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Energy Performance of Buildings Directive implementation in Southern European countries: A review

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A R T I C L E I N F O

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A B S T R A C T

The Energy Performance of Buildings Directive covers a broad range of policies and supportive measures designed to help European Union national governments boost energy performance of buildings and improve existing building stock. This review is a comparative study of Southern European countries with respect to their transposition of successive European Directives developed by each Member State through their own regulations and implementations of specific energy performance requirements. The article presents, on the one hand, a complete study of the literature, showing that Italy, Spain and Portugal are the countries that have developed a greater number of articles with content strongly focused on the scope of this work, with *Energy and Buildings* by far being the reference journal on this topic. On the other hand, conclusions about the applications carried out by each Member State are shown, such as the Directives that were implemented in a reasonable time, although not all countries have done so at the same pace or with the same degree of development. Many of the Southern European countries are not adequately prepared for the correct and effective implementation of nearly zero-energy buildings, and there are still many improvements that should be addressed in the coming years. For these reasons and to increase the effectiveness of the framework Directive, a greater number of common objectives subject to mandatory compliance should be considered. Establishing basic formulas and methodologies while ensuring flexibility for Member States to account for their own unique characteristics is necessary to achieve these common objectives.

Contents

Abbreviations: DHW, Domestic Hot Water; EPBD, Energy Performance of Buildings Directive; EPC, Energy Performance Certificate; EU, European Union; HVAC, Heating, Ventilation and Air Conditioning; MS, Member State; NZEB, Nearly Zero-Energy Building; RES, Renewable Energy Source.

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1. Background

The management of energy demand is an important instrument that allows the European Union (EU) to exert a remarkable influence on the world energy market. Buildings account for 40 % of total energy consumption in the EU, and the building sector is expanding, with an increase in energy consumption expected in the coming years [1]. Considering the long renovation cycle of buildings, new buildings and existing buildings subject to major renovations must meet minimum energy performance requirements adapted to local climatic conditions. The measures to be adopted must consider climatic conditions and local particularities as well as internal environmental conditions and profitability in terms of cost-effectiveness.

Reductions in energy consumption and the use of renewable energy sources (RESs) in the building sector are fundamental measures necessary to reduce the EU's energy dependence and greenhouse gas emissions [2]. The measures that are being developed to reduce energy consumption in the EU will allow the EU to comply with the Kyoto Protocol to the United Nations Framework Convention on Climate Change [3] and meet its long-term commitment to limit global temperature rise to below 2 °C while reducing the total emissions of greenhouse gases by at least 20 % compared to 1990 levels and by 30 % based on the international agreement.

To achieve these ambitious and necessary objectives, it is essential to prevent each Member State (MS) from acting unilaterally; the measures and actions each decides to implement should be integrated within a common framework defining the fundamental guidelines for all MSs. To this end, the European Commission issued a series of Directives and established a comparative methodological framework to calculate optimum levels of profitability for the minimum energy performance requirements [4–8]. MSs should use this framework to compare the results with their adopted minimum energy performance requirements. If there are significant discrepancies (greater than 15 %) between the optimal levels of profitability calculated from the minimum energy performance requirements and the minimum energy performance requirements in force, MSs are obliged to justify the difference or provide appropriate measures to reduce the discrepancy.

In addition, the public authorities of each MS should set an example by implementing the recommendations contained in their national plans so that they are among the first to adopt improvements in energy efficiency and to apply the recommendations included in the energy performance certificates (EPCs) as much as possible [9–10]. Such measures should not affect other requirements applicable to buildings, such as accessibility, security and intended use.

2. Overview

The Energy Performance of Buildings Directive (EPBD) is an instrument for enhancing the effect of building regulations on the energy performance of the building stock in MSs [1]. The Directive sets binding targets that must be transposed into national law and implemented via national regulations. The chronological evolution of European Directives can be examined in Fig. 1 and is presented in this Section.

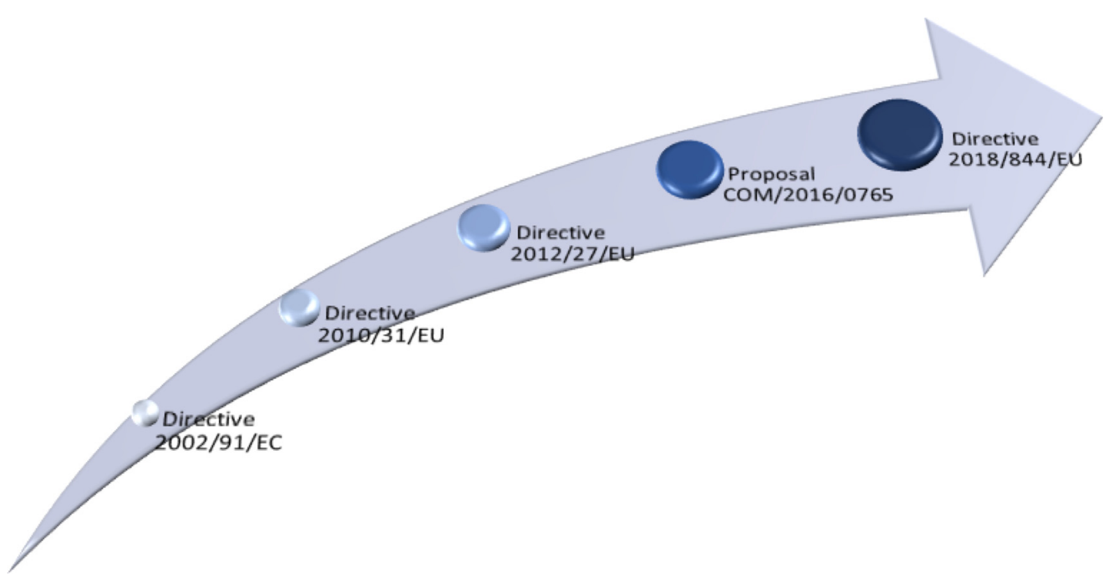

Fig. 1. EPBD evolution.

2.1. Directive 2002/91/EC

The first version of the EPBD, Directive 2002/91/EC, was approved on 16 December 2002 and entered into force on 4 January 2003 [4]. The EU required that all MSs implement the Directive by January 2006. However, an allowance of three years was granted for some articles. The Directive covered four key issues for MSs to address: (i) the establishment of methodologies for calculating the integrated energy performance of buildings; (ii) the application of minimum standards for energy performance in new buildings and certain existing buildings when they are renovated (these standards must be reviewed at least every-five years); (iii) the availability of EPCs for building constructions, sales or rentals and requirements in certain cases for the display of these certificates; and (iv) schemes for inspecting and offering advice on the energy performance of boiler and air conditioning systems.

2.2. Directive 2010/31/EU

Directive 2002/91/EC [4] was later replaced by Directive 2010/31/EU, the so-called 'EPBD recast', approved on 19 May 2010 and entered into force on 18 June 2010 [5]. This version of the EPBD broadened its focus on (i) energy performance requirements; (ii) nearly zero-energy buildings (NZEBs); (iii) EPCs; (iv) cost-optimal levels of minimum energy performance requirements; (v) financial incentives; (vi) market barriers; and (vii) policy improvements.

2.3. Directive 2012/27/EU

Approved on 25 October 2012, the Energy Efficiency Directive, Directive 2012/27/EU, mandated energy efficiency improvements within the EU [6]. The Directive, which entered into force on 4 December 2012, introduced legally binding measures to encourage efforts to use energy more efficiently in all stages and sectors of the supply chain. Moreover, the Directive promoted rules to remove barriers in energy markets and to overcome market failures that may impede the uptake of energy efficiency. Under this Directive, the public sector was assigned an exemplary role, and consumers were given the right to know how much energy they consume.

The following categories were covered by the Directive: energy efficiency targets; building renovation; an exemplary role for public buildings; energy efficiency obligation schemes; energy audits and energy management systems; metering and billing information systems and the right to access these data; consumer information and empowerment; promotion of efficiency in heating and cooling; energy transformation, transmission and distribution; availability of qualification, accreditation and certification schemes; information and training; energy services; an energy efficiency national fund, financing and technical support; and other measures to promote energy efficiency.

2.4. Proposal for a revised EPBD (COM/2016/0765)

On 30 November 2016, the European Commission published 'Clean Energy for All Europeans', a package with three main goals [7]: (i) put energy efficiency first; (ii) achieve global leadership in renewable energies; and (iii) provide a fair deal for consumers. On 26 June 2017, the EU Council agreed to the position in this proposal [8]. Later, on 11 October 2017, the European Parliament's Committee on Industry, Research and Energy voted positively [9] on a draft report [10] on the revised EPBD.

2.5. Amending the EPBD (Directive 2018/844/EU)

Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018, amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency [11], introduced new elements, with its main target to build 'a resilient energy union and a forward-looking climate change policy'. Adopted in July 2018, it sent a strong political signal of the EU's commitment to a clean energy transition, as the building sector has had a vast potential contribution to a carbon–neutral and competitive economy. The amended EPBD [11] in conjunction with Commission Recommendation (EU) 2019/786 of 8 May 2019 on building renovation [12] and Commission Recommendation (EU) 2019/1019 of 7 June 2019 on building modernisation [13] cover a broad range of policies and supportive measures designed to help national EU governments boost the energy performance of buildings and improve existing building stock in both the short and long term: (i) EU countries must establish stronger long-term renovation strategies for decarbonising national building stocks by 2050, with indicative milestones for 2030, 2040 and 2050. These strategies should contribute to achieving National Energy & Climate Plan energy efficiency targets; (ii) a common European scheme must be established for rating the 'smart readiness' of buildings, which is optional for EU countries; (iii) smart technologies must be further promoted, for instance, through requirements on the installation of building automation and control systems and on devices that regulate temperatures at room level; (iv) e-mobility must be supported by introducing minimum requirements for car parks over a certain size and for other minimum infrastructure for smaller buildings; (v) EU countries must express their national energy performance requirements, which will be reviewed every-five years and updated if necessary, in ways that allow cross-national comparisons; (vi) the health and well-being of building users must be promoted, for instance, through increased consideration of air quality and ventilation; (vii) all new public buildings must be NZEBs after 31 December 2018, and all other new buildings must be NZEBs after 31 December 2020; (viii) EPCs must be issued when a building is sold or rented and inspection schemes for heating and air conditioning systems must be established; (ix) EU countries must set cost-optimal minimum energy performance requirements for new buildings, for the major renovation of existing buildings, and for the replacement or retrofitting of building elements, such as heating and cooling systems, roofs and walls; and (x) EU countries must draw up lists of national financial measures to improve the energy efficiency of buildings.

3. Methodology

The implementation of European Directives in MSs is an issue of vital importance that requires specific and continuous control over time to achieve satisfactory and homogeneous results.

The transposition of the EPBD into each of the MSs must be adequately studied and controlled since it aims to improve energy efficiency in the building sector, which is a strategic priority of the EU and is a fair and necessary measure for the responsible use of energy and progression towards a sustainable society.

The scope of this work consists of gathering into a single document a summary of the steps that each MS has taken to achieve European Directives and referencing most of the extant literature that relates to each MS considered.

The objective of this work is to analyse the implementation of the EPBD in each of the MSs studied, including a complete study of the literature, the methodology and the measures that each MS has developed to comply with the guidelines given by the current European Directive. This is the first comparative study characterizing the transposition of the EPBD by MS.

The main contributions are as follows. Regarding the study of the literature, (1) MSs that have developed a greater number of articles with content strongly focused on the scope of this work, (2) the most active reference journals on this topic have been determined, and (3) the best authors with respect to the number of citations and articles published have been determined.

Regarding the applications carried out by each MS, the following are shown: (1) the way in which the Directives have been implemented, showing the implementation times and the degree of development, (2) the position regarding the use of available low energy and RES construction techniques, (3) the preparation for the correct and effective implementation of the NZEB, and (4) the improvements that should be addressed in the coming years.

3.1. Selection criteria for the literature analysed

The SCOPUS platform database was searched for publications covering twelve years (*from 01 January 2010 to 31 December 2021*), including articles, reviews, book chapters and data papers. The search term used was 'EPBD Energy Performance of Buildings Directive'.

TITLE-ABS-KEY (**epbd** AND **energy** AND **performance** AND **of** AND **buildings** AND **directive**)

Table 1 and Fig. 2 show, first, the distribution of publications for each EU country with content focused on the scope of this work. A total of 184 publications were found. The countries with the most numerous relevant publications were Italy (48), Spain (22) and the United Kingdom (16), while a total of 6 countries did not have publications.

Likewise, Table 1 and Fig. 2 show, second, the distribution of publications for each EU country with content strongly focused on the scope of this work. The authors understand that by strongly focusing on the scope of this work, those articles that show the implementation that an MS has carried out in its national regulations that transpose European Directives. They clearly appreciate in their work the energy requirements implemented in their national legislation either through a theoretical study or through an applied practical study. A total of 124 publications were found. The countries with the most numerous relevant publications were Italy (36), Spain (17) and Portugal (9), while a total of 7 countries did not have publications.

3.2. Selection criteria for the analysed MSs

The authors considered it necessary to select MSs for analysis based on the following criteria.

First, if all MSs were considered together, the complexity of the study would make analysis of the different MSs difficult and result in an unwieldy document. It was decided that the goals of this work were more appropriately achieved by analysing MSs that met objective and well-founded criteria based on several studies.

Second, the variability of existing climates among the different MSs greatly complicates their comparison. In reality, each MS has demonstrated variations in implementing the EPBD for the strategies employed and for the methodology and in the measures implemented. This variation is accentuated for MSs with different climates since the situations faced by MSs with Mediterranean climates are not the same as those faced by other MSs with maritime climates on the west coast, dry climates of the middle latitudes or humid continental climates, among others.

Table 1
First, the distribution of works (articles, reviews, book chapters and data papers) for each EU country whose content is focused on the scope of this work. Second, the distribution of works (articles, reviews, book chapters and data papers) for each EU country whose content is strongly focused on the scope of this work. The SCOPUS platform database was searched using the term 'EPBD Energy Performance of Buildings Directive'.

Country	Number of publications	References	Country	Number of publications	References
Austria	4 (***1***)	[14–17] ([17])	Italy	48 (***36***)	[66–113] ([66,68,70–73,75–76,78–79,81–82,85,87,89–100,103–112])
Belgium	8 (***7***)	[18–25] ([19–25])	Latvia	0 (***0***)	- (-)
Bulgaria	0 (***0***)	- (-)	Lithuania	1 (***1***)	[114] ([114])
Croatia	0 (***0***)	- (-)	Luxembourg	0 (***0***)	- (-)
Cyprus	6 (***3***)	[26–31] ([27,30–31])	Malta	2 (***2***)	[115–116] ([115–116])
Czech Republic	3 (***3***)	[32–34] ([32–34])	Netherlands	12 (***6***)	[117–128] ([118–120,125–127])
Denmark	5 (***3***)	[35–39] ([36–38])	Poland	4 (***0***)	[129–132] (-)
Estonia	2 (***2***)	[40–41] ([40–41])	Portugal	10 (***9***)	[133–142] ([133–139,141–142])
Finland	4 (***2***)	[42–45] ([42,45])	Romania	2 (***1***)	[143–144] ([143])
France	2 (***1***)	[46–47] ([47])	Slovakia	0 (***0***)	- (-)
Germany	5 (***4***)	[48–52] ([48–49,51–52])	Slovenia	4 (***2***)	[145–148] ([145,148])
Greece	10 (***8***)	[53–62] ([53–58,60,62])	Spain	22 (***17***)	[149–170] ([149–153,155,157–159,162–164,166–170])
Hungary	2 (***1***)	[63–64] ([63])	Sweden	0 (***0***)	- (-)
Ireland	1 (***1***)	[65] ([65])	United Kingdom	16 (***8***)	[171–185] ([171–172,174,177–179,181–182])
Other	11 (***6***)	[186–196] ([186–187,189,191–192,196])			

Fig. 2. First, the distribution of works (articles, reviews, book chapters and data papers) for each EU country whose content is focused on the scope of this work. Second, the distribution of works (articles, reviews, book chapters and data papers) for each EU country whose content is strongly focused on the scope of this work. The SCOPUS platform database was searched using the term 'EPBD Energy Performance of Buildings Directive'.

Additionally, Bruno et al. [197] and Carpino et al. [198,199] used climate zones to make clear assessments in their studies. Likewise, many authors and published works, such as Serghides et al. [200], Serghides and Georgakis [201], Serghides et al. [202], Detommaso et al. [203], Gagliano et al. [204] and Moschella et al. [205], have limited their analyses to the Mediterranean climate. Therefore, this segmentation has been generalized and considered adequate, justified and effective. Finally, the authors have developed several works based on a segmentation of the study countries by climate zone, focusing on the Mediterranean countries, as seen in López-Ochoa et al. [153,155,157,168].

Finally, based on the above, the authors adopted the selection criteria for the present study to include only MSs that are partially or totally influenced by a Mediterranean climate. The countries thus analysed are Croatia, Cyprus, France, Greece, Italy, Malta, Slovenia, Spain and Portugal. Although Portugal is not partially or totally under the influence of a Mediterranean climate, the authors decided to include it due to its similar latitude, affinity and geographic proximity to Spain.

3.3. Literature of the MSs analysed

The resulting literature from the 9 selected MSs with content strongly focused on the scope of this work includes 78 publications. Figs. 2 and 3 show the distribution of these publications and relevant statistical data as indicated below.

Regarding the number of publications per country, research carried out in Italy was most noteworthy (36), followed by Spain (17) and Portugal (9). According to Journal Citation Reports (Rank by Journal Impact Factor in the area of application of this work), regarding the distribution of publications by quartile, 45 publications occurred in Q1 (57.69 %), 3 in Q2 (3.85 %), 12 in Q3 (15.38 %) and 18 in Q4 (23.08 %). Regarding the chronological distribution of publications, a positive trend was demonstrated, with the largest number of articles (13) published in 2019 and the smallest number (2) published in 2011. Regarding the publication distribution of the articles, *Energy and Buildings* (17) was clearly the reference journal, followed by *Energies* (8), *Energy Policy* (6), *Applied Energy* (6), *Energy* (6), *Sustainability* (4), *Renewable and Sustainable*

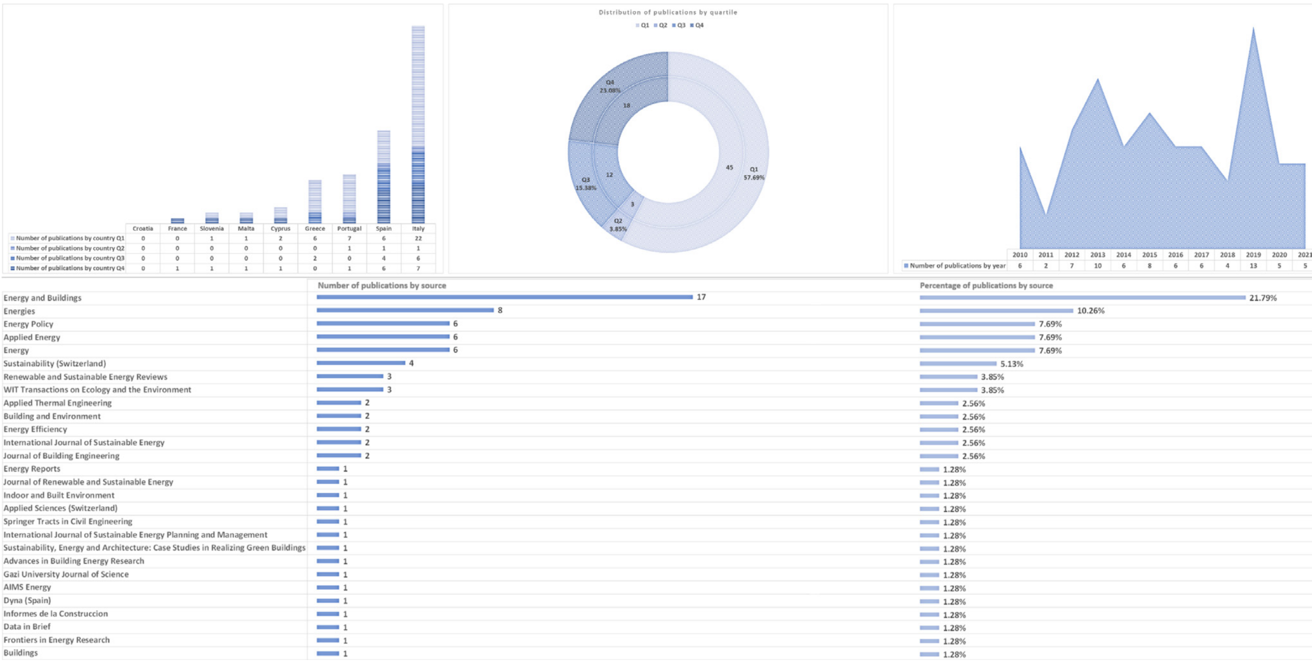

Fig. 3. Relevant statistical data for works (articles, reviews, book chapters and data papers) whose content is strongly focused on the scope of this work for each of the countries selected in this study. Sources: SCOPUS platform database (term 'EPBD Energy Performance of Buildings Directive') and Journal Citation Reports (Rank by Journal Impact Factor in the area of application of this work).

Energy Reviews (3) and *WIT Transactions on Ecology and the Environment* (3). Regarding citations, the total number of citations was 2,607, meaning that the average number of citations for each article was 33.42 citations.

Finally, regarding the influence of the main authors of these 78 publications, the following data are noted: (i) Italy: D'Agostino, D., 423 citations and 6 publications / Baglivo, C., Congedo, P.M., and Zacà, I., 232 citations and 4 publications / Ferrara, M., 215 citations and 4 publications; (ii) Greece: Balaras, C. A., Dascalaki, E. G., and Droutsa, K. G., 237 citations and 5 publications; (iii) Spain: López-Ochoa, L. M., and Las-Heras-Casas, J., 80 citations and 7 publications / De Ayala, A., 59 citations and 1 publication; (iv) Portugal: Brandão De Vasconcelos, A., 80 citations and 2 publications / Silva, P. C. P., 47 citations and 2 publications / Ferreira, J., 38 citations and 1 publication; (v) Cyprus: Fokaides, P. A., 71 citations and 2 publications; (vi) France: Chadiarakou, S., 36 citations and 1 publications; and (vii) Malta: Gatt, D., and Yousif, C., 15 citations and 2 publications; (viii) Slovenia: Domjan, S., and Medved, S., 3 citations and 2 publications; and (ix) Croatia: no publications were found for Croatia.

4. Legislative implementation of the EPBD

When implementing European Directives, each MS has set its own pace and strategy within the guidelines and the timeframes that the European Commission has granted for this task. It is necessary to emphasize that each MS has its own casuistry, possessing different local climatic conditions and diverse constructive historical strategies at a technical and cultural level.

If the varying political sensitivities and legislative independence of each MS are added, the disparity of criteria employed in implementing the given European Directives is easily understood. Therefore, analysing the different implementations by the various MSs is of great interest.

Legislative implementation of the EPBD in each of the MSs under study is shown in Table 2, which lists, for each country, the regulations created for the transposition of the EPBD, as well as the institutions responsible for their implementation and links of interest to their national websites.

The transposition of the different Directives has led to an average of 6 regulations in each analysed MS. This fact shows the commitment and effort that the different MSs have made in creating their own regulatory framework. Over time, many of these rules have been modified and updated.

Nevertheless, after analysing the work done over the last two decades, it can be verified that, in general terms, the Southern European countries have proceeded to implement European Directives within a reasonable timeframe. Although not all began at the same time, the countries studied made the first transpositions of Directive 2002/91/EC [4] to their state regulations during the second half of the first decade of the XXI century. Specifically, France and Italy developed their first standards in 2005; Cyprus, Malta, Spain and Portugal did so in 2006; Slovenia in 2007; and Greece and Croatia formalised their first regulations in 2008. Once this starting point was exceeded, the regulatory adaptations of each MS to successive European Directives progressively normalized, reaching satisfactory response times in the second decade of the XXI century.

Table 2 comprises a single source of information for the legislative implementation of the EPBD in the analysed MSs.

5. Energy requirements in the implementation of the EPBD

Based on the regulations drawn up by each MS (Table 2), the energy performance requirements for both new and existing buildings under compliance with the EPBD are presented in this Section.

5.1. Croatia

In Croatia, the maintenance, construction and design of all buildings must respect the prescribed principles of energy efficiency based on the stated purpose and use of the building. Individual consumption of energy, fuel and water is tracked through remote readings and must be controlled without accruing signif-

Table 2
Comparison of countries: Transposition of the EPBD, institution responsible for its implementation and national websites.

Country	Transposition of EPBD	Institutions	National websites
Croatia [206]	Official Gazettes 153/13, 20/17, 39/19; Official Gazette 128/15; Official Gazette 48/14, 150/14,133/15, 22/16, 49/16, 87/16; Official Gazette 73/15 and 133/15; Official Gazette 73/15 and Official Gazette 88/17	Ministry of Construction and Physical Planning. Ministry of Environmental Protection and Energy.	https://www.mgipu.gov.hr, https://www.mzoe.gov.hr
Cyprus [207–210]	Decree 142/2006, Decree 568/2007, Decree 366/2014 and Decree 359/2015	Ministry of Energy, Commerce, Industry and Tourism	https://www.mcit.gov.cy
France [211–214]	Thermal Regulation 2005, Law 2010/788 of 12 July 2010, Thermal Regulation 2012, and Energy Transition for Green Growth Act of 17 August 2015	Ministry for an Ecological and Solidarity Transition. Ministry of Territory Cohesion. Agency for Ecological Transition.	https://www.ecologie-solidaire.gouv.fr, https://www.cohesion-territoires.gouv.fr, https://www.ademe.fr, https://www.rt-batiment.fr
Greece [215–218]	Law 3661/2008, Law 4122/2013, Law 4342/2015 and Law 4409/2016	Ministry of Environment and Energy.	https://www.ypeka.gr, https://www.buildingcert.gr
Italy [219–222]	Decree 192/2005 of 19 August 2005, Decree 311/2006 of 29 December 2006, Law 90/2013 of 3 August 2013, Decree 26/06/2015 of 26 June 2015	Ministry of Environment and the Protection of Land and Sea. Ministry of Economic Development. National Agency for New Technologies, Energy and Sustainable Economic Development.	https://www.minambiente.it, https://www.mise.gov.it, https://www.efficienzaenergetica.enea.it, https://www.regioni.it/materie/ambiente-energia/energia
Malta [223–231]	Legal Notice 238 of 2006, Legal Notice 261 of 2008 Subsidiary Legislation 423.33, Legal Notice 376 of 2012, Subsidiary Legislation 513.01, Legal Notice 47 of 2018, Technical Document F Part 1, Technical Document F Part 2, Building Regulation Office	Ministry for the Environment, Climate Change and Planning. Ministry for Energy and Water Management. Building Regulation Office. Building Regulation Board of the Government.	https://www.environment.gov.mt, https://www.energy.gov.mt, https://www.bro.gov.mt, https://www.brb.gov.mt
Slovenia [232–235]	Energy Act, Official Gazette 27/07, 17/14 and 81/15; Rules, Official Gazette 18/16	Ministry of Infrastructure. Ministry of the Environment and Spatial Planning.	https://www.mzi.gov.si, https://www.arso.gov.si, https://www.energetika-portal.si, https://www.energetskaizkaznica.si, https://www.ekosklad.si, https://www.eu-skladi.si
Spain [237–248]	Royal Decrees 47/2007, 235/2013, 564/2017 and 390/2021; Regulations for Thermal Installations in Buildings; Basic Document on Energy Saving of the Technical Building Code 2006, 2009, 2013 and 2019	Ministry for Ecological Transition and the Demographic Challenge. Ministry of Industry, Commerce and Tourism. Institute for the Energy Diversification and Saving.	https://www.miteco.gob.es, https://www.minetur.gob.es, https://www.idae.es
Portugal [249–252]	Decree-Law 78/2006, Decree-Law 79/2006 and Decree-Law 80/2006 of 4 April 2006, and Decree-Law 118/2013 of 20 August 2013	Ministry of Environment and Energy Transition. Ministry of Infrastructure and Housing. Agency for Energy.	https://www.portugal.gov.pt/pt/gc22/area-de-governo/infraestruturas-e-habitacao, https://www.portugal.gov.pt/pt/gc22/area-de-governo/ambiente-e-acao-climatica, https://www.adene.pt, https://www.dgeg.gov.pt

icant additional costs [206]. Reporting of optimal profitability calculations and results to the European Commission is mandatory. Energy performance requirements for individual types of buildings include minimum requirements for the energy performance of a building and its particular parts, minimum mandatory share of RESs in the total energy consumption of a building, criteria for NZEB, and contents of the study on alternative energy supply systems [206]. The requirements are prescribed for annual primary energy, annual delivered energy, annual energy needs for heating and cooling, thermal transmittance for individual building envelope components, effects of thermal bridges, efficiency of building systems, airtightness of buildings and share of RESs [206].

The primary energy requirements for NZEBs were established in 2014, and at least 30 % of the annual primary energy must be covered using RESs generated on site. The alternative energy supply system suggestions are (i) decentralized energy supply systems based on energy from renewable sources; (ii) cogeneration; (iii) district or block heating or cooling, particularly where it is based entirely or partially on energy from renewable sources; and (iv) heat pumps [206]. For existing buildings undergoing major renovations, such as more than 75 % of a heated building envelope and building expansion, requirements for energy performance are set. The thermal transmittance value must also fulfil the requirements if only certain building elements covering an area over 25 % are renovated. Both new buildings and renovated buildings are included in the same definition of NZEB. This makes it notoriously more difficult to achieve the NZEB standards in existing buildings due to the dated features of their construction, the limitations of the building perimeter determined by their location and the difficulty of applying the required share of RESs [206].

It has not been possible to find publications for Croatia with content strongly focused on the scope of this work (Table 1 and Fig. 2). Therefore, exploring the main contributions of this MS is not possible.

5.2. Cyprus

In Cyprus, measures have been developed to improve the energy performance of its buildings, which have a high potential for improvement and energy savings. To achieve these measures, the Government of Cyprus has launched tax incentives both for the new housing stock and for the existing housing stock. Technological improvements have been promoted to comply with strict and inflexible regulations. For example, the increasing thickness of thermal insulation in walls can be replaced by superinsulating materials, thus maintaining an efficient level of insulation and a sense of aesthetics. The minimum energy performance requirements are based mainly on compliance with the maximum permissible thermal transmittance value and a maximum shading factor for window openings. According to the requirements for buildings, at least 3 % of the total energy consumption should come from RESs, both for residential and non-residential buildings [207–210].

The National Action Plan for increasing the number of NZEBs identifies several actions to implement after 2020. The requirements do not differ in their application between new buildings and existing buildings but are different depending on their use. Buildings undergoing "major renovations" (over 1,000 m^2) should adhere to the energy performance requirements, should be insulated at the same level as a new building and should reach the minimum category B on the EPC to demonstrate that they are technically and financially feasible buildings [207–210].

Cyprus has three publications with content strongly focused on the scope of this work (Table 1 and Fig. 2). Initially, in 2012, Maxoulis [31] pointed out the challenges of effectively implementing the EPBD recast [5] to untap its true potential. In fact, Maxoulis [31] noted that EPBD underperformed because of different factors, including intrinsic weaknesses, market failures and application limitations. Over the years, the application of the EPBD has been consolidated in Cyprus, reducing these challenges and initial deficiencies. In fact, in 2014, Fokaides and Papadopoulos [30] highlighted the importance of the EPBD, pointing out that improvements in the energy performance of buildings are cost-effective ways of mitigating climate change consequences and improving the security of the energy supply while also creating important job opportunities in the building sector.

Fokaides et al. [27] investigated the impact of the EPBD on the energy performance of Cyprus Land Development Corporation dwellings. It is interesting to note the conclusive differences when comparing buildings built before and after the EPBD was implemented. The reduction in the thermal transmittance value was almost five times (from 1.4 $W/m^2{\cdot}°C$ to 0.3 $W/m^2{\cdot}°C$), either with the use of a 5 cm layer of thermal insulation material or with the use of 30 cm thick hollow bricks with advanced thermal properties. The decrease in the overall heat transfer coefficient was even better in the case of exposed roofs, as the use of a 10 cm thermal insulation layer in the post-EPBD period resulted in a decrease in the overall heat transfer coefficient from 3.2 $W/m^2{\cdot}°C$ to 0.3 $W/m^2{\cdot}°C$. Fokaides et al. [27] compared the results obtained in Cyprus with the results of other MSs, such as Spain, Italy and France. The reduction in energy consumption of these countries can be seen starting in 2014 for its residential building stock, while Cyprus has a clear reduction in these values from 2007 onwards.

Fokaides and Papadopoulos [30] noted that the minimum insulation requirements (art. 5 of the EPBD recast [5]) for Cyprus consider primary energy consumption and meet the insulation requirements for summer (dominant conditions against winter) to ensure the efficient thermal behaviour of the building throughout the year. Likewise, the main indicator currently used in the energy consumption of the building sector is the energy consumption per area per year ($kWh/m^2{\cdot}year$), which is not the most appropriate metric to define the actual energy performance of a building. Instead, Fokaides et al. [27] suggested using the energy consumption per capita per hour of building occupancy as a more reliable indicator. It should be noted that this indicator is not adopted in the European Commission report on the State of the Energy Union concerning key energy indicators [253] or in the energy efficiency indicators report of the International Energy Agency [254].

Fokaides et al. [27] indicated that it is the ambition of Cyprus to limit carbon dioxide (CO_2) emissions through the improvement of energy efficiency in (i) energy certification and thermal insulation of buildings; (ii) third-party financing for investments in energy efficiency in the public sector; (iii) billing for heating, air conditioning, and hot water costs based on actual consumption; (iv) energy audits of companies with high consumption; and (v) adequate inspection of building boilers [27].

5.3. France

In France, the energy policy is based on these 7 pillars: (i) promote the emergence of a competitive and green economy; (ii) ensure security of supply and reduce dependence on imports; (iii) maintain a competitive and attractive energy price at an international level and allow consumers to control energy expenditure; (iv) preserve human health and the environment; (v) guarantee social and territorial cohesion by ensuring the right of access for all households to energy without excessive cost in relation to their resources; (vi) fight against energy poverty; and (vii) contribute to the establishment of a European Energy Union, which attempts to guarantee supply security and build a low-carbon and competitive economy, through the development of renewable energies, interconnections physical, support to the improvement of energy efficiency and establishment of instruments for the coordination of national policies [214].

France has established several climate zones, H1a, H1b, H1c, H2a, H2b, H2c, H2d, and H3. Energy consumption is expressed as a kWh/m^2 coefficient of primary energy. There are two categories of premises in terms of comfort, CE1 and CE2 [211]. The heat losses of a building by transmission through the walls and openings are characterized by the average loss coefficient through the walls and openings of the building, expressed in $W/m^2{\cdot}K$, and determined in the calculation method Th-C-E [211].

France set a goal of vigorously renovating 500,000 housing units per year starting in 2017, at least half of which were expected to be occupied by low-income households, with the goal of reducing energy poverty by 15 % by 2020 [212]. Before 2025, all private residential buildings with a primary energy consumption of more than 330 $kWh/m^2{\cdot}year$ must have undergone an energy renovation [213].

Only one publication for France has been found for which the content is strongly focused on the scope of this work (Table 1 and Fig. 2). Chadiarakou and Santamouris [47] pointed out that the building sector is sufficiently important to justify unified criteria for a holistic approach encompassing the energy performance of its elements. They also noted that significant savings can be obtained in existing buildings, for which modernization and improvement are essential. Chadiarakou and Santamouris [47] created an integrated thermal insulation scheme with the goal of strengthening the building envelope to minimize energy losses as much as possible.

The carbon footprint of the building stock in France can be reduced, as most of it was built according to regulations that lacked energy efficiency guidelines; its main objective was the comfort of users instead of setting clear standards to develop a sustainable construction industry. As one of its main pillars, the current Directive 2018/844/EU [11] implements a long-term strategy that promotes highly energy-efficient and decarbonised building stock by 2050. The objective is to reduce greenhouse gas emissions in France by 80–95 % compared to 1990, to guarantee highly energy-efficient buildings, to seek the highest possible degree of decarbonization and to facilitate the conversion of existing buildings to NZEBs [47]. Specifically, France has developed specific regulations since 2015 to proceed with decarbonization in accordance with the objectives set. The French Climate and Resilience Law of 2021 [255] is a clear example of the progress made in this field, placing France as the leading country that is applying economic incentives to meet this objective that has been set.

5.4. Greece

In Greece, Law 4122/2013 [216] is harmonized with Directive 2010/31/EU [5]. Law 3661/2008 [215] indicates that new buildings are mandated to use solar thermal systems to cover part of the domestic hot water (DHW) needs. The minimum percentage of the solar share on an annual basis is set at 60 %. Likewise, for existing buildings that are radically renovated, the energy efficiency must be upgraded to meet the minimum energy performance requirements to the extent that is technically, operationally and economically feasible. For these purposes and in particular to ensure the gradual transition to buildings with nearly zero energy consumption, the Ministry of Environment and Energy promotes financial, institutional, administrative and/or other incentives [218]. Additionally, the Ministry of Environment and Energy established an indicative national energy efficiency target for the total energy consumption of 2020 [217].

Greece has eight publications with content strongly focused on the scope of this work (Table 1 and Fig. 2). The results of these publications suggest that although the energy performance certification of Hellenic buildings has been in progress since January 2011 [57], the implementation of the new EPBD requirements [4] in Greece is still at an early stage [55]. Dascalaki et al. [60] indicated that the road towards EPBD transposition has been lengthy, rough and bumpy, but on a positive note, the delays have offered opportunities to introduce and implement several key points from the EPBD recast [5] into national legislation and technical regulations.

According to Droutsa et al. [56], residential buildings compose the vast majority of the building sector and play a significant role in the energy and environmental footprint of the whole building stock. Most Hellenic residential buildings are ranked last in the lowest energy class; replacing windows and installing solar collectors are the most popular individual renovations. The European and national commitment to improving the energy performance of buildings is not only a strategic objective but also has practical benefits for all [60]. On a positive note, further analysis of the available Hellenic data reveals that the use of solar thermal collectors for DHW production reduces the total electrical energy consumption by 27–37 % in single buildings and 36–57 % in apartment buildings [53,58,62].

Touloupaki and Theodosiou [54] propose that Hellenic buildings can save a very large amount of energy even with small thicknesses of insulating material, and more rigorous national energy efficiency requirements could create much needed local jobs and healthier indoor environments. Finally, Balaras et al. [58] predicted that by 2020, all new buildings in Greece would be NZEBs and that very low energy requirements would be covered to a very significant extent by energy from RESs.

Pallis et al. [53] indicated that improving the energy efficiency of the building stock in Greece is a major goal, not only for achieving the EU's 2020 and 2030 targets but also for meeting the long-term objectives set by the low carbon economy roadmap 2050. According to Droutsa et al. [56], CO_2 emissions are estimated using the following national conversion factors: 0.989 kg CO_2/kWh for electricity, 0.264 kg CO_2/kWh for heating oil and 0.196 kg CO_2/kWh for natural gas.

5.5. Italy

In Italy, initially Decree 192/2005 of 19 August 2005 [219], the implementation of Directive 2002/91/EC [4], established the criteria, conditions and ways to improve the energy performance of buildings to favour the development, enhancement and integration of renewable sources and energy diversification; contribute to achieving national emissions limitation targets of greenhouse gases set by the Kyoto Protocol; and promote the competitiveness of the most advanced sectors through technological development. Then, Decree 311/2006 of 29 December 2006 [220] corrected and supplemented provisions to the aforementioned decree by implementing Directive 2002/91/EC [4]. Later, Law 90/2013 of 3 August 2013 [221], which was converted into a law with amendments that became Decree Law no. 63, contained urgent provisions for the transposition of Directive 2010/31/EU [5]; included in this law was the definition of infringement procedures initiated by the European Commission, as well as other provisions regarding social cohesion. Finally, Decree 26/06/2015 of 26 June 2015 [222] applied the methodologies for calculating energy performance and defining the prescriptions and minimum requirements for buildings.

Italy has thirty-six publications with content strongly focused on the scope of this work (Table 1 and Fig. 2). Italian national energy policies have evolved considerably with the introduction of new laws, regulatory measures and technical methodologies to promote a more reasonable use of energy and the generation of RESs [70,90]. However, some of the requirements are still left to local or regional authorities for implementation [110], and there is a lack of homogeneity in the information on how energy efficiency can be achieved [68]. Therefore, more controls should be established to verify the accuracy of the declared and established data [93].

Political decision-makers therefore have a legislative instrument that allows them to promote specific actions such as financial support for energy improvement in buildings belonging to a certain period of construction or in buildings of a particular size [92]. In Italy, mandatory measures and incentives play a key role in energy savings in buildings [91]. Current national energy incentives and sales price policies limit the return on investment, as in other Southern MSs, thus reducing massive implementation in Italian new buildings [75,76].

Several years have passed since the introduction of the EPBD recast [5], and the cost-optimal methodology has been the main driver to carry out important research about NZEBs throughout Europe [75]. The cost-optimal approach introduced by the EU global cost method, implemented with the net present value related to the energy performance index values, was demonstrated to be efficient enough to establish the renovation potential of a building and/or a built asset over a long period [73]. Other models and approaches have been analysed in Italy [96,99,107,111,115].

The application of highly efficient solutions that reduce primary energy consumption and CO_2 emissions is more significant in older buildings than in newer buildings since the room for improvement is greater [82,89,100]. Different solutions can be defined to maximize the contribution of renewable sources in a warm climate such as Italy [102,106]. Among them are the use of high-efficiency window frames [105], quality envelopes [66,108], efficient energy generation systems [72], heating, ventilation and air conditioning (HVAC) and RES systems [85,87]. In addition, the light wood envelope represents a suitable option for a single-family home since it achieves good energy performance with limited costs [95]. The long sides of the building should face north and south, if possible [98]; additional costs should be targeted to improve energy performance [94].

In recent years, the construction industry has moved quickly towards the standards of sustainable architecture, characterized by low energy consumption and reduced environmental impacts [109]. The attention given to NZEBs over the last decade has increased due to their great potential for reducing energy consumption [78]. The zero-energy goal has now been proven to be technically achievable [75], and NZEBs are becoming relatively common in developed countries such as Italy, where the cost of energy is periodically increasing [103]. To obtain a nearly zero energy balance, it is necessary to improve the performance of the building envelope in combination with the power generation system [81]. The introduction of the heat pump as an alternative to the traditional boiler for space heating and DHW are important contributions for achieving the objectives of the NZEB [104]. Italy must design policy packages that consider technical, economic and financial aspects to provide the necessary long-term stability for investors in these highly efficient buildings [83]. Furthermore, it is necessary to systematically verify the environmental performance of future NZEBs [71,97].

Salvalai et al. [91] argue that increasing the energy performance of buildings is of vital importance to achieve the transition to a low-carbon economy and to achieve Italian energy and climate goals. The reduction of consumption in the building sector is possible, and in this way, energy efficiency is the first option in the provision of energy services for a low-carbon energy system. Likewise, according to Zangheri et al. [76], the favourable climate scenario shows a necessary transition towards long-term decarbonisation, with important objectives in energy efficiency.

However, Guardigli et al. [73] considered that certain social and environmental aspects must be addressed since it is believed that CO_2 emissions are not considered with the necessary importance from a sustainability perspective. Additionally, according to Dell'Anna et al. [68], with the current renovation rate in Italy, which is approximately 1 % on average, it would take a century to decarbonize the existing building stock, showing the need to dedicate more resources and efforts to the achievement of this purpose.

5.6. Malta

In Malta, Legal Notice 238 of 2006 [223] first legislated the minimum requirements for the energy performance of buildings. The Building Regulation Office is responsible for the administration of building regulations and building control regulations made in accordance with regulations in force [231]. Later, Legal Notice 261 of 2008 [224–226] codified the provisions of Directive 2002/91/EC [4]. Additionally, Legal Notice 376 of 2012 [227] and Legal Notice 47 of 2018 [228] transposed Directive 2010/31/EU [5] to codify its provisions. According to this legal framework, the Building Regulation Board has been tasked with updating current minimum energy performance requirements as informed by cost-optimal studies. The Technical Document F [229,230] has been drafted by a working group consisting of members from the Building Regulation Board, the Building Regulation Office and the Ministry of Energy and Health. The requirements addressed in this document apply to fixed building services that are being designed and/or installed in both new and existing buildings.

Malta has two publications with content strongly focused on the scope of this work (Table 1 and Fig. 2). According to Maltese authors, despite the positive push enabled by the EPBD cost-optimal method to improve the energy performance of buildings in the EU, a review of recent research has established limitations in the potential of the EPBD cost-optimal method because the EPBD cost-optimal approach uses "noncalibrated deterministic reference buildings" [115,116]. The authors propose an innovative update to the current EPBD cost-optimal method to handle uncertainties in energy efficiency packages, better cater to building stock diversity and produce a more realistic cost-optimal range. According to Gatt et al. [115], although the EU has understood inadequacies and has mandated MSs to express energy performance benchmarks that allow "cross-national comparisons" and to establish "stronger long-term renovation strategies", the EU has not established the technical methodology that MSs are to adopt to satisfy these requirements.

Gatt et al. [115] recommended that Malta continue to work to combat climate change and achieve the goal of a carbon–neutral society by 2050. The importance of a cost-effective renovation approach to NZEBs means that deep renovation is an amazing process that will ultimately lead to full decarbonization of the building stock by 2050. Furthermore, Gatt et al. [116] believe that while a flexible approach allows Malta to set its own definition that has the potential to better meet its specific requirements, it adds complexity when comparing NZEB benchmarks and makes it quite difficult to correctly measure the ambition levels in building stock decarbonization.

5.7. Slovenia

Slovenia ensures competitiveness in the energy market according to the principles of impartiality and transparency, considering consumer protection and effective control implementation over energy supply [232,233]. The objectives in the field of energy supply and use are detailed: security of energy supply, assurance of effective competition in the energy market, competitiveness in the implementation of nonmarket activities, efficient energy conversion, reduction of energy consumption, efficient use of energy, energy efficiency, increased production and use of RESs, the transition to a low-carbon society using low-carbon energy technologies, provision of energy services, assurance of social cohesion, protection of consumers as final consumers of energy, and assurance of effective control over the implementation of the provisions of this Act [234,235].

Slovenia has two publications with content strongly focused on the scope of this work (Table 1 and Fig. 2). According to Slovenian authors, the planning process of NZEBs, as defined in EPBD, requires that designers check their solutions at all stages of planning. For the planning process, buildings with a large proportion of advanced glass façades and even all-glass buildings can fulfil NZEB requirements [145]. In addition, the link between environmental protection and energy policy on future energy supply and demand is essential. The contents of the EPBD recast [5] as direct results of global warming mitigation policy, as well as the energy performance indicators of NZEBs, are key factors to achieve appropriate performance [148].

Domjan et al. [145] consider that one of Slovenia's aims is to make its existing building stock more energy efficient as part of its plan for a low-carbon energy economy. This is well justified given that 40 % of total final energy consumption and one-third of CO_2 emissions in Slovenia are attributed to the building sector.

5.8. Spain

In Spain, in 1979, the first basic building standard and thermal conditions on buildings were created [236]. Subsequently, in 2006, the Technical Building Code was approved, thereby establishing a fundamental pillar on which Spanish regulations were developed [237]. From then until 2013, because of European Directives, a series of updates were made to the Basic Document on Energy Saving of the Technical Building Code [238,242,243]. These updates were carried out until 2017 through modifications to the Basic Document on Energy Saving and the Basic Document on Health of the Technical Building Code [244] and until 2019 through modifications of the Basic Document on Energy Saving [247].

On the other hand, in 2007, the basic procedure for the energy performance certification of new buildings was approved; its main objective was to determine the methodology for calculating the energy performance rating [238–241]. Subsequently, in 2013, the basic procedure for the energy performance certification of buildings was updated [245] and then profoundly modified in 2017 [246].

Spain has seventeen publications with content strongly focused on the scope of this work (Table 1 and Fig. 2). According to Spanish authors, compliance with the EPBD recast [5] in Spain ensures major energy savings in buildings [155,166,167], and a positive aspect of the EPBD is that, for all MSs, compliance requires a tightening of minimum energy performance requirements or a change in the application model of the existing ones [164].

In addition, some authors present a comprehensive analysis of the regulatory changes in the fields of energy saving and efficiency that apply to educational buildings, the third most widespread typology within the diverse non-residential building sector in Spain [150,170]. The methodologies adopted in Spain can lead designers to make incorrect decisions that may affect the protected heritage values of historic buildings [152]. The proposed solutions with the appropriate methods can serve as an example for other Mediterranean countries [157]. Likewise, other authors consider them applicable to Latin American countries [149,151].

Finally, as Europe moves towards NZEBs, EPCs can play a relevant role in encouraging property developers and the rest of the market to move in this direction [159,162]. The energy consequences of these changes highlight aspects that must be improved to comply with upcoming regulations: creation of guidelines to meet the new requirements, greater importance of thermal bridges, creation of the NZEB model, and redesign of the EPCs [153,163,167]. These measures contribute to reducing the current gap between the most energy-efficient solutions and cost-optimal renovations [158,169].

López-Ochoa et al. [168] indicate that the current Spanish legislation [247] redefines the NZEBs and ensures considerable energy savings compared to the previous Spanish legislation [244] for both new and refurbished buildings, thus contributing to achieving buildings with high energy efficiency and low carbon emissions for the period 2030–2050. Furthermore, Galiano-Garrigós et al. [152] found that these improvements not only save energy and money but can also reduce the carbon footprint by an average of 16 %. The carbon emissions costs of energy use increase the return on energy efficiency investments because energy is more expensive, making some profitable projects economically viable. Likewise, López-Ochoa et al. [157] believe this is due to less carbon-intensive energy consumption due to the use of renewable energy and more efficient installations, as well as a greater emphasis on insulation standards.

5.9. Portugal

In Portugal, the State ensures the improvement of energy performance and indoor air quality in buildings through the National System of Energy Certification and Indoor Air Quality in Buildings [249]. The regulations [250,251] transpose Directive 2002/91/CE [4] into the current national legal orders. In addition, the regulation [252] transposes Directive 2010/31/EU [5] into the national legal order. Through these rules, the following are established: (i) the conditions to be observed in the design of new HVAC systems; (ii) the maximum energy consumption limits in existing large service buildings; (iii) the maximum energy consumption limits for the entire building; (iv) the maintenance conditions of the HVAC systems, including the necessary requirements to assume responsibility for their operation; (v) the conditions for monitoring and auditing the functioning of buildings in terms of energy consumption and indoor air quality; and (vi) the requirements, in terms of professional training, to which the technicians responsible for the design, installation and maintenance of air conditioning systems must comply, in terms of both energy efficiency and indoor air quality.

Portugal has nine publications with content strongly focused on the scope of this work (Table 1 and Fig. 2). According to Portuguese authors, one of the best opportunities to improve the energy efficiency of buildings is during retrofitting. One of the key steps in building retrofitting is the selection of retrofit actions from many possibilities, which are derived from a large set of materials for different purposes and display different characteristics [138]. However, to reach the EPBD's goals, especially considering the existing building stock, new retrofit solutions are needed, which must be well adapted to the specific building stock needs and ensure that the building retrofit can achieve the NZEB standards [137,142].

The measurement campaign confirmed the necessity of reducing the thermal transmittance values of the envelope using higher thermal insulation levels [134,135]. It was observed that the parameters with the highest influence on the cooling and heating needs do not have a significant influence on primary energy needs. On the other hand, the parameters with the highest influence on the DHW needs strongly influence primary energy needs [136]. In addition, the current comfort requirements of the Portuguese regulation are not sufficient by themselves to achieve the comfort categories specified in the European legislation in the building studied, since their main concerns are energy efficiency [140,141].

Finally, as the world faces constant increases in oil prices and consequently energy prices, annual savings from energy reductions may have a significant benefit on the life cycle analysis of the building and may be the only way to maintain competitiveness and functionality [139].

Ferreira and Pinheiro [139] considered the reduction of energy and carbon impacts a priority for Portugal in sustainable construction, and it can be achieved in two complementary ways: passive and active. The aforementioned authors consider that after carrying out a correct passive design, this must be complemented with efficient active measures to reduce energy consumption and provide electrical energy produced by renewable systems to achieve carbon- and energy-neutral buildings.

5.10. NZEB status in the analysed MSs

Once all the MSs that are the object of this study have been analysed, Table 3 is drawn up. The results of the literature written by national regulators and experts in the 9 MSs studied are presented. This comparative summary focused on the NZEB legislation available, climate zones, construction quality, primary energy use intensity, overheating risk, life cycle assessment CO_2 status, thermal comfort standards, and airtightness.

The analysis is summarized in Table 3, providing a single source of information for the NZEB status in the analysed MSs. The following data present valuable and representative findings on the implementation approaches of NZEBs.

6. Discussion

Abela et al. [179] pointed out that although there is considerable variety in the methodology of implementation of the EPBD in different MSs, several common difficulties are quite clear. It has not been an easy task for each MS to adapt the European Directives [4–13] to the peculiarities and realities of their climates. Some countries have been sanctioned by the EU for being late in transposing European Directives [4–13] to their national regulations [60]. At the legislative level, the initial development of definitions and regulations for each of the countries analysed has been satisfactory, and all have been implemented within five years (2012–2017). In the authors' opinion, this seems reasonable. Specifically, Cyprus developed its standards in 2012; France, Greece and Italy did so in 2013; Croatia and Portugal in 2014; Malta and Slovenia in 2015; and Spain formalised their first regulations in 2017.

It can be verified that the MSs analysed have distributed their responsibilities in similar manners [27]; implementation has occurred through a corresponding ministry with competence in the matter and centralized through specific offices/institutes/agencies, such as the French Agency for Ecological Transition, Maltese Building Regulation Office, Institute for Energy Diversification and Saving in Spain or Portuguese Agency for Energy, each of

Table 3
Comparison of countries. NZEB legislation available, climate zones, construction quality, primary energy use intensity, overheating risk, life cycle assessment CO_2 status, thermal comfort standard, airtightness.

Country	NZEB legislation available	Climate zones	Construction quality	Primary energy use intensity	Overheating risk	Life cycle assessment CO_2 status	Thermal comfort standard	Airtightness	RES most used
Croatia [206]	Yes, National Plan is in place		Low	No	Low	Initial	No	No	Selectable between wind energy, solar systems or cogeneration processes
Cyprus [207–210,256]	Yes, National Plan is in place	1, 2, 3, 4	Low	100–125	High, 35 deaths registered every year in residential buildings	Initial	No	No	Mainly used thermal or photovoltaic solar systems
France [211–214,256]	Yes, with positive energy buildings and low carbon label	H1a, H1b, H1c, H2b, H2c, H3	High	70–110	Low	Consolidated	Yes, adaptive comfort model based on EN 15251 and ISO 7730	Yes	Selectable between wind energy, solar systems or cogeneration processes
Greece [215–218,256]	Yes, National Plan is in place recently	A, B, C, D	Low	No	High, 300 deaths registered every year in residential buildings	Initial	Yes, adaptive comfort model based on EN 15251	No	Mainly used thermal or photovoltaic solar systems
Italy [219–222,256]	Yes, National Plan is in place	A, B, C, D, E, F	Medium	It should be lower than the baseline building	High, 1,700 deaths registered every year in residential buildings	Initial	Yes, PMV and PPD from ISO 7730:2005 and presciptions on surface and interstitial condensation from EN 13788	Yes	Prioritizes the use of thermal solar systems, although their partial or total replacement by other RES is allowed
Malta [223–231]	Yes, National Plan is in place	Unique	Low	No	High, 15 deaths registered every year in residential buildings	Initial	No	No	Mainly used thermal or photovoltaic solar systems
Slovenia [232–235]	Yes, National Plan is in place		Low	No	Low	Initial	No	No	Selectable between wind energy, solar systems or cogeneration processes
Spain [237–248,256]	Yes, National Plan is in place recently	α3, A2, A3, A4, B2, B3, B4, C1, C2, C3, C4, D1, D2, D3, E1	Medium	No	High, 1,300 deaths registered every year in residential buildings	Initial	Yes, indoor limits based on Fanger model and ISO 7730	Yes	Prioritizes the use of thermal solar systems, although their partial or total replacement by other RES is allowed
Portugal [249–252,256]	Yes, National Plan is in place	I1, I2, I3 V1, V2, V3	Medium	No	Medium	Initial	Yes, ISO 7730, EN 15251 preliminary study done on adaptive comfort	Yes	Selectable between wind energy, solar systems or cogeneration processes

which has developed energy policies based on guidelines defined by its own governing bodies. Likewise, these offices/institutes/agencies carry out relative control of compliance with the minimum requirements by reviewing the construction projects of new buildings or by reviewing the projects of building refurbishment [115]. However, the main control was carried out by the regional and local administrations of each MS through specialized officials (mainly architects or engineers) who have the obligation not to grant building permits that do not comply with the established regulations.

García-Hooghuis and Neila [164] highlight the positive aspects of the EPBD for MSs, finding value in the measures adopted by the MSs in their respective national regulations. Therefore, in each of the MSs analysed, as a result of transpositions from the European Directives [4–13], a set of national regulations has been issued to introduce established measures: (i) obligations to renew a percentage of the total floor area of heated and/or cooled public buildings to meet the minimum energy performance requirements; (ii) technical requirements for NZEBs and for building systems; (iii) increases in the minimum requirements for buildings, building components and technical building systems, as well as conversion factors; (iv) use of RESs in buildings; (v) updates of the rules of independent experts for inspection of air-conditioning systems; and (vi) limitations on energy demand, energy efficiency of lighting installations, limits on energy consumption and definitions of the NZEBs, among many other measures.

In terms of the construction quality used, France is in first place and stands out from the rest of the MSs analysed. France is an MS with a more boreal geographical position and therefore is subject to colder weather conditions, which has led to more demanding regulations regarding the requirements for its thermal envelope [214]. Croatia, Cyprus, Greece, Malta and Slovenia use construction materials of lower quality (Table 3). In the case of Cyprus, Greece and Malta, this situation is justified due to their geographical position in a more southern area and in the heart of the Mediterranean Sea (with warmer and more temperate weather conditions). In the case of Slovenia and Croatia, the requirements demanded in their regulations [206,235] should be increased to improve their construction quality to make it similar to the intermediate level currently held by MSs such as Portugal, Spain and Italy.

On the one hand, the criteria used by the MSs analysed regarding the establishment of primary energy consumption limits are similar for all of them, with no major differences [33]. The 9 MSs analysed establish a requirement for primary energy consumption, which imposes a limitation on the primary energy consumed for the combined use of heating, cooling, DHW, lighting and auxiliaries, with unanimity of criteria for this variable. A similar fact occurs with the thermal transmittance values, which are also transposed into their national regulations in a similar way for all the MSs analysed, in which the definition of their limit values is mainly influenced by the climate zone to which they belong depending on the geographical location of the construction to be carried out. Likewise, all the MSs analysed have been reducing the maximum limits allowed over the years, in accordance with the mandate of the published European Directives [4–13].

On the other hand, there are situations when the criteria used by the MSs analysed vary substantially from one to another [202]. For example, the variation in the definition of the refurbishment level of a building depending on the MSs analysed is significant. These differences can be seen both in the definition itself and in the number of levels established. For example, while Italy uses 3 levels, Spain and Slovenia use only 2 levels. Italia (3): Major renovations (first level) are defined as refurbishment of at least 50 % of the envelope and renovation of the heating and/or cooling plant of the entire building. Major renovations (second level) are defined as refurbishment of at least 25 % of the external surfaces of the building with or without renovation of the heating and/or cooling plant. Minor renovations are defined as refurbishment of less than 25 % of the external surfaces of the building and/or modification of the heating and/or cooling plants. Spain (2): Major renovations are defined as renovation work in which more than 25 % of the total surface area of the final thermal envelope of the building is renewed. Minor renovations are defined as renovation work in which less than 25 % of the total area of the building's thermal envelope is renewed. Slovenia (2): Major renovations include if at least 25 % of the area of the building envelope is subject to renovation. Minor renovations include if a renovation is less than 25 % of the thermal envelope area or if buildings have a floor area smaller than 50 m^2.

D'Agostino [90] pointed out that the analysis of national plans and templates submitted by MSs up to January 2020 reveals a positive development in favour of the adoption of NZEB definitions, which is undoubtedly very positive for MSs in terms of sustainability and energy savings, as shown by existing studies, for instance, Gagliano et al. [81], López-Ochoa et al. [153] and Salem et al. [171]. The NZEB definitions for some of the MSs analysed are being formulated differently for new buildings and for existing buildings, while in other of the MSs analysed, there is no difference [76]. In terms of maximum primary energy values in kWh/m^2 year, France requires a value of 40–65 for new buildings and a maximum of 80 for existing buildings, and Slovenia requires values of 45–50 and 70–90, respectively. However, other countries do not take this approach, such as Cyprus, which requires the same value of 100, or Italy, which requires achieving the Class A1 label regardless of whether they are new buildings or existing buildings.

Regarding airtightness, within the MSs analysed, two clearly differentiated blocks are found. On the one hand, Italy, Spain and Portugal have advanced regulations regarding the control of airtightness and the requirements that must be met in their buildings [221,242,252]. On the other hand, Croatia, Cyprus, Greece, Malta and Slovenia have more lax regulations in this field, which puts them at an energy disadvantage compared to the first mentioned block (Table 3). France is once again the MS with the most complete and consolidated regulation in this field, which was developed to adapt to a more continental climate [213].

However, there is debate about the types of renewable technology to be used [29]. External generation and nearby generation begin to have more weight compared to on-site generations, the latter being the ones mostly used to date, although the gap between both RES options is decreasing. As seen in Table 3, the variations in RES use by the different MSs analysed are small. On the one hand, Cyprus, Greece and Malta mainly used thermal or photovoltaic solar systems. On the other hand, Croatia, France, Slovenia and Portugal most commonly select wind energy, solar systems or cogeneration processes. Finally, Spain and Italy prioritize the use of thermal solar systems, although all the states analysed are allowed to replace partial or total use with other RESs.

Regarding the risks of overheating, Medved et al. [148] note that one of the effects of climate change is undoubtedly the increase in temperatures. This statement is beyond discussion and is widely recognized by the scientific community. Among the countries analysed, Italy and Spain exceed 1,000 deaths per year and must lead measures to prevent the number of deaths that are occurring (Table 3). Specifically, Spain recently promoted both financial incentives for the improvement of energy efficiency and an increase in the inspection work of the administration to implement energy-efficient buildings to prevent these deaths [248].

Evaluating the trajectory through the information published by the MSs, without a doubt, shows that there is still a great margin for improvement [37]. Therefore, clear targets must be set to contribute to progress in the next decade, especially to achieve a highly energy-efficient and decarbonized building stock. Regarding achieving high energy efficiency, Attia et al. [256] show that most Southern European countries are poorly prepared for NZEB implementation, especially for the challenge/opportunity of retrofitting existing buildings. With some frequency, ambiguous data or definitions can be found; it is unknown if they are new versions of the regulation of the MSs or are designed solely to comply with the requirements established by the EPBD. A stronger connection between policies, measures and NZEB needs to be established. Additionally, it would also be advisable to create a common approach to further develop NZEB concepts, and definitions in synergy with the climatic, societal and technical state of progress in Southern Europe are essential. Regarding decarbonised building stock, Sicignano et al. [70] show an ambitious target based on the notion of neutralizing the consumption of resources through zero carbon buildings whose facilities work with the maximum possible efficiency. To achieve this goal, a sustainable design and an architecture focused on functionality instead of aesthetics are fundamental aspects to take into consideration. To this end, the design and architecture process should contemplate the following: (i) to improve the thermal envelope of the building to mitigate energy needs, being able to use passive heating and cooling techniques for this; (ii) to reduce the energy consumption of the building's active systems, and (iii) to incorporate the use of RESs in percentages higher than those needed. It must also be a fundamental objective to extend, as France is already doing, the adoption of low-carbon labels of the positive-energy and low-carbon type with the establishment of various levels of graduation, economically encouraging those promoters who opt for these types of buildings.

Finally, with respect to the COVID-19 pandemic, it has not caused a paralysis of legislative regulation (i.e., Spain published its national plan on NZEB during the pandemic), nor has it caused a decrease in activity in the building sector, which has continued its normal activity in an environment of growth. The war in Eastern Europe has not had a significant influence on issues of legislative regulation in any of the MSs. However, in recent months, there has been a rise in prices and an incipient slowdown in activity in the sector, which could have an influence in the coming years depending on its evolution and the current macroeconomic situation. Although the measures currently in place should allow these types of emergencies to be addressed normally, a legislative effect could occur, as has been clearly seen in the EU in the field of energy with the new inclusion of fossil gas and nuclear energy as sustainable or green energy [257].

7. Conclusions

Undoubtedly, the impact of the EPBD has been very positive over the last decade. In all MSs, these European Directives have implemented a tightening of minimum energy efficiency requirements, have limited the consumption of non-renewable primary energy or have developed changes in the application models for existing ones. These factors are applicable to new buildings and renovations of existing buildings. New buildings represent a very small part of the building stock compared to existing buildings. In the authors' view, it is clear and necessary that advanced regulation for existing buildings is the main focus of the Directive.

Regarding the study developed for the selected MSs in relation to the existing scientific literature, it is concluded that Italy (36), Spain (17) and Portugal (9) have the largest number of scientific works. In agreement with this conclusion, an Italian author D'Agostino, D. (423), and the Spanish authors López-Ochoa, L.M., and Las-Heras-Casas, J. (7), are at the forefront with respect to the number of citations received and articles published, respectively. Likewise, *Energy and Buildings* is clearly consolidated as the reference journal on this topic, with 17 published articles, followed by *Energy*, with 8 published articles.

As the Directive currently proposes, MSs are allowed to adapt the regulations to their specific needs with a progressive tightening of minimum requirements towards an NZEB model. This is an unquestionable advantage in that it allows the use of the specific resources of each country to achieve the common objective of zero consumption. It has been widely recognized by the scientific community that NZEBs have great potential to reduce energy consumption while increasing renewable energy contribution, thereby alleviating the depletion of energy resources and the deterioration of the environment. Progress is undoubtedly slow, but it can be seen in many MSs compared to the initial stages of implementation of European Directives. Although all the MSs analysed have developed and published their NZEB legislation, many of them are not adequately prepared for the correct and effective implementation of the NZEBs, and there are still many improvements that should be addressed in the coming years.

To be successful, it is important to have consistent NZEB requirements and apply them consistently. Energy efficiency measures must be used to reduce demand, and the use of RESs to supply the remaining demand is also notable. The MSs regulate their standards, in a general way, regarding both public and private, residential and non-residential buildings, and also separating new buildings from the rehabilitation of existing buildings. In individual buildings, RES techniques are considered the most operational alternative. The main technologies chosen are solar technologies such as photovoltaic, solar thermal and passive solar energy. Likewise, heat pump technologies, geothermal energy, passive cooling, wind energy, biomass, biofuels, micro-cogeneration and heat recovery are also used.

Regarding the construction quality used, France stands out positively compared to the other MSs analysed. Slovenia and Croatia must tighten the requirements established in their regulations to improve the quality of the construction materials used. Regarding airtightness, Croatia, Cyprus, Greece, Malta and Slovenia have less advanced regulations in this field compared to the rest of the MSs analysed, once again highlighting French regulations as the benchmark. Regarding the overheating risk, Italy and Spain suffer the highest number of deaths per year and require additional effort to mitigate this difficult situation. Regarding decarbonisation in the different MSs analysed, most of them are still far from reaching acceptable values in this field. Except for France, all the other MSs analysed have recently included the relevant regulations on the reduction of carbon emissions and are in the early stages of implementation. It is France, therefore, that leads the construction of low carbon buildings, as well as the use of low carbon labels.

Events that have occurred recently, such as the COVID-19 pandemic and the current war in Eastern Europe, have thus far not had a remarkable influence on the development and evolution of the EPBD policies put into operation by each of the MSs.

Finally, it is the opinion of the authors that to increase the effectiveness of the framework Directive and achieve common goals, a greater number of common objectives with mandatory compliance should be implemented, thereby establishing basic formulas and methodologies without neglecting the flexibility necessary for MSs to develop their own final guidelines that account for their unique characteristics.

Data availability

Data will be made available on request.

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.

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