the methods used for the techno-economic analysis. The results from the simulation of the scenarios under the selected locations are presented and discussed in Section 3. Finally, the main contributions of the paper and future research are summarized in Section 4.

2. Materials and methods

The assessment is carried out for a typical residential building, which can be defined as a reference building due to its main characteristics. The reference building is modelled using Design Builder software [30], which allows the energy performance of the building to be calculated for a year. Design Builder is a graphical user interface for the EnergyPlus solver [31], a well-known energy simulation software tool, which started in 1996 and its suitability for building energy assessment has been extensively validated in the literature for different purposes [32–35]. The authors have already used this software in previous research, where the results were validated with experimental data for a similar application [36]. Additionally, the use of this tool in this paper is motivated by its potential to automatize large sets of simulations and the ability it offers to perform joint dynamic simulations of the building together with the HVAC system, reflecting the operational interactions between the two.

A set of alternative scenarios, considering both ESM and ESS, are defined. In particular, four ESM (apart from the current reference building envelope) and 52 ESS (including RES for electricity and thermal energy production) alternatives are preselected. Considering that not all combinations are possible, since some of them condition others (i.e., roof availability is limited), the feasible designs are limited to 170 scenarios. These scenarios are simulated for the five inland climatic zones in Spain, specifically, Bilbao (climatic zone C), Almeria (A), Valencia (B), Madrid (D) and Burgos (E). Their locations are presented in Fig. 1. The annual energy results are evaluated and the economic analysis is carried out, enabling the existing relationship between primary energy (both non-renewable and total) consumption and annual cost, which is expressed in terms of the Equivalent Uniform Annual Cost (EUAC), to be assessed. These results are assessed in detail and compared to the requirements of the Spanish Technical Building Code that currently defines the nZEB standard in the country.

2.1. Spanish Technical Building Code

The Spanish Technical Building Code is made up of several Basic Documents. Regarding energy performance (DB-HE), there are several requirements that should be met for any building, new or renovated, which are adjusted depending on building typology, action and climatic zone. The requirements for new buildings are covered by the different sections of the DB-HE. The subsections applicable to the case study are described below.

For new residential buildings, both non-renewable and total primary energy consumption are restricted. This consumption limit is set by the HE0 subsection and depends on the climatic zone where the building is located (Fig. 1). These limits are summarized in Table 1. As can be seen, the non-renewable primary energy (NRPE) consumption limit is exactly half the maximum value allowed for primary energy consumption. To determine these indicators, the Technical Building Code considers all energy flows consumed in the building for heating, DHW, ventilation and cooling (in the case of tertiary buildings, lighting needs are also taken into consideration). It should be noted that, for the calculation of these indicators, the Spanish regulations do not take into consideration, in any case, electricity used by non-energy supply-related equipment, such as household appliances (Fig. 2).

In addition to energy consumption, energy demand is also limited for new residential buildings. Unlike the energy consumption in HE0 (performance-based approach), the HE1 subsection sets the maximum thermal transmittance value that can be taken by the envelope elements (prescriptive-based approach) and also the overall transmittance value, depending on the compactness of the given building (V/A). Again, this transmittance threshold is climate dependent, as can be appreciated in Table 2.

The HE4 subsection sets the minimum contribution of thermal renewable energy to meet the DHW demand. Whenever demand exceeds 100 l/day (reference consumption per person is 28 l/day), the contribution from thermal renewable energy sources should be at least 70 % or, alternatively, 60 % when the overall DHW demand of the building does not exceed 5000 l/day, as is the case of the selected case study (see Section 2.2) and the vast majority of buildings (as a reference, buildings with up to 60 two-bedroom apartments, or 45 three-bedroom apartments). Finally, ventilation requirements are set by the HS3 subsection to prevent the CO_2 concentration from exceeding 900 ppm. Specifically, volumetric air flows are set as a function of the dwelling size and use of the spaces.

2.2. Reference building

It should be noted that, as previously mentioned, this study aims to evaluate the minimum requirements set by the Spanish regulation, in terms of cost-effectiveness and cost optimal solutions. Hence, the study does not aim to evaluate the energy performance of a given building under specific conditions, but to assess the energy performance of a "virtual" building assuming different scenarios (for energy saving measures and energy systems) in relation to the requirements established by the Spanish Technical Building Code. To do that, such performance indicators as primary energy consumption are calculated based on the procedure and assumptions defined in the Spanish regulatory framework (tools, assumptions related to the thermal properties of the envelope, schedules and operation...).

Thus, for the definition of a reference building representative of new multifamily buildings in Spain where different solutions and scenarios are evaluated, three different main sources have been used to determine its geometry, the thermal performance and the energy systems considered. As far as geometry is concerned, the results of the TABULA project are taken as a reference [37]. The TABULA project carried out an integral assessment of building typologies representing the residential building stock of different Member States [38]. For the case of Spain, three different climatic zones were identified in the TABULA project (continental, North-Atlantic and Mediterranean area), and common characteristics were identified for the building stock, typology amongst them. It should be noted that the different boundary conditions in the urban environment, as a result, give a heterogeneous geometry in new buildings and, in consequence, defining a geometry representative of the whole building stock in Spain is quite complex. In that sense, the aim of this definition is mainly to select a geometry that could usually be found in new constructions in urban environments, using a real building as an example. Specifically, newly constructed multifamily buildings were defined as semi-exposed, with one of the facades in contact with an adjacent existing building, as new buildings are usually constructed on plots of land previously occupied by other buildings or uses. These apartment buildings are regular in shape, prismatic, with facades parallel to urban roads.

On the basis of this analysis, a planned new apartment building located in the city of Ermua, near Bilbao (climate zone C), is taken as the reference building. The building has 22 dwellings on eight floors (including the ground floor) with a total height of 25 m and a total conditioned area of 1,883 m^2, which is coherent with building occupancy in cities and, to the knowledge of the authors, is representative of the current construction trends in the climate

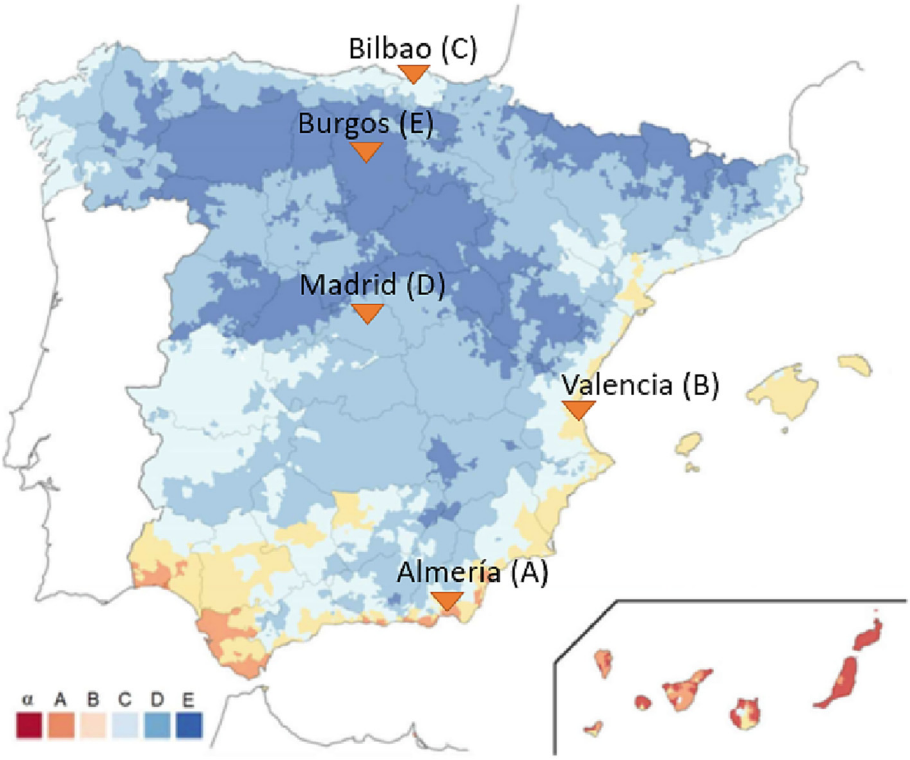

Fig. 1. Climatic zones defined by the Spanish Building Code (source: MITMA: Ministry of Transport, Mobility and Urban Agenda).

Table 1
Primary energy consumption limits for new buildings under the Spanish Technical Building Code (HE0).

Climatic Zone	A	B	C	D	E
City	**Almeria**	**Valencia**	**Bilbao**	**Madrid**	**Burgos**
Non-renewable primary energy consumption (kWh/m^{2}y)	25	28	32	38	43
Total primary energy consumption (kWh/m^{2}y)	50	56	64	76	86

zone where it is located. A typical floor plan of the building is depicted in Fig. 1, and a capture of the 3D model of the building in DesignBuilder is presented in Fig. 3. The building is currently in the design phase and meets all the specifications of the Spanish Technical Building Code for new residential buildings (see Table 2). Specifically, being located in the climatic zone "C", the thermal transmittance of the different elements of the reference building are summarized in Table 3.

The ESS of the reference building consists of two condensing boilers running on natural gas, sized respectively to meet the peak load for space heating and DHW, the latter supported by a solar thermal collector installation to meet 60 % of the needs, in line with the Spanish Building Technical Code (Section 2.1). Space heating is provided by floor heating, favouring low temperature solutions. The electricity needs are fully covered by the local electricity network. Following the specifications of the Technical Building Code, only the electricity consumption of the active systems are taken into account. Roof availability is a key issue for the implementation of renewable energy sources. In this case, the usable surface for that purpose is limited to 162 m^2.

In any case, as previously mentioned, the selected building is used as a reference for defining the geometry of the different scenarios evaluated in this study. In this regard, it should be noted that, as the building has three external façades, two of them facing different narrow streets, with only the main façade (the north façade) overlooking an open space. As solar exposure is an issue when designing nZEBs, the north exposure of the building can be considered as a conservative assumption, as any other building with a better solar exposure will benefit from higher solar gains, which increase the profitability of the integration of renewable energy sources and improves the cost-optimality of the building. From this assumption, the results of the assessment can be considered as a worst-case scenario.

Regarding the thermal characteristics of the envelope, the different solutions considered are defined in relation to the requirements set by the Spanish Building Technical Code (see Section 2.3). Finally, as previously mentioned, the most usual and available HVAC technologies in Spain have been considered for defining the energy systems related solutions. Both of them are presented in detail in section 2.3. Parameters such as occupancy, lighting, or equipment, as well as heating set point temperatures and ventilation ratios, were defined according to the specifications used for energy performance certification in Spain [39]. From the application of the HS3, a constant ventilation rate was set per dwelling, resulting in a value of 24 l/s for 2-bedroom dwellings (0.35 ach) and 33 l/s for 3-bedroom dwellings (0.48 ach).

2.3. Definition of scenarios

The analysis is carried out for a set of scenarios, which are created from the combination of passive (ESM) and active (ESS) solutions. As stated in the introduction, the aim is to cover, if not all, the most usual solutions currently available in the market for residential buildings.

Fig. 2. Typical floor plan of the building.

Table 2
Maximum transmittance for the envelope elements for new buildings under the Spanish Technical Building Code (HE1).

Climatic Zone		A	B	C	D	E
City		**Almeria**	**Valencia**	**Bilbao**	**Madrid**	**Burgos**
External walls and floors (W/m^{2}K)		0.70	0.56	0.49	0.41	0.37
Roof in contact with outside air (W/m^{2}K)		0.50	0.44	0.4	0.35	0.33
Partitions in contact with non-habitable spaces (W/m^{2}K)		0.80	0.75	0.70	0.65	0.59
Windows (W/m^{2}K)		2.7	2.3	2.1	1.8	1.8
Doors (W/m^{2}K)		5.7				
Floors between rooms with the same use (W/m^{2}K)		1.80	1.55	1.35	1.20	1.00
Walls between rooms with the same use (W/m^{2}K)		1.40	1.20	1.20	1.20	1.00
Floors and walls between areas with different uses (W/m^{2}K)		1.25	1.10	0.95	0.85	0.70
Overall transmittance (W/m^{2}K)	V/A $\leq$ 1	0.87	0.83	0.73	0.63	0.54
	V/A $\geq$ 1	0.94	0.90	0.81	0.70	0.62

ESM are mainly based on the modification of the thermal transmittance of the external envelope elements, namely, roof, external walls, partitions between non-habitable zones and windows. For setting different insulation levels for these elements, various standards are used as a reference: the "business as usual" ("BAU Envelope", S1) scenario refers to the minimal requirements set out by the Spanish Technical Building Code; the second ("EECN Envelope", S2) refers to the same document, but in this case to the recommendations made in Annex E of the said document; the third option ("B Envelope", S3) is an intermediate between the second and the fourth; the latter ("PH Envelope", S4) being the one used for Passive House Institute (PHI) certification.

The limits established by the regulation and how these affect the insulation level of the reference building are summarized in Table 4. The resulting thermal transmittance values are obtained from adapting the thermal characteristics of the reference building (Table 3) to the minimum requirements set by each of the standards under consideration. The adaptation has been made through assuming usual and standard solutions (e.g., in terms of insulation thickness, amongst others), which explain that the resulting thermal transmittance considered in each scenario is not exactly the same as the limit set by the standard assumed. These limits correspond to the climatic zone C, which presents intermediate outdoor temperatures in relation to the other warmer (A and B) and colder

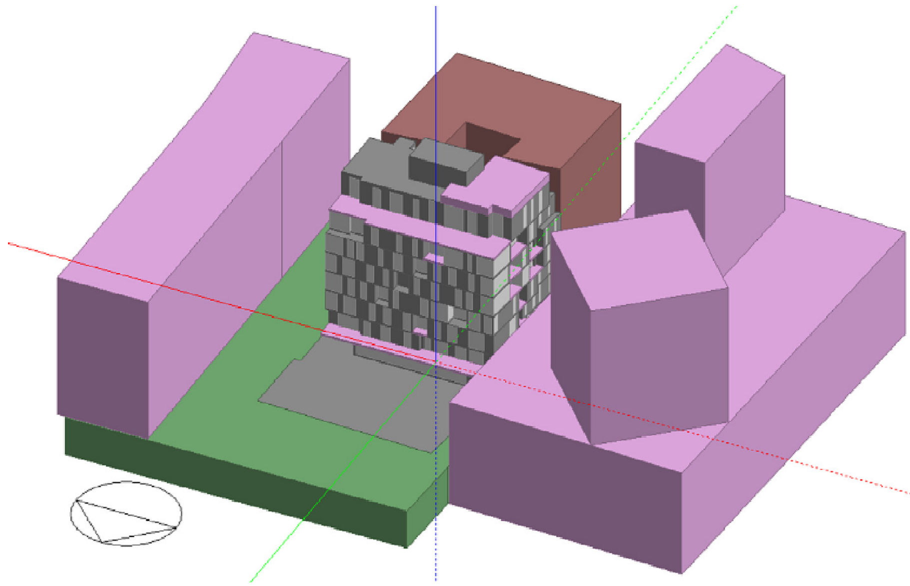

Fig. 3. 3D model of the building in DesignBuilder.

Table 3
Summary of thermal transmittance of building elements of the reference building.

Building component	Transmittance (W/m^2·K)
Underground floor	0.568
Floor between underground spaces	0.620
Floor between underground floor and ground floor	0.611
Floor between dwellings	0.460
Roof	0.259
Façade	0.252
Walls between dwellings and common areas	0.631
Walls between dwellings	0.346
Windows and doors	2.100

(C and D) regions of Spain. It should be noted that, besides these 4 scenarios (from S1 to S4, in relation to the insulation level of the envelope), a fifth scenario would be generated (S0), which represents the reference building based on the thermal characteristics presented in Table 3, which, as previously mentioned, is representative of the current construction trends in the climate zone where it is located, in such a way that it can be considered a benchmark to put into context the results obtained for the different combinations assumed. To facilitate comparison between the results, these four sets of actions are used for all the climatic zones, which, in turn, have been proven to meet the limits set by the standards for all of them (see values in Table 2). For all the cases, the insulation level was modified by the thickness of the insulation level; while for the case of the windows, the pane composition was modified to meet the specifications. In Fig. 4, the range of solutions evaluated in relation to the current requirements of the CTE (Technical Building Code) for the different climate zones is graphically presented for each element of the envelope. Additionally, the value of the actual building used for defining the geometry has also been included.

In turn, ESS configurations are made from a combination of energy conversion units, resulting in a set of scenarios as described in Table 5. Apart from the elements listed here, ancillary elements

Table 4
Summary of Energy Saving Measures.

	Standard	Limit set by the standard	Resulting thermal transmittance (W/m^{2}K)
FAÇADE	S0_REFERENCE BUILDING	U ≤ 0.49 W/m2 K	0.252
	S1_BAU ENVELOPE - CTE HE1	U ≤ 0.49 W/m^2 K	0.252
	S2_EECN ENVELOPE - CTE HE-E Annex	U ≤ 0.29 W/m^2 K	0.252
	S3_B ENVELOPE – B Energy Certification*	Demand = 7.7 – 17.9 kW/m^{2}a	0.158
	S4_PH ENVELOPE - Enerphit Certification*	U ≤ 0.30 W/m^2 K	0.252
ROOF	S0_REFERENCE BUILDING	U ≤ 0.40 W/m^2 K	0.259
	S1_BAU ENVELOPE - CTE HE	U ≤ 0.40 W/m^2 K	0.259
	S2_EECN ENVELOPE - CTE HE-E Annex	U ≤ 0.23 W/m^2 K	0.209
	S3_B ENVELOPE – B Energy Certification*	Demand = 7.7 – 17.9 kW/m^{2}a	0.176
	S4_PH ENVELOPE - Passive house*	U ≤ 0.30 W/m^2 K	0.259
WINDOWS	S0_REFERENCE BUILDING	U ≤ 2.1 W/m^2 K	2.1
	S1_BAU ENVELOPE - CTE HE	U ≤ 2.1 W/m^2 K	1.4
	S2_EECN ENVELOPE - CTE HE-E Annex	U ≤ 2 W/m^2 K	1.4
	S3_B ENVELOPE – B Energy Certification*	Demand = 7.7 – 17.9 kW/m^{2}a	0.98
	S4_PH ENVELOPE - Passive house*	U ≤ 1.05 W/m^2 K	0.98
PARTITIONS	S0_REFERENCE BUILDING	U ≤ 0.70 W/m^2 K	0.630
	S1_BAU ENVELOPE - CTE HE	U ≤ 0.70 W/m^2 K	0.630
	S2_EECN ENVELOPE - CTE HE-E Annex	U ≤ 0.48 W/m^2 K	0.391
	S3_B ENVELOPE – B Energy Certification*	Demand ≤ 7.7 – 17.9 kW/m^{2}a	0.351
	S4_PH ENVELOPE - Passive house*	U ≤ 0.30 W/m^2 K	0.291

* *These solutions present cross-ventilation with heat recovery*

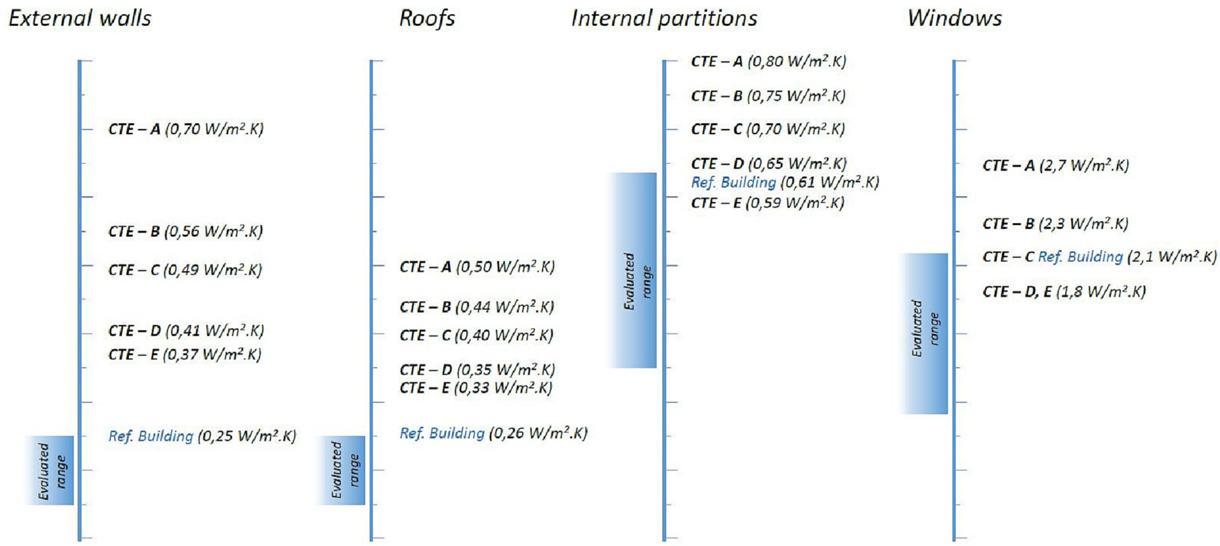

Fig. 4. Range of evaluated solutions (considering thermal transmittance), in relation to the current requirements of the CTE (Technical Building Code) for the different climate zones.

Table 5
Summary of Energy Supply Systems.

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13
Condensing Gas Boiler (heating)	■	■											
Condensing Gas Boiler (DWH)	■	■				■	■	■	■				
Air-source heat pump - ASHP (heating)			■					■	■		■		
Air-source heat pump - ASHP (DWH)			■										■
Ground-source heat pump - GSHP (heating)				■		■	■			■			
Ground-source heat pump - GSHP (DHW)				■								■	
Cogeneration - CHP (DWH)										■	■		
Biomass - BIO (heating)					■							■	■
Biomass - BIO (DWH)					■								
Solar collector thermal CTE - STm	■					■		■					
Solar collectors thermal 100% - STM		■					■		■				
Photovoltaic (50% area) - PV50	From S14 to S26												
Photovoltaic (100% area) - PV100	From S27 to S39												
Photovoltaic tile - PVF	From S40 to S52												

are also included in the economic analysis (Section 2.4). As stated, it should be considered that not all the 52 scenarios are feasible, since some technologies cannot be installed together. This is the case of the solar technologies (solar thermal collectors, PV panels and PV tiles), that compete for the usable roof (162 m^2 as stated in Section 2.2). As a result, the number of effective scenarios is reduced to 34. All these ESS include a ventilation system to meet the specification of the HS3, including a heat recovery system if required by the ESM (the B and PH ENVELOPE do include it). In similar way to the ESM scenarios, S1 would correspond to the ESS scenario of the reference building presented in section 2.1 (in the project phase, the proposal consists of condensing gas boilers for heating and DHW and the mandatory share of solar thermal set by the technical building code).

From the combination of the different ESS and ESM over the reference building, the aforementioned 170 scenarios were defined for each location, resulting in a total of 830 effective simulations, once the unfeasible scenarios due to existing constraints had been removed.

2.4. Techno-economic analysis

2.4.1. Energy assessment

As stated, each scenario is simulated by the building energy simulation software DesignBuilder. Specifically, a "Detailed HVAC" model option was used, which allows the comprehensive design and dynamic simulation of the integrated HVAC components that make up each ESS presented in Section 2.3. As an example, the S1 configuration, as defined in DesignBuilder, is presented in Fig. 5, where heating, DHW and ventilation loops space are represented. The solar loop meets part of the DHW load, which is backed up by a natural gas boiler. An additional natural gas boiler is work-

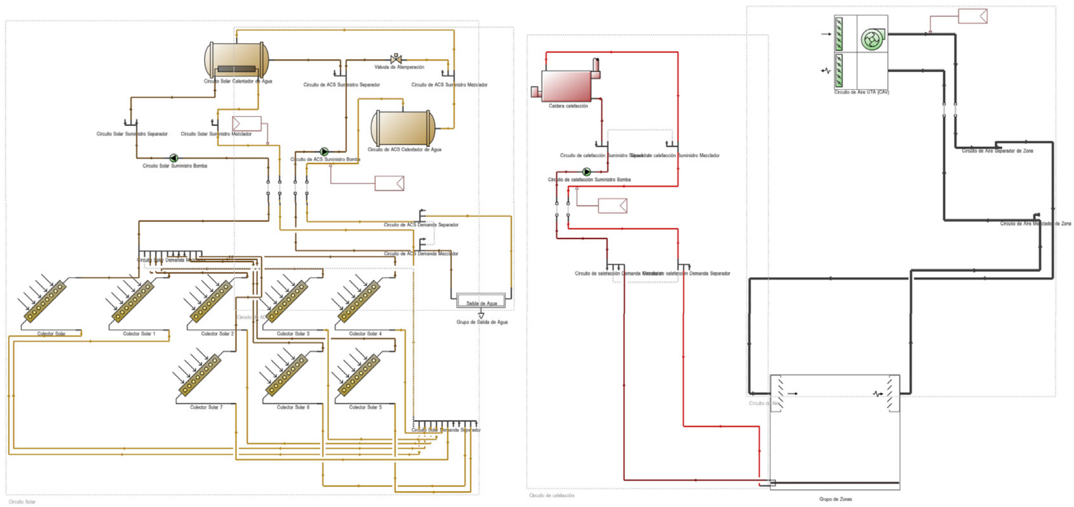

Fig. 5. HVAC scheme for the S1 configuration.

ing at low temperature to meet the space heating loads through the floor heating system. Finally, the ventilation system meets the ventilation needs set by the HS3. This scenario corresponds to the ESM of the reference building as presented in Section 2.2.

For the aim of this analysis, ESS are composed of reference technologies whose efficiency at nominal conditions are summarized in Table 6. For the simulations, DesignBuilder considers the performance curves of each technology to calculate the actual efficiency from the efficiency under nominal conditions.

It should be taken into account that each ESS must be sized according to the energy needs of each case, which depends on the heating and DHW load. These, in turn, depend on the climate zone and ESM scenarios. Thus, it is necessary to carry out an appropriate sizing for each ESS component that is part of the scenarios presented in Table 5.

Sizing depends on whether the technology under consideration is used for space heating (and possibly DHW) or only for DHW production. When used for meeting the space heating demand, the heating load calculation method is applied, which basically depends on the building constructive characteristics and building location. Specifically, condensing gas (S1 and S2) and biomass boilers (S5) are sized by DesignBuilder's 'Autosize' tool which applies the ASHRAE heating load calculation method [40]. Autosizing cannot be applied to the rest of the energy supply units, such as aerothermal (S3 and S11) and geothermal heat pumps (S4 and S10), which should be manually defined for each scenario, for which the ASHRAE method is also used. For this purpose, a standard nominal COP value of 3.2 was set for the aerothermal heat pump (nominal conditions: 30 °C in the evaporator and 55 °C in the condenser). For the geothermal heat pump, specific curves were derived from the datasheet of commercial equipment, as requested by DesignBuilder. Additionally, for the geothermal heat exchange, boreholes with a unit length of 76 m were considered, as well as a ground thermal conductivity of 0.7 W/m°C. From this information, the actual COP of the heat pumps is derived from the operative temperatures at any given time.

If space heating is coupled to DHW production (when the same technology provides both needs, i.e., S1 as it appears in Fig. 3), the latter is provided by means of a thermal energy storage tank, which is charged by additional thermal energy production, storing the surplus with the instantaneous space heating demand. The size of the tank is derived from the DHW peak load set by the Spanish normative in [39]. When used exclusively for meeting the DHW demand, the same procedure is followed, considering the thermal

Table 6
Efficiency of the technologies under consideration.

Energy conversion unit	Nominal efficiency
Condensing gas boiler	$\eta_t = 95\%$
Biomass boiler (BIO)	$\eta_t = 85\%$
Air-source heat pump (ASHP)	$COP = 3.2$
Ground-source heat pump (GSHP)	$COP = 4 - 4.8$(Depending on the case)
Cogeneration unit (CHP)	$\eta_t = 70\% \eta_e = 27\%$
Water pump	$\eta_m = 90\%$
Ventilation fan	$\eta_m = 75\%$
Heat recovery system (HR)	$\eta_t = 75\%$
Solar thermal collector (ST)	$\eta_t = 78\%$(corrected by the loss coefficients)
PV panels (PV)	$\eta_{PV} = 15\%$
PV tiles (PVF)	$\eta_{PV} = 6\%$

power of the heating production unit; as is the case for cogeneration (in S10 and S11), geothermal (in S12) or aerothermal heat pump (in S13). A 3-hour storage capacity thermal energy storage tank is added to cover instantaneous peaks, since the DHW load is given by the normative on an hourly basis, while DHW discharges are usually in the order of minutes. Additionally, it should be noted that geothermal heat pumps additionally require a ground source heat exchange loop where the boreholes are integrated. 76-depth boreholes are taken as a reference, while their number is derived from applying a sizing method proposed by DesignBuilder.[1]

The number of solar thermal collectors (S1, S2, S6 and S7) required to meet the different percentages of the DHW need was manually determined for each location by a parametric set of simulations and, for the PV production, each case is exclusively determined by the available roof area.

Annual hourly simulations are performed using the weather data files available in the EnergyPlus site for the five selected locations and the total final energy consumption data were aggregated for an entire year, considering the energy conversion units, as well as the pumps and fans. The temperature setpoint values (20 °C from 8.00 h to 23.00 h, 17 °C the rest of the time) and occupation profiles were set according to the general specifications for demand quantification as set by the IDAE [39]. Final energy data are converted into renewable and non-renewable primary energy

[1] https://designbuilder.co.uk/helpv4.5/Content/GSHPCaseStudy.htm.

Table 7a
Weighting factors to translate final energy to primary energy.

Final Energy	Renewable Primary Energy	Non-renewable Primary Energy
Electricity	0.414	1.954
Natural gas	0.005	1.190
Biomass	1.003	0.034
Electricity generation (cogeneration)	0.000	0.000
Electricity generation (photovoltaic)	1.000	0.000

according to the weighting factors published by the Spanish Ministry for Ecological Transition [41]. The weighting factors used in this work are summarized in Tables 7a and 7b. It is assumed that, if any, the electricity production of the ESS is subtracted from its electricity consumption, even though this could lead to negative values. This assumption comes from the fact that the electricity production is consumed in the building itself or in the surrounding area, avoiding having to purchase that electricity from the local electricity network. This is backed by the Spanish legislation on self-consumption that sets the concept of collective ownership of renewable and high-efficiency cogeneration for those consumptions located within a radius of up to 500 m from the electricity production source [42].

2.4.2. Economic assessment

The economic analysis is performed through the Equivalent Uniform Annual Cost (EUAC) method that allows annual costs over a single lifetime to be homogenized for the whole project [43]. So, EUAC brings together investment costs, operational and maintenance costs, final energy costs and the life time of the project in a single indicator (Eq. (1).

$$EUAC = \left(I + A\frac{(1+i)^n - 1}{i(1+i)^n}\right) \cdot \frac{i(1+i)^n}{(1+i)^n - 1} \tag{1}$$

Investment I is calculated for each case and climatic zone, taking as a reference the Spanish database for construction costs [44]. A corresponds to annual costs, which is the sum of the final energy and the operational and maintenance energy costs. The final energy prices have been obtained from Eurostat, these being 0.2403 €/kWh for electricity, 0.0736 €/kWh for natural gas and 0.0635 €/kWh for biomass pellets [45]; while the operation and maintenance cost has been estimated on an annual basis as 2.5 % of the initial investment, as proposed by Arumägi et al. [22]. A single 20 year lifetime (n) value and a discount rate (i) of 5 % are considered for the investment. Taking the same assumption as that presented in Section 2.4.1 for the calculation of the primary energy consumption, any electricity surplus is considered to be consumed nearby and can be computed as an avoided cost, i.e., a negative final energy cost at the electricity purchase price.

3. Results and discussion

This section presents the results obtained from the techno-economic analysis of the 830 simulations as presented in Section 2. Annual simulations on an hourly basis were carried out for each of the scenarios. As an example, the monthly space heating and DHW demand values for the S1 under climatic zone C are summarized in Fig. 6. There, it can be seen that space heating concentrates in the winter season, while DHW has a quasi-constant presence throughout the year.

To complement this information, Fig. 7 contains the air zone mean temperature variation for the 22 dwellings of the reference building. For the sake of clarity, only one winter week has been included, i.e., the typical winter week according to the weather file. It can be seen that the temperatures meet the heating temperature set points set by the Spanish Technical Building Code (20 °C from 8.00 h to 23.00 h, 17 °C the remaining hours). There is a certain degree of overheating that comes from the joint contribution of occupational internal gains and solar gains. This can be avoided by user interaction with the building, but has not been included in the simulations, as it is preferred to comply with the official standard for inter-comparison purposes, even if it leads to a slight overestimation of the demand. The number of unmet load hours was checked for all the cases, resulting in less than 1 % of the simulated time.

To make the analysis easier, data are presented in detail for the climatic zone C, for which the reference building was designed. Then the analysis is extended to the rest of the cities selected and the general distribution and main insights of these results are summarized. Additionally, a dataset related to this article is available at https://data.mendeley.com/datasets/swz7xn2575, an open-source online data repository [46], where all the results can be found in detail.

The data are presented relating the energy consumption of each potential building (scenario) with its EUAC. This allows the cost optimal curve, which represents the minimum annual cost for a given energy consumption level, to be extracted. The benchmark is represented by the reference building (S0), which presents a EUAC of 82.47 €/m^2.year, a total PE consumption of 35.98 kWh/m^2.year and a NRPE consumption of 36.18 kWh/m^2.year. In that sense, it should be noted that the current proposal, even meeting all the remaining requirements defined in the CTE in terms of maximum transmittance for envelope elements (defined in Table 2) and total PE consumption (see Table 1) in terms of NRPE consumption, it does not comply with the minimum requirements set by the CTE with the proposed EES (natural gas boilers and the

Table 7b
Cost-optimal and minimum NRPE cases for each climatic zone.

Climatic zone	Case	ESM	ESS				Investment (€/m^2)	EUAC (€/m^2)	NRPE (kWh/m^2·year)
			Heating	DHW	HR?	RES			
A	**Cost-optimal**	No ESM	GSHP	CHP	No	PVF	104.32	−97.27	−22.92
	Min NRPE	No ESM	GSHP	BIO	No	PVF	109.31	−58.87	−46.64
B	**Cost-optimal**	BAU	ASHP	CHP	No	PVF	119.42	−84.71	−18.70
	Min NRPE	BAU	ASHP	BIO	No	PVF	124.77	−46.38	−42.45
C	**Cost-optimal**	BAU	GSHP	CHP	No	PVF	133.31	−46.66	−3.07
	Min NRPE	EECN-E	GSHP	BIO	No	PVF	121.88	1.85	−26.95
D	**Cost-optimal**	BAU	GSHP	CHP	No	PVF	127.76	−75.54	−17.13
	Min NRPE	EECN-E	GSHP	BIO	No	PVF	149.79	−32.72	−41.06
E	**Cost-optimal**	B ENV	GSHP	CHP	Yes	PVF	183.87	−60.19	−3.55
	Min NRPE	EECN-E	GSHP	BIO	No	PVF	138.7	−19.23	−31.78

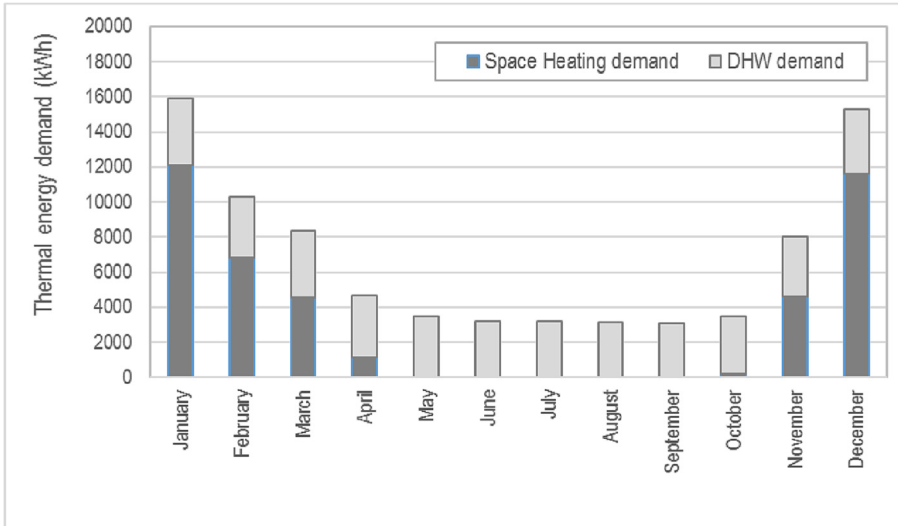

Fig. 6. Monthly space heating and DHW demand values for the reference building, S1 configuration under climatic zone C.

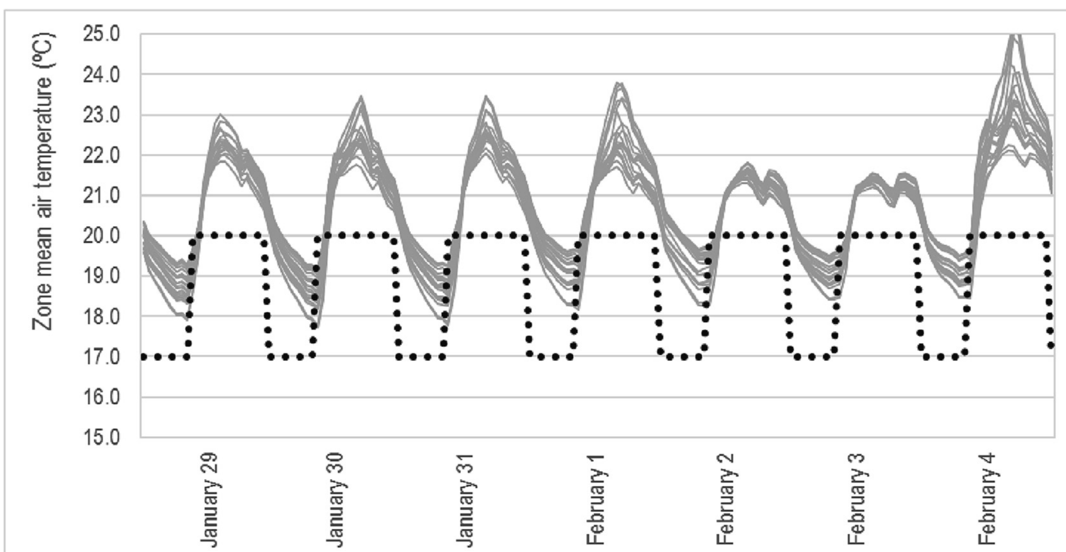

Fig. 7. Set point assumed according to the Spanish Technical Building Code (in black, dotted line) and hourly mean air temperature variation (in grey) for the S1 configuration under climatic zone C (typical winter week, from January 29 to February 4).

minimum share of ST for DHW set in the CTE), so that another alternative will have to be sought for EES in the building. As specified in Section 2.2, as the reference building can be considered a conservative case, the results should be understood as a bottom-line in terms of cost-efficiency; since, for instance, other building orientations more exposed to the sun will benefit from a lower EUAC and Primary Energy consumption as it reduces the space heating load.

As the Spanish Building Technical Code limits the non-renewable and overall primary energy consumption, two graphs are presented, where the specific EUAC and primary energy consumption (in terms of non-renewable primary energy consumption and total primary energy consumption) per conditioned area are represented in Fig. 8 and Fig. 9, respectively. In the figures, the colour of the bubble represents the ESS scenario (see Table 5) and the size of the bubble represents the ESM solution (see Table 4). Additionally, labels are included identifying the scenarios with the highest and lowest PE or NRPE consumption and lowest EUAC values. These labels provide information that indicate the main energy systems of those scenarios (heating, DHW supply and RES if any), as well as an ID number, a unique identifier which helps to identify those scenarios in the dataset presented in [46].

The dashed line linking those solutions presenting the lowest EUAC serves as an estimation of the cost-optimal curve for the scenarios under consideration in this analysis. In both figures, the grey area represents those designs that exceed the maximum non-renewable and total primary energy consumption limit, respectively. As could be expected, the bubbles corresponding to each scenario present the same EUAC in both figures, the only difference being the specific position on the x-axis.

The first thing to notice is that almost all the possible configurations meet the HE0 requirements, with only a couple of cases exceeding the maximum non-renewable primary energy consumption. Thus, it can be stated that meeting the demand

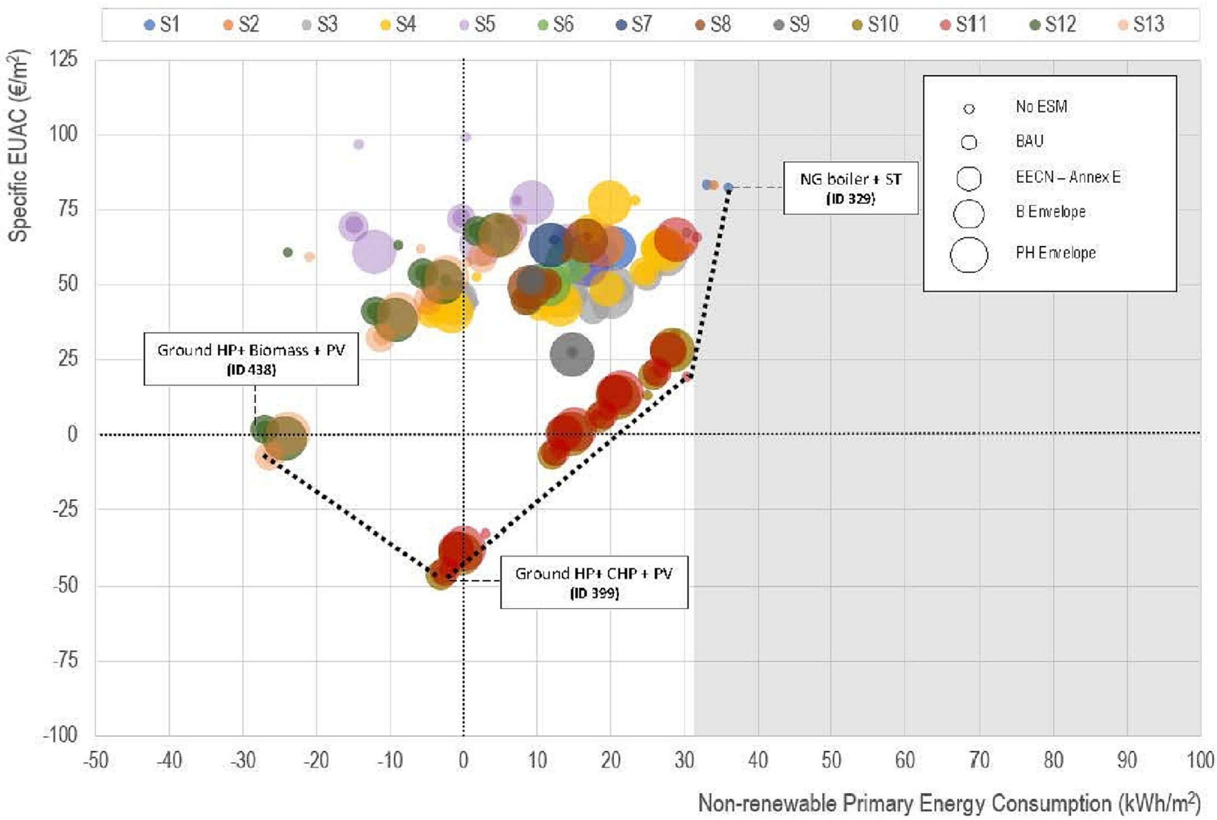

Fig. 8. Specific EUAC versus specific non-renewable primary energy consumption (climatic zone C).

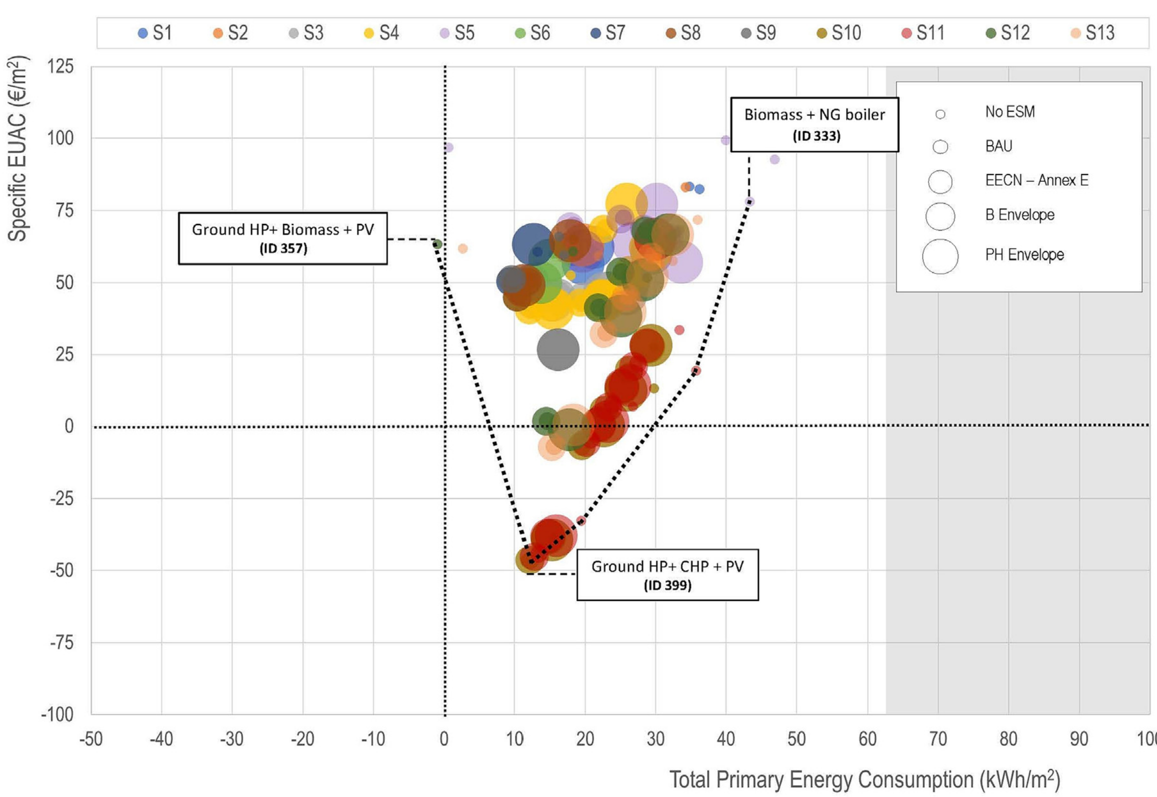

Fig. 9. Specific EUAC versus specific overall primary energy consumption (climatic zone C).

limitation (HE1) eases meeting the primary energy consumption requirement (HE0). In other words, the specifications of the new Spanish Technical Building Code somehow ensure a building to be nZEB.

The minimum of the cost optimal curves (bubbles in the lower positions) corresponds to those solutions including an air-source (S11) or ground-source heat pump (S10) for space heating, a cogeneration unit for DHW production and electricity generation by PV tiles, these covering all the available roof area. As stated by Galimshina et al. [47], the application of ESM has a lower impact on the cost-efficiency of the solutions, which can be explained by the fact that the reference building already presents quite a low equivalent thermal loss coefficient, as it already meets the specifications of the envelope set by the HE1. However, amongst them, the lowest EUAC is shown by BAU and EECN-E envelopes, more efficient than the reference case, but not including heat recovery within the ventilation system. The non-inclusion of heat recovery is justified by the fact that the additional electricity consumption it causes does not compensate the reduction in the heating demand. The minimum of the cost optimal curves (leftmost bubbles) corresponds to a non-renewable and total primary energy consumption of around0 and 15 kWh/m^2, respectively, which can be obtained at a negative EUAC (ranging from −30 to −50 €/m^2). This negative value is caused by the electricity production from the combined operation of the cogeneration and the PV roof, which, as stated, is consumed in the building or the surroundings. This implies an additional income that compensates for the investment, operation and final energy costs of the system over its lifespan. The minimum non-renewable and total primary energy consumption values range around −25 and 0 kWh/m^2, respectively. These correspond to space heating production with a biomass boiler, DHW production with a geothermal (S12) or aerothermal heat pump (S13) and, again, electricity production by PV tiles on the rooftop. In comparison with the cost-optimal solutions, we have a significantly lower primary energy consumption at the expense of a higher EUAC. However, this is around 0 €/m^2, which means that the costs can be covered by the income from avoiding the purchase of the electricity produced from the local network.

At the design stage, the available budget is a common barrier to implementing the most efficient solutions. In order to explore this limitation, Fig. 10 presents the non-renewable primary energy consumption versus the initial investment per square metre. Initial investment ranges from 75 to 200 €/m^2 and, although weak, there is a negative correlation between the non-renewable primary energy consumption and the investment. It should be noted that both cost-optimal and minimum consumption solutions can be obtained from initial investments at around 110 €/m^2. This confirms that these optimal scenarios do not require a disproportionate investment and could be easily reached if the environmental and economic benefits are properly taken into account. When results are analysed in detail, it can be seen that the integration of the RES increases the initial investment, but this increase is relatively low if compared to the total investment and has a great impact in reducing the primary-energy consumption.

Finally, from the results, it can be stated that it is much easier to reduce the EUAC and primary energy consumption by a proper design of the ESS than by implementing ESM. This is justified by the high standards that the Spanish Technical Building Code imposes for the envelope, which is translated into the fact that meeting the HE1 practically ensures meeting the HE0. The same analysis carried out for climatic zone C is performed for the rest of the climatic zones. The general distribution of these results are depicted in Fig. 11, and additionally, all the detailed results for the 830 scenarios can be found in the dataset available online in [46] (see data availability related to this paper). The same labels for identifying the scenarios with the highest and lowest PE or NRPE consumption and lowest EUAC values are used. At a glance,

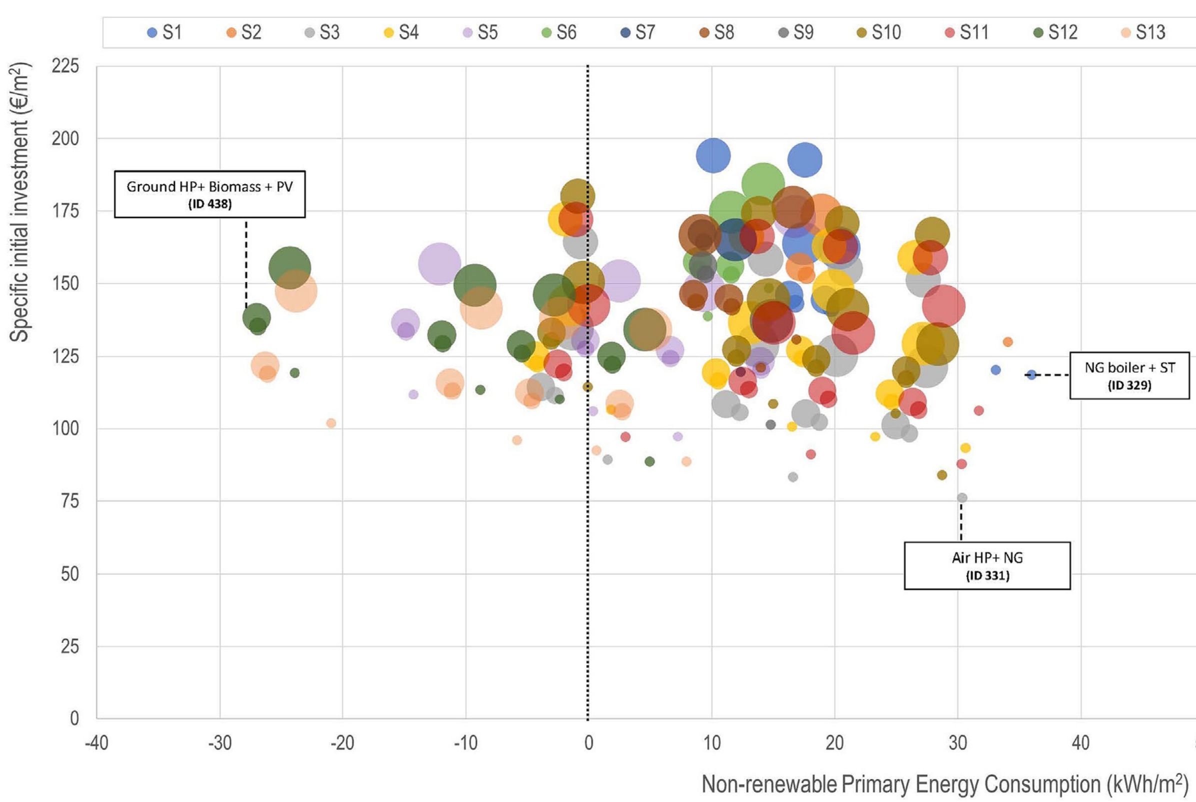

Fig. 10. Specific EUAC versus specific initial investment (climatic zone C).

similar conclusions can be drawn regarding the compliance of the Technical Building Code, i.e., the non-renewable primary energy consumption limit is more demanding than the maximum total primary energy consumption. Specifically, only a few scenarios exceed the former ones, while all of them present a lower total primary energy consumption than the threshold.

For a general analysis of the results from the five climatic zones, cost-optimal and those cases presenting the lowest non-renewable primary energy (NRPE) consumption levels are summarized in Tables 7a and 7b. There, ESS and ESM configurations, as well as the orders of magnitude of both EUAC and non-renewable primary energy consumption, are presented.

A common pattern is observed for all the climatic zones. Specifically, heat pumps are selected as the production technology for space heating; specifically, a ground-source heat pump is selected for all the cases, except for the climatic zone B, for which an air-source heat pump is chosen. For DHW, the same results were observed for all the scenarios: a cogeneration unit is selected for the cost-optimal cases, while for the minimum non-renewable primary energy consumption case, a biomass boiler is chosen. This is explained by the fact that cogeneration uses natural gas to meet part of the thermal demand, while electricity is self-consumed, which is translated into an additional income that significantly reduces the EUAC. This cogeneration unit is substituted by a bio-

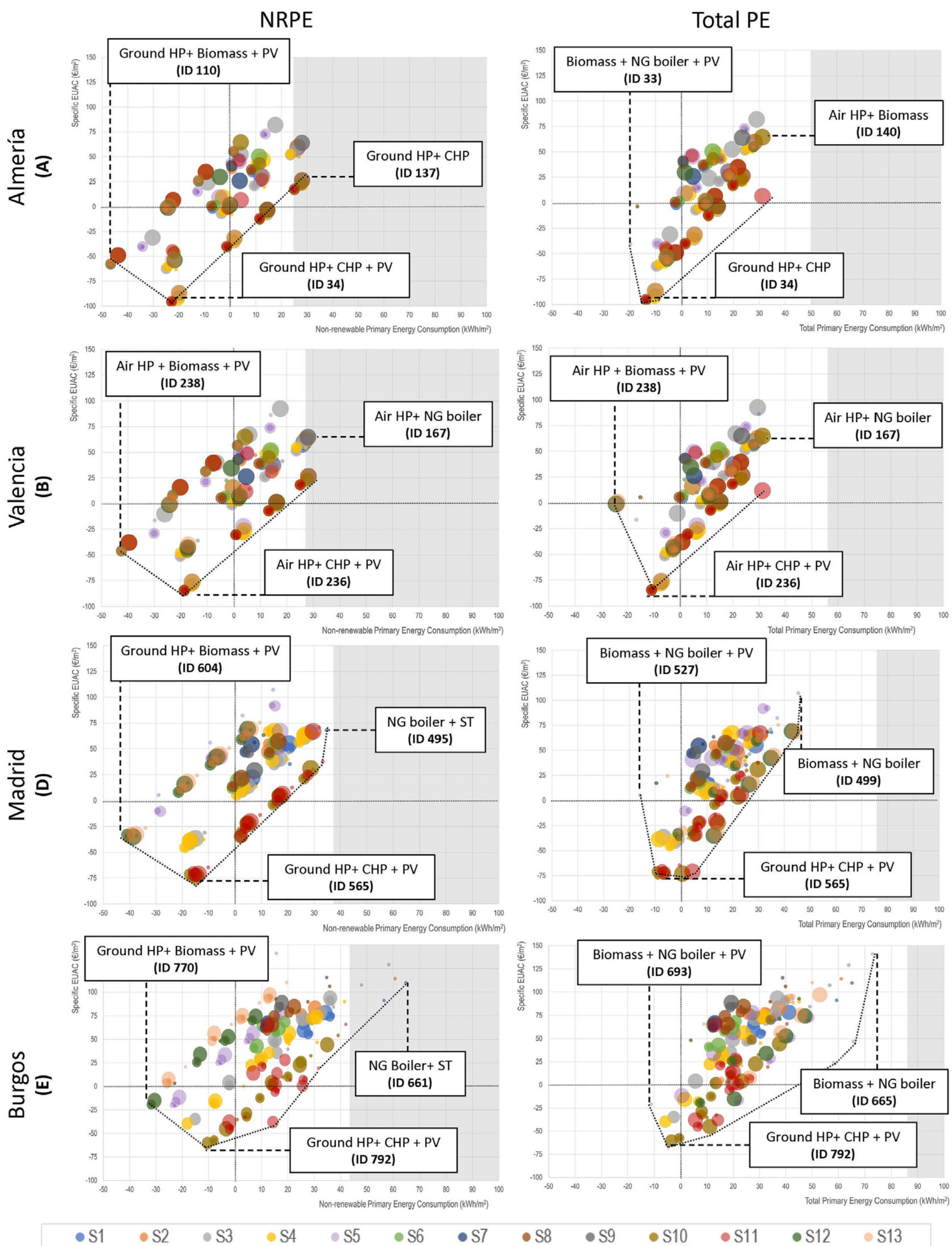

Fig. 11. Specific EUAC versus specific primary energy consumption for climatic zones A, B, D and E.

mass boiler when the objective is to minimize the non-renewable primary energy consumption.

Heat recovery from ventilation is selected for only one of the cases. The reason for this is that, in general, the additional electricity consumption required by the ventilation due to the additional pressure drop caused by the required compact heat exchanger and the double duct system, exceeds the fuel consumption reduction caused by the heat recovery effect. This is partially explained by the fact that all the passive solutions meet the HE1 and, therefore, space heating in general presents low values in comparison to DHW demand (see Fig. 5). As a result, the heat recovery selection is limited to the most demanding case (cost-optimal for climatic zone E). Regarding the integration of RES, it should be noted that the photovoltaic system is preferable to the solar thermal options. Specifically, PV tiles give better results than conventional PV panels since, even though the electricity performance is poorer, they require lower investment and additionally allow the whole roof to be used. The influence of ESM in minimizing EUAC or non-renewable primary energy consumption is limited. This is explained by the fact that all the scenarios already meet the demand limitation set by the Spanish Technical Building Code (HE1), which is much more demanding than the primary energy consumption limitation (HE0). However, as the climate is more severe, the optimal cases slightly increase the insulation level, as this increases its potential in reducing the space heating demand. From the results, it can be seen that the cost-optimal and minimum non-renewable primary energy consumption cases, with the exception of the natural gas-fired CHP units used for DHW production for cost-optimal cases, are RES driven solutions. It is worth noting the main role that PV production plays in this, as it brings a twofold benefit: it allows on-site electricity to be produced to feed the heat pumps and, in the case of any surplus, that exported electricity is translated into an economic saving, since it avoids the need to import electricity from the local network. With all this, it is worth noting that the Spanish Technical Building Code has not set any specification for residential buildings in terms of electricity self-consumptions, at least until the last update in June 2022, in spite of its great potential to achieve optimal cases (especially considering the current energy context, where an increase of energy costs is expected in the future). The reinforcement of this issue can be taken as an essential point to be developed in oncoming updates of the legislation.

In general, it is observed that the non-renewable and total primary energy consumption limitation set by the Spanish Technical Building Code (HE0) lacks ambition, as the vast majority of designs that meet the rest of the specifications meet this constraint, while not being even close to cost-optimality. This is in conflict with the initial definition of nZEB, which aimed for lower primary energy consumption than the cost-optimal solutions [48]. Therefore, there is room for more ambitious limitations for the case of Spain, in line with the conclusions reached by the BPIE in their recent report, where the ambition levels of new buildings standards across the EU was assessed in detail [49]. These could be overcome by the proposals made by Garcia and Kranzl, who investigated the main barriers and opportunities to large-scale implementation of the nZEB standard across Europe [50].

4. Conclusions

Several conclusions on the implications of the new Spanish Technical Building Code can be drawn from the paper, which are summarized as follows:

i) HE1 compliance virtually guarantees HE0 compliance, even though there is a great potential for reducing the primary energy consumption and the EUAC. When focusing on PE consumption, minimum requirements for total PE consumption are between 50 and 86 kWh/m2.year, depending on the climate zone; whereas optimal values in general range between 0 and 20 kWh/m^2.year. Thus, it can be stated that there is indeed room for setting more ambitious primary energy consumption limitations in future updates of the Spanish Technical Building Code.

ii) ESS design optimization presents more room for achieving lower EUAC and primary energy consumption than passive actions (ESM). This is explained by the fact that demand specifications (maximum thermal transmittance of the envelope) set by the HE1, already minimize the thermal demand.

iii) It is possible for all the climatic zones to reach negative values of EUAC and primary energy consumptions, which is largely explained by the fact that the Spanish Technical Building Code does not compute the electricity consumption of household appliances in calculating the primary energy consumption in residential buildings.

iv) PV systems play a central role in ensuring these optimum cases, the benefits of their integration being twofold: the electricity surplus represents an income to the system accounting and the self-supplied electricity feeds heat pumps with renewable energy.

In general, it can be stated that new residential buildings can easily reach negative non-renewable primary energy consumption levels whenever the domestic electricity consumption is not considered in the equation. Given the ever decreasing consumption of thermal uses in the building sector, not including domestic electricity consumption acts as a self-limiting obstacle to encourage the role of buildings as boosters for the energy transition. In this sense, given the potential of PV systems in minimizing EUAC and primary energy consumption, it is worth noting the inclusion, for the first time, of a minimum target of electricity generation from RES in the regulation. This, which aimed to boost self-consumption, together with other recently approved regulations, is essential to be able to set a distributed energy system. The authors recommend including all this learning in subsequent updates of the Technical Building Code.

Data availability

Data is available in mendeley Data-in-Brief

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The project leading to these results has received funding from "La Caixa" Foundation under the project code LCF/PR/SR20/52550013.

Data availability

Datasets related to this article can be found at https://data.mendeley.com/datasets/swz7xn2575, an open-source online data repository hosted at Mendeley Data [46].

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