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From Nearly Zero-Energy Buildings (NZEBs) to Zero-Emission Buildings (ZEBs): Current status and future perspectives

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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 building sector holds a relevant position in decreasing greenhouse gas (GHG) emissions within the European Union (EU). The revised Energy Performance of Buildings Directive (EPBD), recently adopted, sets forth ambitious goals to make the EU building stock carbon–neutral by 2050.

Currently, the Nearly Zero-Energy Building (NZEB) standard remains mandatory for all new buildings from 2021 to 2030. This paper assesses the progress of Member States in implementing NZEB standards, based on extensive data collection and harmonization. The findings reveal that the NZEB concept is well-established and average energy performance has improved by about 10 % over the past four years. New NZEB have about 30 % lower energy demand than renovation to NZEB level. However, many countries still lag behind in meeting recommended benchmarks, particularly when looking at the non-renewable energy demand.

Looking ahead, the 2024 revised EPBD sets Zero-Emission Building (ZEB) as the goal for all new buildings starting in 2030. The paper explores how ZEB requirements might evolve from current NZEB definitions. Projections suggest that future ZEBs, which are 10 % more ambitious than current NZEB levels for total primary energy demand, would show better alignment with recommended benchmarks. However, the renewable energy contribution in NZEBs vary from 9 % to 55 %, and integrating enough renewables to meet the ZEB standard of zero on-site carbon emissions remains a challenge. In some countries, the high total primary energy demand can further complicate this goal. The conclusion highlights the need for stricter energy thresholds and further integration of renewables to achieve ZEB requirements.

1. Introduction

Worldwide, buildings – comprising residential, commercial and public service buildings – are responsible for around 30 % of total energy consumption and 26 % of energy-related greenhouse gas (GHG) emissions [1]. In the European Union (EU), the building sector consumes about 40 % of total energy and contributes one-third of related emissions [2]. Consequently, this sector has become a primary focus of energy and climate policies in major economies, leading to significant progress in decarbonisation over recent decades through targeted policies and measures [3].

Recognised globally for their effectiveness in reducing operational energy use and GHG emissions, nearly or net zero-energy building concept is considered a key solution for achieving a climate-neutral building sector [4]. While there are several differences in how major global economies (such as China, India, the EU, Japan, the United States) adopt the zero-energy building concept—through supporting policies and measures, timeline of adoption, stakeholders involved, goals for achieving zero energy consumption or emissions, and the technologies used—it is generally observed that all definitions are fundamentally centred around the "energy efficiency first" principle [5,6].

Within the EU, the nearly zero-energy building (NZEB) concept is defined under the Energy Performance of Buildings Directive (EPBD), which was introduced in 2002 and has been revised multiple times to align with increasingly ambitious energy and climate targets. The EPBD

Abbreviations: CA, Concerted Actions; DHW, Domestic Hot Water; EC, European Commission; EPBD, Energy Performance of Buildings Directive; EPC, Energy Performance Certificate; EU, European Union; GHG, Greenhouse gas; JRC, Joint Research Centre; SFH, Single-Family House; NZEB, Nearly Zero-Energy Building; PEC, Primary Energy Consumption; PV, Photovoltaics; U-value, Thermal Transmittance; ZEB, Zero-Emission Building.

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mandates that all new buildings must comply with NZEB standard starting from January 2021 [7]. An NZEB is defined as a building that has a very high energy performance, with the nearly zero or low amount of energy required being covered to a significant extent by energy from renewable sources, also considering on-site and nearby sources. Based on the broad NZEB outlined in the EPBD, EU Member States have formulated their own definitions, taking into account national, regional, or local climate, social, and economic conditions [8]. This led to a wide range of definitions and, consequently, varying levels of ambition.

Recent assessments have highlighted significant disparities in NZEB progress across the EU. A 2021 assessment of NZEB progress in the EU conducted by D'Agostino et al. [9] revealed that, by 2020, the legislative NZEB performance level in most EU Member States, although 70 % more demanding than the national energy performance levels in 2006, was less ambitious than the European Commission (EC) recommendation [10]. The most common approach is the energy balance over a year at a single building level considering also on-site renewables, and using as indicator the primary energy demand for heating, cooling, ventilation, domestic hot water (DHW), built-in lighting and auxiliary energy. Few definitions include other energy uses such as appliances, and central services [11,12]. Other studies have shown that compliance with NZEB criteria varies significantly across different regions in Europe. In northern European countries, such as Finland, Sweden, Estonia, and Norway, differences in national NZEB definitions and the availability of heating sources (like district heating and geothermal energy) play a crucial role. In Finland and Norway, for example, buildings can more easily comply with NZEB standards using only energy efficiency measures. In contrast, in Sweden and Estonia, buildings require the addition of on-site renewable energy sources, such as photovoltaic (PV) systems, to meet these standards [13]. In Southern Europe, a study found that countries like Cyprus, France, Greece, Italy, Portugal, Romania, and Spain were not well prepared, especially for renovations to NZEB levels, and noted that NZEB standards generally favour colder climates [14]. Focusing on the Mediterranean climate, another study on Spain concluded that NZEB non-renewable primary energy demand decreased by 46 % compared to the situation before the 2018 amendments to the EPBD [15]. Moreover, Harkouss et al. [16] provided a comprehensive review of existing NZEB definitions and presented case studies from various climate zones. The research also explored the NZEB design optimization, analysing objective functions, variables, and constraints to achieve optimal results.

However, progress is uneven across the EU. A recent study found that in Eastern Member States (Bulgaria, Croatia, Czechia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, and Slovakia), NZEB deployment is advancing too slowly to achieve climate neutrality by 2050 [17]. Insufficient measures to phase out fossil fuels, misleading primary energy factors, inconsistencies with the cost-optimal approach, and a lack of attention to indoor environmental quality are the main reasons attributed to this slow pace. Another study found high upfront costs, design complexity, climate and site constraints, maintenance and operation as main challenges to achieve NZEB performance levels [18].

Significant efforts are still required to meet the climate and energy goals. As Wang et al. observed "achieving zero energy is a process not an endpoint" and the actual implementation of the national/regional NZEB definition eventually makes the difference in achieving a climate neutral building stock [19]. This success may depend on factors such as the initial design of the building, materials selected, construction execution, and the building's use. Aljashaami et al. provided a comprehensive review of active and passive efficient technologies with renewable energy integration to boost zero-energy buildings [20]. Kınay et al. identified the key factors that have the highest impact on energy consumption in buildings during renovation, and found thermal insulation and building airtightness as key aspect across various climatic zones [21]. Bui et al. emphasized the importance of a collaborative and integrated approach in decision-making for zero-carbon renovation of buildings. Given that the majority of buildings already exist, cost-effective retrofitting has become a crucial strategy for meeting global net-zero carbon emission targets [22]. Additionally, user behaviour can significantly and unpredictably impact the building's real energy performance, as it is well known that the extent to which a zero-energy building remains "zero" largely depends on how it is used [23]. Stronger policies to enhance the energy performance of both new and existing buildings, agreed approaches to address whole-life carbon emissions from building materials and construction, increased investment in energy efficiency and raising user awareness are all essential [24].

To accelerate progress, the 2024 recast EPBD aligns with the EU Green Deal strategy [25], and broader climate goals for 2030 and beyond. The core elements of the Directive to achieve an EU decarbonised building stock by 2050 can be summarised within the following areas:

- Decarbonisation (zero-emission building concept, solar deployment in buildings, whole life-cycle carbon calculation, phasing out fossil fuels);
- Renovation (Minimum Energy Performance Standards for non-residential buildings, national trajectories for progressive renovation of residential buildings, National Building Renovation Plans);
- Enabling framework (renovation passports, One-Stop-Shops, deep renovation standard, national energy performance databases, sustainable finance, energy poverty, harmonised energy performance certification scheme),
- Modernization and system integration (digitalisation and national databases, infrastructure and sustainable mobility, indoor air quality, ventilation and other technical building systems).

The recast EPBD introduces a definition for Zero-Emission Buildings (ZEBs) (Article 11). A ZEB is characterized by a very high energy performance, requiring zero or a very low amount of energy, producing zero on-site carbon emissions from fossil fuels, and generating zero or a very low amount of operational GHG emissions. The total annual primary energy use must be covered from on-site and nearby renewables, renewable energy communities (as defined by the Renewable Energy Directive [26]), efficient district heating and cooling systems (fulfilling the criteria laid down in the recast Energy Efficiency Directive (EED) [27]), or other carbon-free sources. According to the Article 26 of the 2023 recast EED, district heating and cooling systems shall progressively increase their renewable energy, waste heat or cogenerated heat shares, from a minimum of 50 % at the end of 2027 to 100 % in 2050. Alternatively, Member States may choose to set sustainability criteria (GHG emissions) for their district heating and cooling systems. Moreover, the recast EPBD mandates Member States to introduce maximum thresholds for the total annual primary energy demand of ZEBs with the aim to achieving at least the latest cost-optimal levels and these thresholds should be at least 10 % lower than the current national NZEB thresholds. Furthermore, the operational GHG emissions must adhere to a national maximum threshold. The primary objective at the EU level is for public-owned new buildings to be ZEB by 2028, with the broader goal that all new buildings meet the ZEB standard by 2030 and existing buildings be transformed into ZEBs by 2050. The Directive also defines deep renovations, prioritising energy efficiency and aiming to transform buildings into NZEBs before 2030 and ZEBs thereafter, addressing additional aspects such as indoor environmental quality, safety, and disaster resilience [28].

However, the transition from NZEB to ZEB standards brings several challenges. The effectiveness of the ZEB definition is potentially limited by its close alignment with the NZEB concept, particularly regarding energy use requirements, which continue to vary widely across Member States. In addition, inconsistencies in renewable energy integration and the current lack of GHG emission thresholds, point to challenges in meeting the new ZEB targets.

This paper systematically assesses the progress of EU Member States in standardising their NZEB definitions by 2024 and evaluates their readiness to transition to ZEB standards by 2030. The study aims to answer the following key research questions:

- How do the current NZEB performance levels align with the EU's climate goals?
- What potential do the current NZEB standards indicate for the future ZEB requirements?
- What are the primary challenges that need to be addressed to facilitate the transition from NZEB to ZEB standards by 2030?

To address these questions, a methodology has been developed based on structured data collection to evaluate NZEB progress across all Member States using common indicators such as non-renewable primary energy demand, total primary energy demand, and renewable energy share. The approach allows comparison with recommended values and enables an assessment of potential ZEB performance levels based on current NZEB levels. It is worth noting that direct comparison between Member States' ambitions is beyond the scope of this work, as each country's NZEB definition was tailored to its unique climatic, economic, and social context, making such comparisons imbalanced.

The paper is organized as follows: after current state of play in Section 1, Section 2 introduces the methodology employed in this research. Section 3 introduces the results and evaluates the progress made by countries, particularly in light of adopting the new ZEB target. Section 4 discusses the identified key challenges towards ZEBs and Section 5 draws conclusions.

2. Methodology

2.1. Data collection

This study investigates the definitions and implementation of NZEBs across the EU Member States (26 countries and 3 regions of Belgium).

Data on current NZEB definitions and criteria were collected using a country-specific template (reported in the Annex of this paper) that was distributed to designated contact points and experts within each Member State over the last year. The collected data were managed by the EC Directorate General for Energy and shared with the Joint Research Centre (JRC). For more information on the implementation of the EPBD in the Member States, including experts' contact points, see the Concerted Action (CA) EPBD project [29]. The template was designed to capture information on the energy performance of NZEBs, analysing the following elements:

- General information: date of definition, relevant legal national acts, and definitions for both new and NZEB renovation;
- Envelope and technical systems requirements: thermal transmittance (U-values) and airtightness, minimum performance requirements for technical systems;
- Renewable energy requirements: details on renewable energy share, technologies employed, and location of energy generation;
- Energy performance requirements: metrics, i.e., total, non-renewable and renewable energy demand and energy performance class by building subcategories (e.g., single-family houses, multi-family houses, offices, hotels, hospitals, schools), and included end-uses;
- GHG emission requirements.

Out of 29 contacted entities, 24 provided feedback, while 4 did not respond (Bulgaria, Brussels, Italy and Latvia), and 1 response was marked confidential (France). To update existing data for non-responding entities and the confidential response, we referenced the CA EPBD database [30]. Recent scientific literature was also consulted to complement missing data or to crosscheck initial inputs. Specifically, Attia et al. was consulted for NZEB performance in Eastern EU countries [17,31], Pallis et al. for NZEB performance in Greece [32], Niskanen and Rohracher for NZEB performance in Sweden [33], Simson et al. for NZEB performance in Estonia, Denmark and Finland [34], Bienvenido-Huertas et al. for NZEB performance in Spain [35], Theokli et al. for NZEB performance in Cyprus, [36], Di Turi et al. for NZEB performance in Italy [37].

2.2. Data harmonisation

Following the authors' data collection, a main difference observed relates to the approach used to define and benchmark the NZEB level in terms of primary energy demand. While most countries and regions defined fixed primary energy thresholds, several countries and regions define the NZEB energy performance relative to the energy performance of a reference building, while others rely on a formula, as illustrated in Table 1. In addition, several countries have varying performance values based on national climatic zone, geometry, such as floor area, volume, compactness, and/or thermal characteristics such as Energy Performance Certificate (EPC) classes, efficiency coefficients, thermal mass, and others.

To provide an overall NZEB progress at the EU level, this section further introduces the methodology to estimate numerical values of NZEB performance levels.

The focus is on the primary energy demand, which is defined as the energy that has not been subjected to any conversion process. This includes both renewable and non-renewable energy and is calculated from the delivered and exported energy using conversion factors (primary energy factors), as defined in ISO 52000–1 [38,39]. Building on this, the analysis focuses on the maximum allowed non-renewable primary energy demand, which is framed by many national definitions and also allows for comparison with previous assessment of NZEB levels. Similar methodology was previously employed by [9]. When countries refer to total primary energy, the non-renewable energy share is calculated

Table 1
Approaches to define NZEB thresholds for primary energy demand in the EU Member States.

NZEB approach	Numerical value	Relative to a reference building	Computed through equation
Invariable	Flanders Wallonia Cyprus Estonia Finland Hungary Ireland Luxembourg Malta Netherlands Poland Sweden Slovenia Slovakia Latvia	Czechia Germany Finland (renovation) Hungary (other non-residential) Slovenia (non-residential)	
Varies by climatic zones	Croatia Spain Romania	Greece Italy	France Spain
Varies by geometry		Brussels (non-residential)	Austria Brussels (residential) Denmark Estonia (single-family houses) France Lithuania
Varies by energy and thermal characteristics	Bulgaria	Brussels (non-residential) Greece Portugal	Austria France Lithuania Spain (non-residential)

Source: authors' data collection and CA EPBD database [30] considering the renewable energy requirements; for those cases providing the total primary energy and not quantifying the share of renewable energy, the non-renewable energy demand was considered equal with the total primary energy demand.

The steps to derive performance values for residential and non-residential, new and existing NZEBs are as follows:

1. **Building sub-categories**: The values examined correspond to single-family houses and offices, where this distinction was made by the national definition between building sub-categories. This approach was adopted to enable comparison with the recommended NZEB performance levels that are set for single-family houses and offices through the EC recommendations [10]. Where no distinction is made, values correspond to residential and non-residential categories.
2. **Climatic zones**: For countries that have in place performance values that vary with the national climatic zones, the average values across the zones are considered for Croatia and Spain, the representative climatic zone in the country for Italy (zone E) and Romania (zone II), and the maximum value across the climatic zones for Greece. The choice is based on how the country usually reports its values [30].
3. **Renewable energy share**: The share of renewable energy is subtracted from the primary energy demand value provided in the national definition (Flanders, Bulgaria, Cyprus, Croatia, Luxembourg, Malta, Netherlands, and Romania).
4. **Country-specific methodologies**: Due to the use of formulas or reference building comparison to define the national NZEB performance levels, certain countries require tailored methodologies to estimate an average NZEB energy indicator:
   a. Austria: The NZEB levels for new buildings are sourced from CA EPBD database, where indicative energy indicators are calculated based on the national NZEB formula (table 6 and 7 in [40]).
   b. Brussels-Capital Region: The NZEB levels of single-family houses correspond to EPC energy class A upper boundary, for new offices it equals the upper boundary of energy class B, and for renovated offices it equals the upper boundary of energy class C [41].
   c. Czechia: The NZEB levels are calculated using the reference buildings for new buildings defined in the 2023 cost-optimal report [42].
   d. Denmark: The NZEB levels are calculated using the reference buildings defined in the 2023 cost-optimal report [43].
   e. Finland: A share of 15 % is subtracted from the Member States values to eliminate appliances and user equipment energy demand, as these end-use are not required by the EPBD. The NZEB levels for building renovation are calculated using the reference buildings defined in the 2023 cost-optimal report [44].
   f. France: The NZEB levels for new buildings are averaged between the two indicated options for each building sub-category (single-family houses and offices), according to CA EPBD output (see table 1 in [45]). The NZEB level of renovated single-family houses is calculated using average values for coefficients a (climatic zone proxy) and b (altitude proxy) provided in the CA EPBD output. Finally, the NZEB level of renovated office is calculated based on the reference office building defined in the 2023 cost-optimal report [46].
   g. Germany: The NZEB levels are referenced from the 2024 cost-optimal report [47].
   h. Greece: NZEB levels corresponds to EPC class A upper boundary for new buildings and class B + upper boundary for renovated buildings. The values of current energy classes were extracted from the 2023 cost-optimal report [48].
   i. Italy: The NZEB levels are calculated using the results of the latest cost-optimal report [49], based on the Italian NZEB criteria [50,51]. For new single-family houses, the multi-family house NZEB level is considered as a proxy. For renovated buildings, the NZEB threshold is assumed to be equal to the cost-optimal level (reference building).
   j. Poland: The NZEB levels of offices include primary energy for cooling and lighting according to the CA EPBD database [52].
   k. Portugal: The NZEB levels are calculated using the reference buildings for new buildings defined in the 2018 cost-optimal report [53].
   l. Slovenia: The NZEB levels for offices are calculated using the reference buildings defined in the 2018 cost-optimal report [54].

Consequently, the derived energy performance values are not necessarily exact representations of the national definition, but rather average performance levels based on those definitions.

Regarding renewable energy, the analysis focuses on the share (in percentage) that the renewable energy must cover from the total energy demand, for both new and renovated NZEBs. In most countries that have the quantification, they also provide the minimum renewable energy share. Some countries or regions provided the absolute value, and based on this and the total primary energy demand, the share was calculated (i.e., Flanders and France).

Furthermore, to enable comparison with the EC recommended benchmarks, Member States were divided into macro climatic zones (Mediterranean, Oceanic, Continental, Nordic). The grouping as well as the recommended benchmarks for single-family houses (SFH) and offices are reported in Table 2.

3. Results and discussion

Following the methodology outlined above, the NZEB primary energy demand for single family-houses and offices—whether total or non-renewable—based on the national definitions, along with the requirements for renewable energy was computed for each country and Table 5 (appendix) reports the results. A first observation is that 16 definitions express performance levels in terms of total primary energy, 7 use non-renewable primary energy, and 6 provide both total and non-renewable figures. New buildings are better addressed, with all countries/regions having an established definition, while for existing buildings, 15 countries/regions have a distinct definition, and 12 apply the same definition as for new buildings. In some cases, although the NZEB renovation is defined, there is no energy indicator requirement. Two countries do not have a legal definition for NZEB renovations. The situation regarding renewable energy contributions is quite varied. Nearly all definitions (23) have some form of requirement in place, but only 12 cover all buildings and all end uses. Finally, 6 countries/regions do not

Table 2
NZEB recommended benchmarks, by climatic zone [10].

Building type	Net primary energy use kWh/(m^2y) (on-site renewable excluded)	Primary energy use kWh/(m^2y) (on-site renewable included)
Mediterranean: Cyprus, Croatia, Italy, Greece, Malta, Portugal, Spain		
SFH	0–15	50–65
Office	20–30	80–90
Oceanic: Belgium, Denmark, Ireland, Germany, France, Luxembourg, Netherlands		
SFH	15–30	50–65
Office	40–55	85–100
Continental: Austria, Bulgaria, Czechia, Hungary, Poland, Romania, Slovenia, Slovakia		
SFH	20–40	50–70
Office	40–55	85–100
Nordic: Estonia, Finland, Latvia, Lithuania, Sweden		
SFH	40–65	65–90
Office	55–70	85–100

have any quantification at all.

Another relevant aspect regards the end-uses included in the primary energy demand of an NZEB. Table 6 (appendix) shows the end-uses considered in the calculation for each country. Almost all definitions include heating, cooling, DHW, and ventilation in residential NZEB primary energy demand, while 15 consider also lighting. All definitions include all end-uses in non-residential buildings. Indeed, Annex I of the EPBD – which provides the calculation framework for building energy performance – specifies that lighting is mainly relevant in the non-residential sector. Auxiliary energy could be included in more definitions; however, the Table 6 reports it only for countries that specifically mentioned 'auxiliary energy' in the reporting template. Regarding other end-uses, Finland reports the inclusion of appliances' energy demand.

The following sections presents the non-renewable energy benchmarks, the renewable energy share and existing operational GHG emission requirements.

3.1. NZEB status

3.1.1. Non-renewable energy benchmarks

Fig. 1 shows that the average non-renewable primary energy consumption for new single-family houses varies from a minimum of 15 kWh/(m^{2}y) to a maximum of 95 kWh/(m^{2}y), with an overall EU average of about 55 kWh/(m^{2}y). For renovated single-family houses, the estimated performance level range is broader, between 35 kWh/(m^{2}y) and 158 kWh/(m^{2}y) with an EU average of 76 kWh/(m^{2}y).

In non-residential buildings (offices), the average non-renewable primary energy consumption ranges between 27 kWh/(m^{2}y) and 220 kWh/(m^{2}y) for new offices (as depicted in Fig. 2) with an overall EU average of 70 kWh/(m^{2}y). For renovation to NZEB level of offices, the values range from 30 to 152 kWh/(m^{2}y), with a corresponding EU average of 85 kWh/(m^{2}y).

In countries with distinct definitions for new and renovated NZEBs, the requirements for new buildings are generally more demanding than those for renovations. On average, the non-renewable primary energy demand for new single-family houses is approximately 30 % lower than for those renovated to NZEB standards, and about 20 % lower for new offices compared to renovated offices. This difference is due to stricter thresholds (Brussels, Flanders, Denmark, Estonia, Finland, France, Ireland, Greece, Romania, Slovenia and Spain) and more extensive renewable energy requirements for new buildings compared to existing ones (Wallonia, Ireland, Malta, and Romania).

3.1.2. Renewable energy requirements

The share of renewable energy in the total primary energy demand in new NZEBs is detailed in Fig. 3 and Table 5. In some cases, the values are averaged across building types (Flanders, Ireland, Netherlands) and renewable technologies (Austria, Germany). Out of 29 definitions, 19 quantify the share of renewable energy in new buildings and 13 in NZEB renovation.

The renewable energy contribution varies widely in both new and renovated NZEBs, ranging from 9-10 % to 55 %. Specifically, for new buildings, 7 countries target 25 % or less renewable energy, while 11 countries aim for up to 50 %. Only Bulgaria reports a renewable energy share of more than 50 % in the total primary energy demand for all buildings (55 %). For NZEB renovation, 5 countries target up to a 25 % renewable energy share, 7 aim for a maximum of 50 %, and only Bulgaria reports 55 % renewable energy share.

Some countries report requirements only for specific end-uses (e.g., Greece 60 % and Portugal 50 % for DHW) or in addition to the overall renewable energy share (Spain 60–70 %, Italy 50 % and Malta 60–80 % for DHW). Moreover, in public buildings, Slovenia requires 55 % renewable energy, while Italy sets a target of 60 %. Luxembourg notes that renewable energy typically constitutes about 65 % in NZEBs,

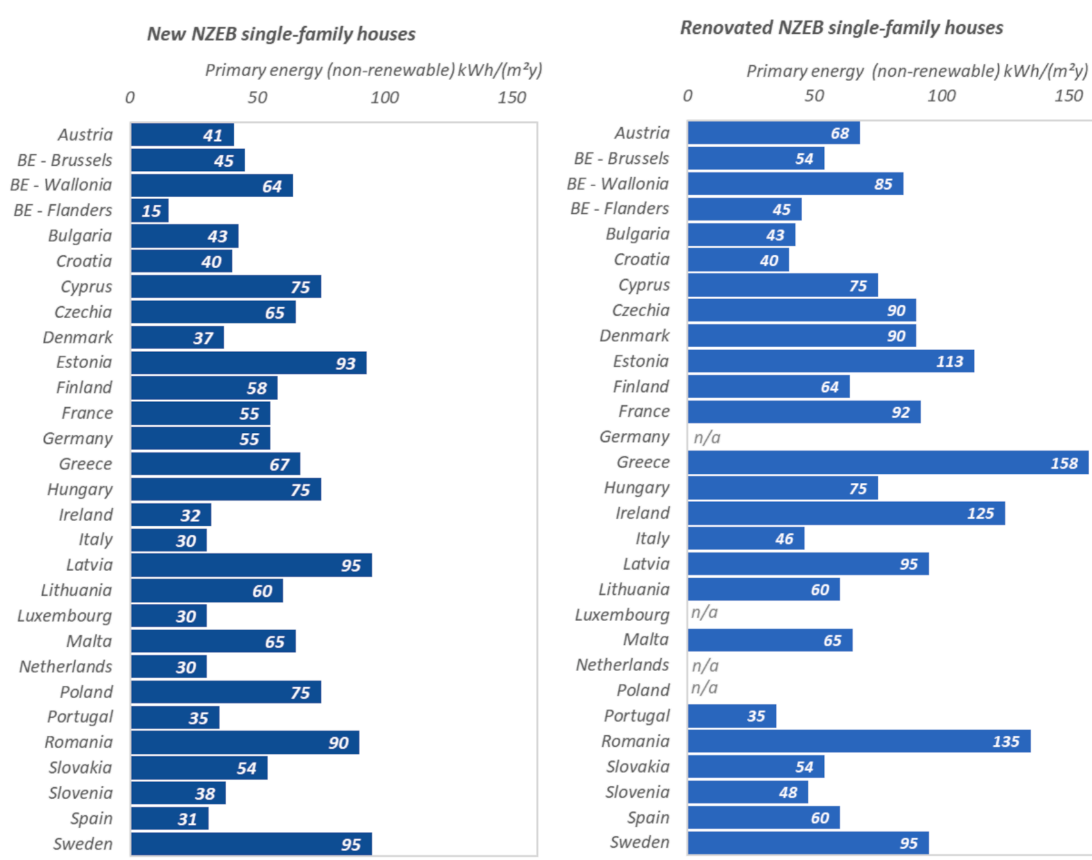

Fig. 1. NZEB energy performance in new and renovated single-family houses expressed in non-renewable primary energy demand kWh/(m^{2}y), by country or region.

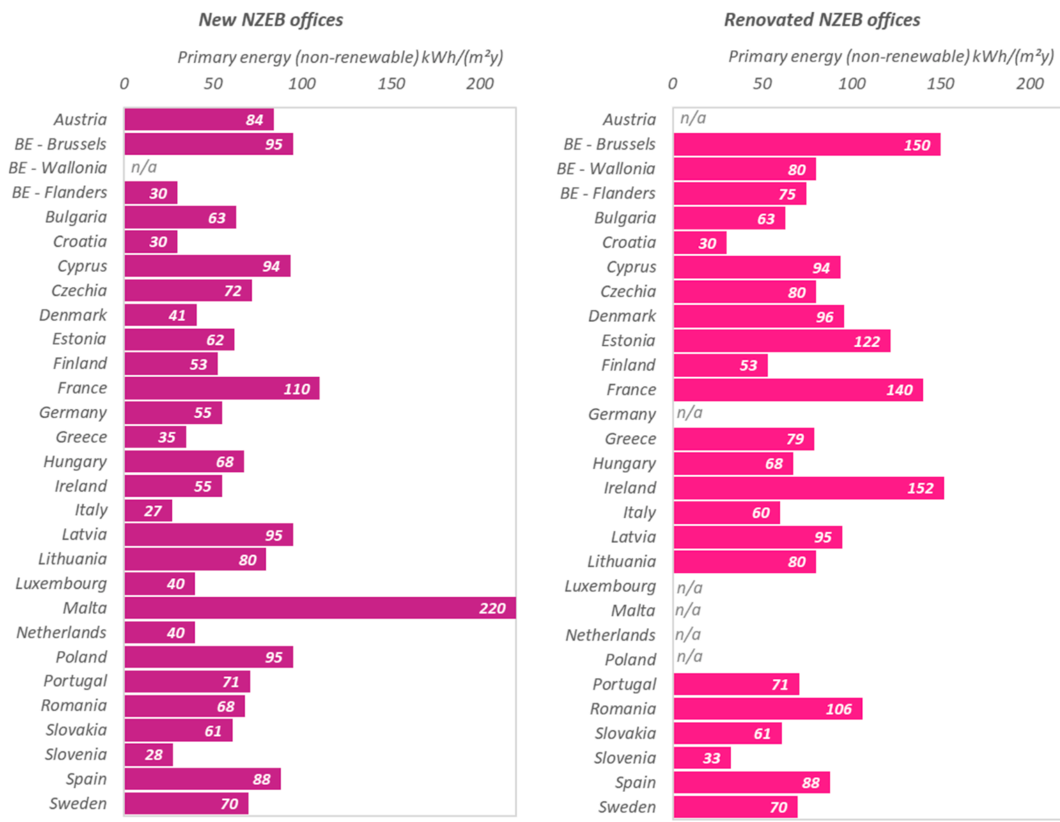

Fig. 2. NZEB energy performance in new and renovated offices expressed in non-renewable primary energy demand kWh/(m^{2}y), by country or region.

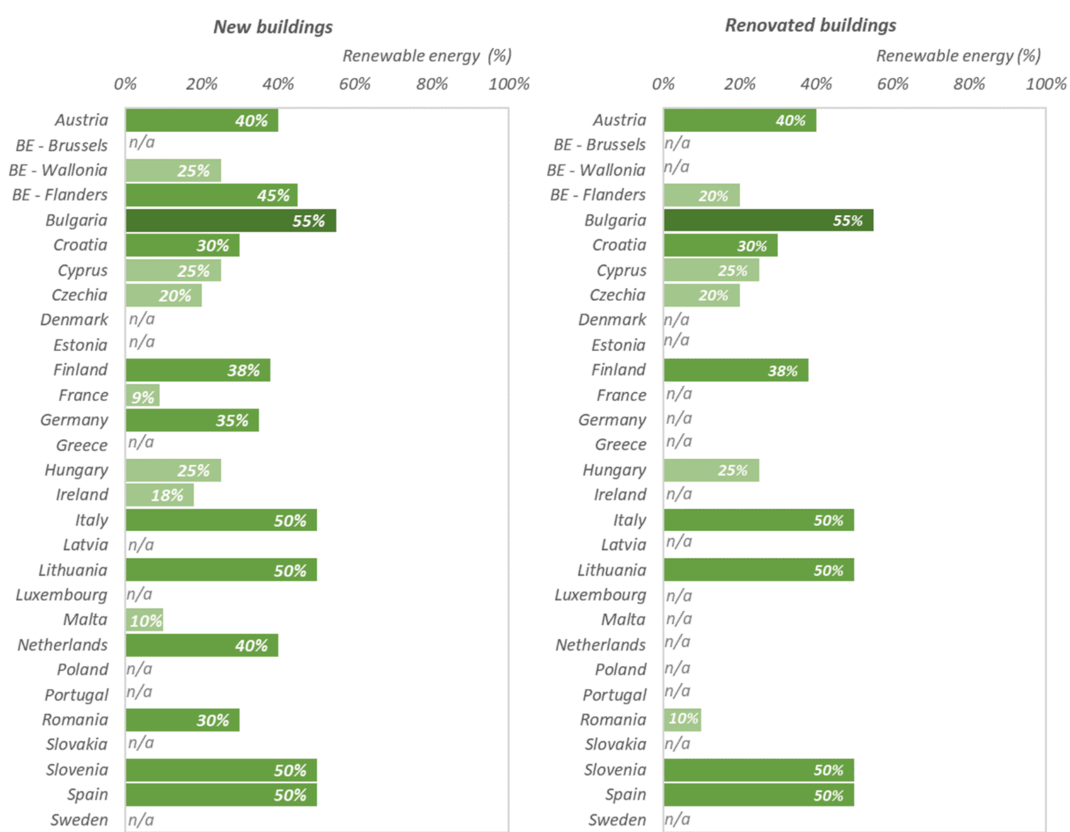

Fig. 3. Renewable energy share (%) from the total primary energy demand in new buildings and renovation to NZEB levels.

although this is not prescribed and depends on the reference building.

3.1.3. Operational GHG emission requirements

Relevant for the transition from NZEB to ZEB is how currently countries are addressing the GHG emissions in their building standards. By 2030, new buildings and ZEB renovations should have no on-site carbon emissions and minimal operational GHG emissions. The inclusion of emissions as a criterion in the existing NZEB definitions may indicate a certain readiness to benchmark operational emissions in ZEBs.

Table 3 shows that, according to the authors' data collection, out of 26 countries and 3 regions, only 5 (Austria, Denmark, Ireland, Germany, and Romania) currently include emission requirements in their NZEB definitions. Denmark limits the life-cycle CO_2-equivalent emissions of new buildings with a floor area exceeding 1,000 m^2, and in Germany, emissions are limited as a percentage of reference building emissions. Ireland and Romania are the only countries with specific operational emission thresholds. Notably, Romania sets thresholds for both new and renovated NZEBs, differentiated by climatic zone and building type.

Operational emissions criteria are generally considered a secondary indicator, with primary energy use—particularly non-renewable energy—viewed as a proxy for these emissions [55]. As a result, countries tend to focus more on limiting primary energy use, in line with current NZEB definitions, rather than directly addressing emissions. However, in most countries, emissions (CO_2 or CO_2-eq) are calculated and displayed on the EPC with some countries (Austria, France, Luxembourg, Romania and Spain) including an EPC class for emissions [41]. This indicates that while emissions are not prominently featured in most current NZEB definitions, they are addressed in several national building standards, paving the way for the introduction of emission thresholds by 2030 [56].

3.2. NZEB developments

3.2.1. Recent advancements

To assess the evolution of NZEB performance levels over recent years, Figs. 4 and 5 compare the NZEB standards from 2020 [9] with those reported in 2023 in residential and non-residential buildings, respectively. This comparison does not indicate a significant reduction in energy indicators, which was not anticipated over such a brief time span. However, it highlights two relevant developments: 1) the introduction of definitions for renovations to NZEB standards in several regions (Wallonia, Flanders, Denmark, Lithuania, Romania, Spain, and Sweden) and 2) the implementation of renewable energy requirements, making the NZEB definitions more stringent (observed in Wallonia, Finland, and Hungary).

Regarding NZEB thresholds, only a few countries have lowered their NZEB energy indicators during this short period. Specifically, Flanders, and Romania have lowered thresholds for residential buildings, while Estonia, Luxembourg, and Spain have done so for all building categories.

On average, NZEBs in 2023 are approximately 10 % more ambitious than those in 2020, with the greatest improvements observed in new residential buildings and lower improvements in residential NZEB renovation.

Table 3
GHG emission requirements in the national NZEB definitions.

Country	*GHG emissions requirements*
Austria	In one region
Denmark	Life-cycle requirements with thresholds
Germany	As comparison with reference building
Ireland	With thresholds
Romania	With thresholds
Brussels, Wallonia, Flanders, Bulgaria, Croatia, Cyprus, Czechia, Estonia, Finland, France, Greece, Hungary, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal Slovakia, Slovenia, Spain and Sweden	No NZEB requirements

Source: authors' data collection

In some countries, determining whether currently NZEBs are more ambitious compared to 3-4 years ago is challenging, as NZEB energy performance is based on the energy performance of the reference buildings (e.g., Czechia, Germany, Greece, Italy and Portugal; see Section 2.2 for more details). For example, the 2023 NZEB values for Czechia are derived from the reference building specified in the latest cost-optimal report (2023), which has lower primary energy demand than the reference building defined in the previous cost-optimal report (2018). Calculating the NZEB performance level using the energy performance of the reference building suggest more ambitious NZEB standards. However, the NZEB definition itself has remained unchanged during this period, but the energy performance of the reference buildings has changed.

3.2.2. Benchmark comparisons

Furthermore, Fig. 6 compares the current NZEB performance level, in terms of non-renewable primary energy demand, with the EC recommended range of thresholds [10] (Table 2) for both new and renovated residential buildings (single-family houses). It can be observed that in most cases the national NZEB primary energy demand is less ambitious than the recommended benchmarks, particularly for existing buildings renovated to NZEB level.

For new buildings, the gap between the current levels and the average benchmark varies from 400 % (Cyprus) to −50 % (Flanders). For NZEB renovation, the gap ranges between 900 % (Greece) and −8 % (Lithuania).

On average, the primary energy demand of new NZEBs is about 75 % higher than the average recommended benchmarks, while the primary energy demand of renovated NZEBs is 170 % higher than the same averaged benchmarks. Lower values are observed in Flanders, Luxembourg, Netherlands, Slovenia, Finland and Lithuania for new buildings, while for NZEB renovation Finland and Lithuania report levels more ambitious than the EC recommendation.

Fig. 7 compares national NZEB performance level and EC recommended values (non-renewable primary energy) for non-residential buildings (offices) [10]. Looking at the performance level of new and renovated NZEB offices, it can be observed that in most cases, the primary energy demand is higher than the average recommended levels. For new offices, the gap between the current levels and benchmarks varies from 633 % (Malta) to −49 % (Slovenia). For NZEB renovation, the gap ranges between 213 % (Cyprus) to −47 % (Finland). However, the situation looks more positive than in the case of residential buildings. On average, the primary energy demand of new NZEBs is about 55 % higher than the recommended benchmarks, while the primary energy demand of renovated NZEBs is 72 % higher than the same benchmarks. Good practices are observed in Croatia, Flanders, Denmark, Germany, Ireland, Luxembourg, Slovenia, Finland, and Sweden for new buildings, while for NZEB renovated offices, Croatia, Slovenia, Finland and Sweden report levels more ambitious than the EC recommendations.

3.3. Projected ZEB levels

To understand how potential ZEB performance levels would look at the national level based on current NZEB levels, Fig. 8 and Fig. 9 compare potential ZEB thresholds with the NZEB recommended thresholds [10] (Table 2). The indicative ZEB thresholds are calculated as 10 % lower than the current national NZEB levels of total primary energy demand in line with the recast EPBD. The estimation of NZEB levels of total primary energy demand for both new and renovated, single-family houses and offices follows the steps provided in Section 2 and the values, by country, are included in Table 5 (appendix). When insufficient information was available, total primary energy demand was considered equal to the non-renewable primary energy demand.

The comparison shows a very diverse landscape when assessing a

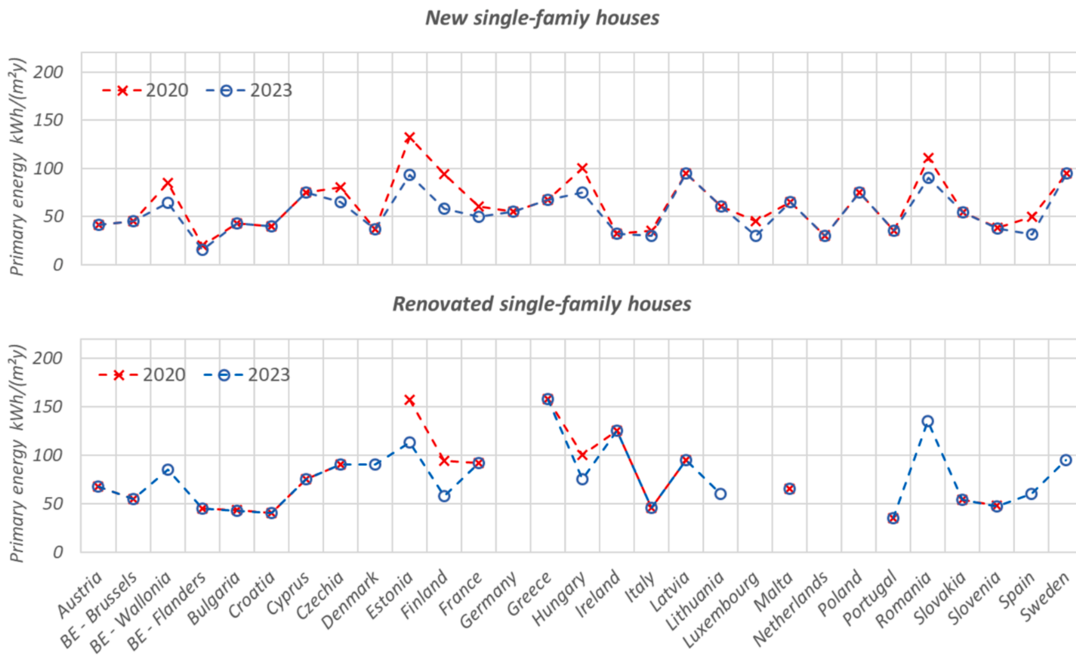

Fig. 4. Comparison between NZEB performance levels in non-renewable primary energy demand of residential buildings, in 2020 and 2023.

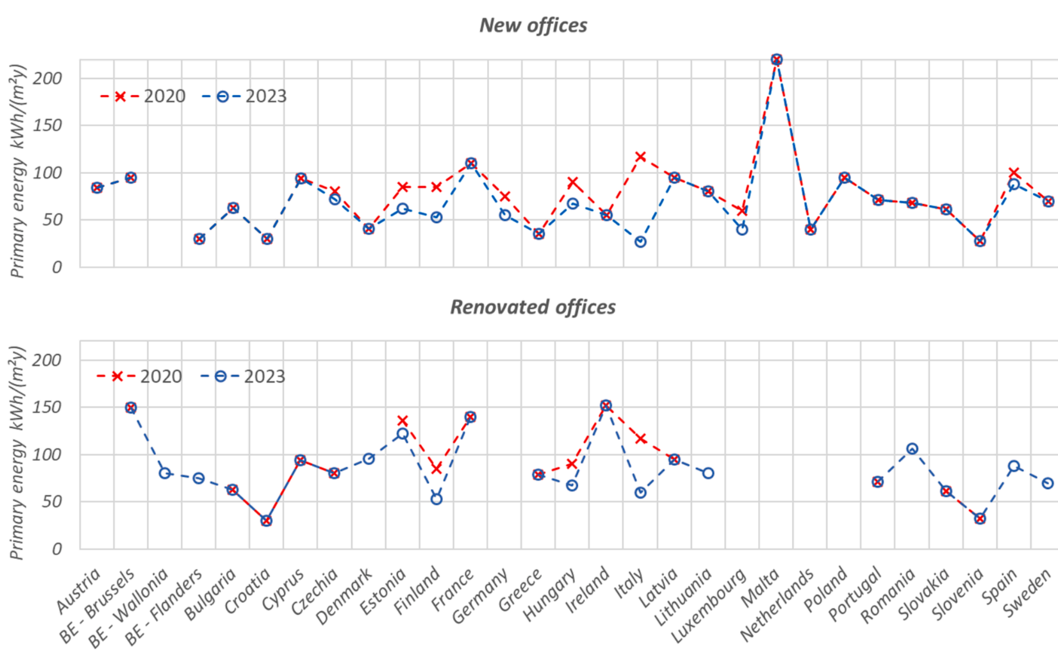

Fig. 5. Comparison between NZEB performance levels in non-renewable primary energy demand of non-residential buildings, in 2020 and 2023.

potential 10 % ZEB more ambitious than NZEB against the recommended benchmarks [10] for total primary energy of single-family houses (Fig. 8). Looking at the upper boundary of the recommended range, 7 definitions are above the recommended threshold. When considering different climatic zones, Continental countries are less ambitious, with 4 out of 8 values exceeding the upper boundary, whereas the Oceanic group has more aligned definitions, with only 1 out of 9 definitions exceeding the upper boundary. However, when assessing the lower boundary of the range, the indicative ZEB levels are not aligned with the recommended values in many countries, with only 10 countries falling below the lower boundary.

Fig. 9 compares the NZEB recommended benchmarks (lower and upper boundary) [10] and indicative ZEB performance levels in total primary energy, for offices. Overall, the comparison reveals a generally positive outlook. Similar to single-family houses, the ZEB primary energy demand was calculated as 10 % lower than the NZEB primary energy demand of offices. In this case, it appears that 5 countries would have a ZEB threshold higher than the upper boundary of the recommended primary energy interval. The situation shows little change when considering the lower boundary of the recommended thresholds, with only 2 additional countries becoming not aligned. Overall, the Mediterranean group appears the least ambitious, while the Oceanic group is the most ambitious.

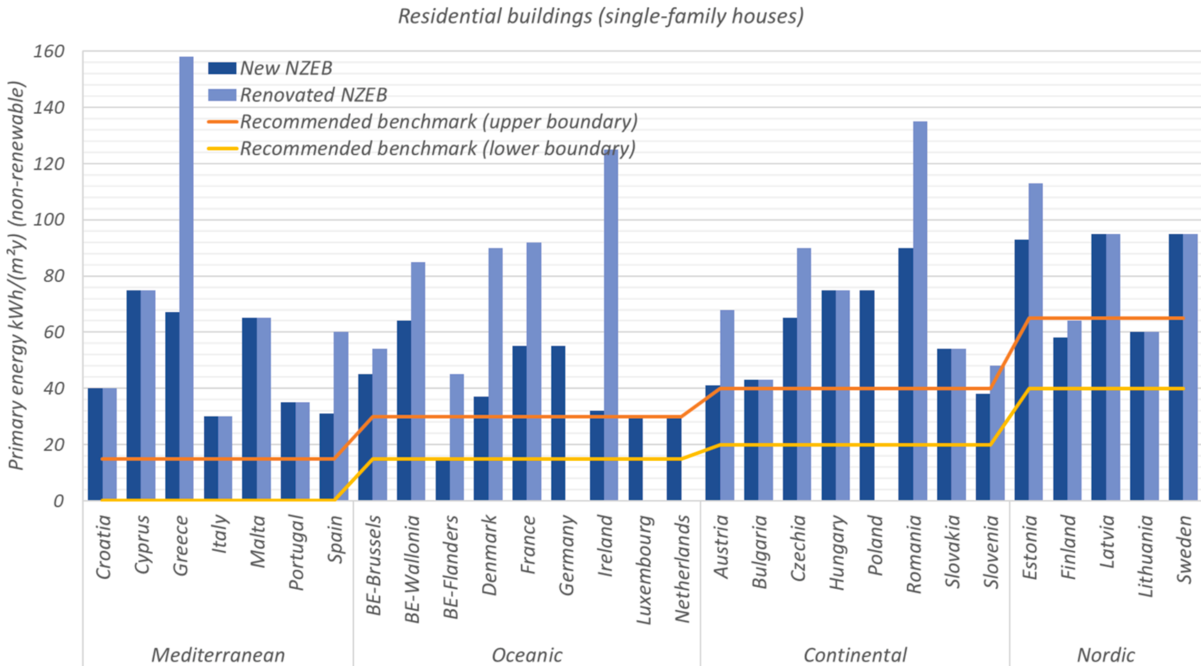

Fig. 6. Comparison between national NZEB performance level and EC recommended values (non-renewable primary energy) for residential buildings (single-family houses).

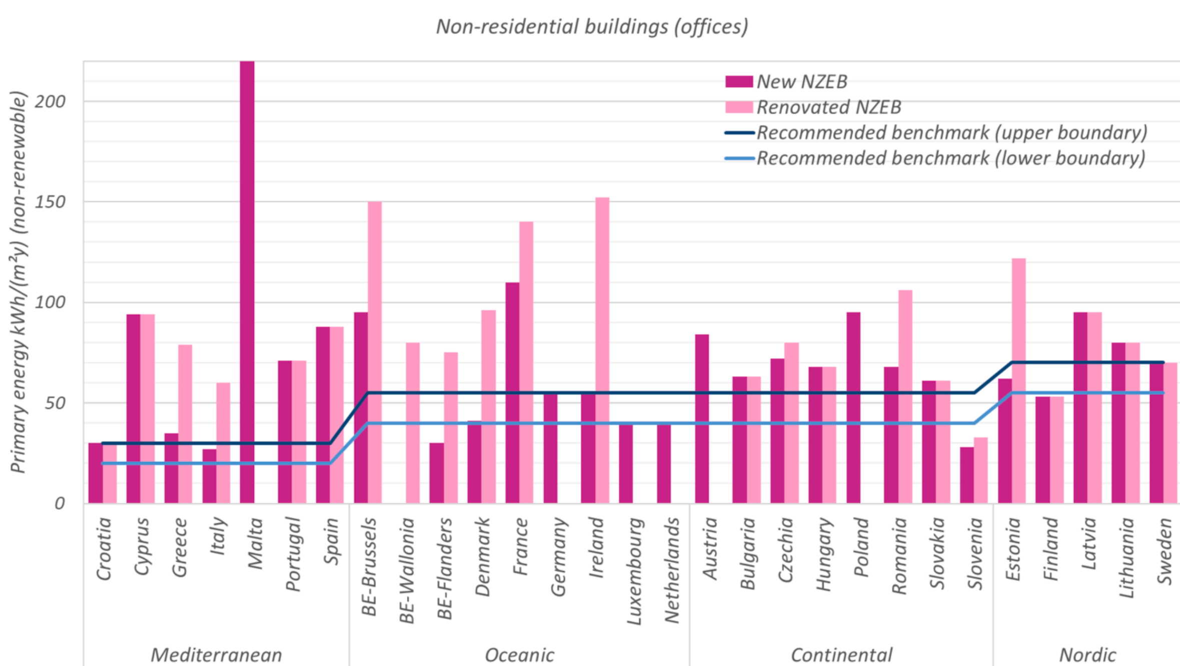

Fig. 7. Comparison between national NZEB performance level and EC recommended values (non-renewable primary energy) for non-residential buildings (offices).

4. Key challenges towards ZEBs

4.1. Energy demand thresholds

ZEBs must have very high energy performance, produce no on-site carbon emissions from fossil fuels, and generate minimal operational GHG emissions. Energy needs must be met by on-site or near-by renewables, renewable energy communities, efficient district heating and cooling systems (according to the 2023 recast EED criteria), or other carbon-free sources. ZEB annual primary energy use must be at least 10 % lower than national NZEB thresholds and at least the cost-optimal levels set in the most recent national report. Operational GHG emissions must comply with national thresholds.

The proposed ZEB definition is more ambitious than the current NZEB standards, but it also raises some concerns. One significant issue is its similarity to the NZEB concept in terms of energy demand requirements. The total primary energy of NZEBs, which vary widely across Member States—from 30 kWh/(m^2y) in Flanders to 128 kWh/(m^2y) in Romania (climate zone II) for new single-family houses, and from 35 kWh/(m^2y) in Greece to 220 kWh/(m^2y) in Malta for offices—highlight this inconsistency (Table 5, appendix). Such variation may impact the ZEB definition's effectiveness, as differences in national

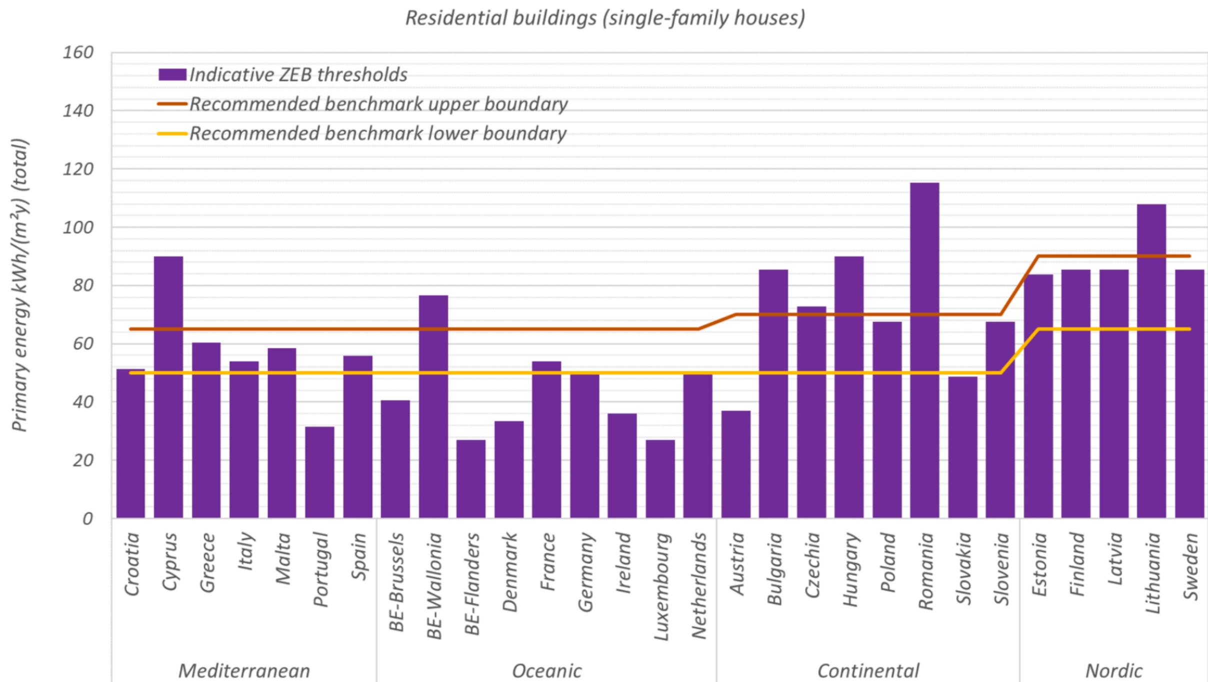

Fig. 8. Comparison between recommended NZEB thresholds and national indicative ZEB thresholds in total primary energy demand for residential buildings (single-family houses).

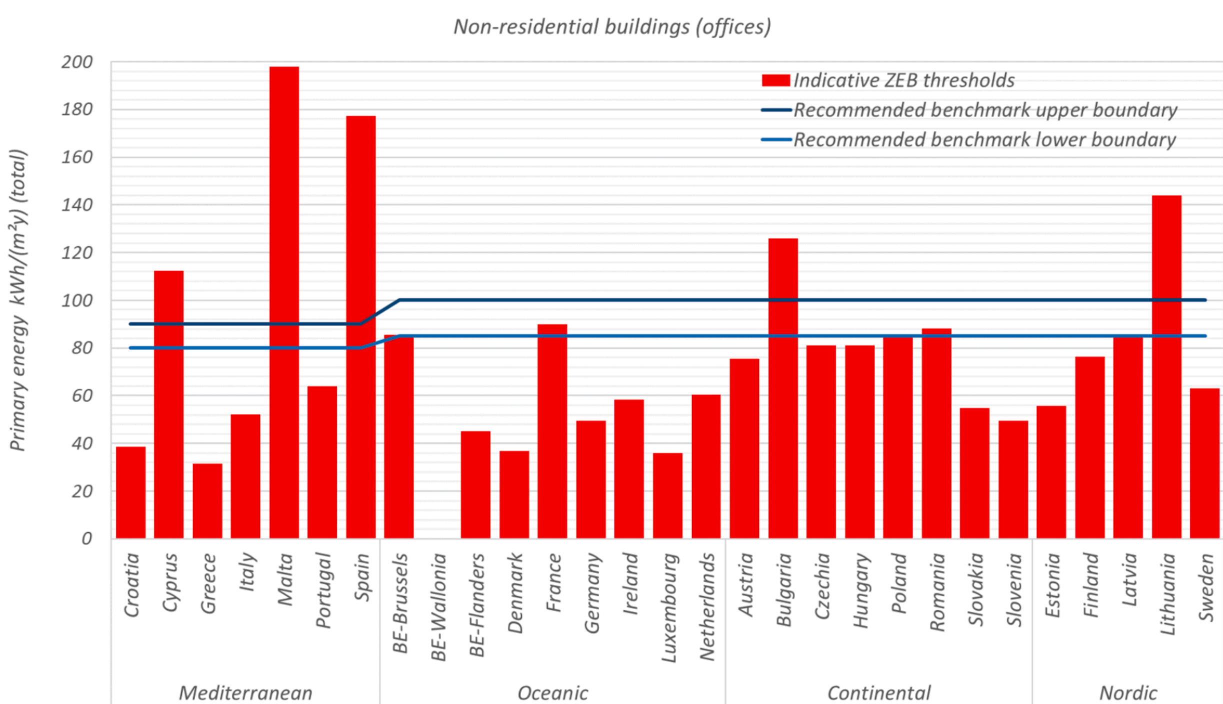

Fig. 9. Comparison between recommended NZEB thresholds and national indicative ZEB thresholds in total primary energy demand for non-residential buildings (offices).

implementation could lead to similar ZEB variation and in some cases, high values.

The ZEB definition also bans any on-site carbon emissions, requiring on-site building systems (for heating, cooling, ventilation, lighting, and DHW) to be powered exclusively by renewable energy. This may prove challenging, particularly for buildings without direct access to on-site renewable energy sources. To meet this requirement, buildings must drastically reduce their energy demand, in line with the "energy efficiency first" principle, to remain within the ZEB criteria. This could require substantial revisions to some existing NZEB thresholds to balance both energy and emissions goals by 2030.

4.2. Renewable energy integration

Another area of concern is the integration of renewable energy sources. Although the recommended contribution of renewables is high

(70 % for Mediterranean countries and 50 % for Oceanic countries, calculated based on the EC recommended benchmarks, Table 2), the legislated renewable energy contributions in national NZEBs vary significantly and are often inadequately quantified [15]. Consequently, total energy demand in many cases effectively mirrors non-renewable energy demand, showing several definitions non-compliant. However, renewable energy, particularly on-site sources such as PV systems, are often indispensable for reaching NZEB levels. When combined with electrically driven heating and cooling systems, such as heat pumps, rooftop PV systems are often a cost-effective solution for maintaining NZEB levels within net primary energy thresholds [32]. Nevertheless, it is well known that not all buildings can access sufficient solar radiation to ensure cost-effective PV deployment [57]. Moreover, the intermittency of solar energy and the need for energy storage solutions may also pose challenges for widespread adoption. The new ZEB requirements aim to address these issues by clearly defining acceptable energy sources from 2030 onwards, such as on-site and nearby renewables, renewable energy communities, efficient district heating and cooling systems, and other carbon-free sources. This shift could promote greater reliance on centralized heating and cooling systems, which are required to achieve decarbonisation by 2050 under the 2023 recast EED, as well as foster the development of renewable energy communities [58]. Additionally, the integration of energy storage systems, such as batteries, and the development of smart grids and energy management systems will be crucial to ensure a reliable and efficient and renewable energy supply [59].

4.3. Operational GHG emission thresholds

A critical consideration for the adoption of ZEB standards by 2030 is the parallel introduction of emissions thresholds. Limiting operational emissions—whether in terms of carbon dioxide or total GHGs—is a vital step toward achieving climate neutrality. While energy efficiency is a key driver, it must be complemented by clean energy to meet the 2050 climate-neutrality objective. Particularly for existing buildings, deep renovation of envelopes coupled with electrification of technical building systems and renewable energy to replace fossil fuels use needs to be further addressed in national policies [60]. The latitude given to Member States in setting their own thresholds for operational emissions could result in considerable variations in ambition levels across the EU and diverse policy measures to support the regulations. However, this flexibility allows for the accommodation of each country's specific climatic, economic, and social conditions. In Mediterranean countries and warmer regions of Continental and Oceanic countries, higher operational emission reduction may be achieved through a proper design of envelope, including features such as controlling solar gains, adopting lighter-coloured surfaces with higher reflectance for roofs and walls, and implementing better solar control from windows (e.g., lower solar heat gain factor) rather than relying solely on higher levels of thermal insulation. Moreover, the electrification of technical heating and cooling systems together with adopting renewable energy systems may prove more cost-effective than higher levels of envelope thermal insulation [32,61]. This aspect is even more crucial considering the projected rising cooling needs across the EU [62]. In contrast, in colder climates, reducing heating energy demand through envelope upgrades remains essential to reduce operational GHG emissions [63]. This approach can be complemented by passive design strategies, such as maximizing solar gains and utilizing internal heat sources effectively, to further enhance energy savings. The established cost-optimal methodology, which is already widely implemented within Member States, could serve as a valuable tool for benchmarking operational emissions by finding the most cost-effective balance between energy efficiency and renewable energy integration, tailored to the specific conditions of each country or region [64].

4.4. Embodied GHG emission concerns

However, as extensively discussed in the literature, while NZEB standards successfully reduce the operational emissions, embodied emissions remain largely unaddressed in most building standards and will pose significant challenges in the coming decades [65,66]. In some cases, it has been observed that buildings with higher energy efficiency can have increased embodied carbon, even as operational emissions decrease [67,68]. This happens primarily because of larger quantities of materials and more complex technical systems. The 2024 recast EPBD calls for the calculation and disclosure of the life-cycle CO_2-equivalent GHG emissions, based on global warming potentials and emissions of individual GHG, beginning in 2030 for all new buildings, as part of a move toward zero life-cycle CO_2-equivalent GHG emissions in the building sector.

Moving forward, it will be crucial to reduce embodied carbon in the design phase of new buildings and renovation of existing buildings and supported perhaps by benchmarks. While there is no one-size-fits-all solution for reducing embodied carbon in buildings, due to the diverse building types, climates, and economies, several common approaches can be employed to minimize embodied carbon. Using locally available, low carbon materials would reduce emissions associated with materials and transportation [69]. For instance, using timber as a substitute for conventional construction materials (such as masonry, concrete and steel) significantly reduces the embodied GHG emissions (−36 % replacing concrete with engineered wood [70]) besides providing improved envelope airtightness (about 40 % higher with timber panels than brick masonry [71]). Regarding the thermal envelope, materials such as glass and rock wool, polystyrene, and polyurethane are currently widely used across the EU, due to their cost-effectiveness and availability; however, they show a high environmental impact [72]. Viable options of thermal insulation materials with lower environmental impacts are cork, reed and wood fibre panels, flax, hemp, straw bale, sheep wool, but also recycled materials, such as cellulose or recycled textile, depending on their local availability and the maturity of the application technology. The use of such materials may result in lower life-cycle CO_2-equivalent emissions, as they combine low thermal conductivity and low embodied carbon. Additionally, bio-based materials show high waste-to-energy potential as a waste management strategy at their end of life, reducing construction waste and supporting circular economy [73]. The emphasis on sustainable materials and construction practices not only reduces the embodied carbon, but also promotes better indoor conditions using of non-toxic, eco-friendly materials.

4.5. Renovation to NZEB and ZEB levels

A well-known and pending challenge is building renovation, particularly deep renovation, which is now defined by the recast EPBD as renovation to NZEB level by 2030, and ZEB after 2030. The results show that the NZEB definition for renovation is less addressed compared to the NZEB definition for new buildings, and in some cases, it is missing completely, lacks specific energy indicators or renewable energy requirements. Although improvements have been observed compared to the 2021 status, more efforts are needed.

Renovation uptake, which refers to the rate at which buildings are renovated, is generally assessed by two indicators: i) annual renovation rate, which refers to the floor area (or number of buildings) renovated yearly from the building stock, and ii) renovation depth, which refers to the actual effectiveness of the renovation in terms of energy savings (or emission reductions). However, both of these indicators remain largely unknown, particularly regarding NZEB renovations. Member States often struggle to distinguish between new and renovated NZEBs or identify NZEB renovations from those that have been carried out [74].

According to previous research [75], final energy use in buildings can be reduced by 14 % by 2030 and by 41 % by 2050, with respect to 2019 levels. Direct operational GHG emissions can also be reduced by

35 % by 2030, finally reaching 94 % reduction by 2050. To achieve these projections, renovation rates need to be more than double the 2020 rate (around 1 %) and involve deep renovations. However, reported planned renovation rates vary from 1 % to 6 %, with most countries aiming for an annual rate between 1.5 % and 3.0 %. This indicates that not all renovation strategies are ambitious enough to sustain the energy and decarbonisation goal. In addition, the depth of these renovations is often not specified, leaving a gap in understanding the potential impact. Without controlling the depth of renovations, a lock-in effect may occur, where buildings are renovated to a level that is not energy-efficient enough to meet energy and emission targets. Light or medium renovations, which bring lower energy savings, would require higher annual renovation rates to reach the targets [76]. However, this can be challenging due to market barriers, such as a lack of skilled labour, costs of site preparation, and high costs of construction materials. To avoid this, it is essential to outline a definition with specific and clear indicators for NZEB renovation, including operational emissions indicators. This will ensure that carried-out renovations can be aligned with deep renovation (i.e., NZEB or ZEB), avoiding energy and emission savings lock-ins and ensuring that targets are met within deadlines.

5. Conclusions

This study provides a comprehensive assessment of the Nearly Zero-Energy Building (NZEB) definitions implementation across the 26 EU Member States and three Belgian regions. The analysis reveals a varied landscape in NZEB standards, highlighting both the progress and the challenges that remain in advancing toward Zero-Emission Buildings (ZEBs).

On average, the non-renewable primary energy demand is by 30 % lower in new NZEBs than renovated NZEBs. Moreover, the renewable energy contribution varies widely in both new and renovated NZEBs, ranging from 9-10 % to 55 %. In several countries there is no quantification of renewables yet. A critical finding is that many current NZEB definitions exceed the European Commission's recommended benchmarks for non-renewable primary energy demand. However, some countries and regions have successfully lowered their NZEB thresholds and introduced more ambitious standards for both new and renovated buildings over the past years. These advancements highlight that while EU-wide harmonisation is complex, targeted national revisions can drive significant improvements in energy performance.

Looking ahead to the future ZEB standard, whose primary energy demand is calculated as 10 % lower than current NZEB levels of primary energy demand, the apparent compliance with recommended benchmarks appears to be partially addressed. However, the compliance is based on total primary energy. An important challenge appears to be the renewable energy contribution, which is a crucial pillar of both NZEB and ZEB standards. While ZEB standards might seem more compliant when total primary energy is considered, the actual renewable energy integration remains inadequate. As a results, ZEB energy use may generate operational emissions, marking their performance non-compliant with the EPBD criteria from a sustainability perspective. To fully comply with ZEB criteria, buildings should prioritise renewable energy sources. The integration is essential to fulfil the zero on-site and very low operational emissions. However, the currently high total primary energy thresholds in many definitions can make this compliance challenging. Therefore, several countries and regions may revise the NZEB definition to enforce energy efficiency and promote the integration of renewable energy. Additionally, to achieve a decarbonised building stock by 2050, accelerating the rate of building renovation should be paired with deep renovation, now clearly outlined in the EPBD. Establishing operational GHG emissions thresholds can guarantee that renovations are aligned with deep renovation standards, preventing energy and emission savings lock-ins.

The transition from NZEB to ZEB is crucial for achieving the EU's climate neutrality goals. While current NZEB definitions show progress, improvements are needed to meet ZEB requirements and fulfil the EU's climate and energy objectives. This shift requires revising and tightening national standards, increasing renewable energy integration, setting operational GHG emissions thresholds, and focusing on adaptable designs and sustainable materials. Additionally, highlighting the health benefits associated with greater energy efficiency stresses the value of ZEB standards in improving both environmental quality and occupants' well-being.

CRediT authorship contribution statement

Carmen Maduta: Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Delia D'Agostino:** Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Sofia Tsemekidi-Tzeiranaki:** Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Luca Castellazzi:** Supervision, Investigation, Formal analysis, Conceptualization.

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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The views expressed here are purely those of the authors and may not, under any circumstances, be regarded as an official position of the European Commission. Sofia Tsemekidi-Tzeiranaki is a consultant at the European Commission, JRC.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2024.115133.

Data availability

Data will be made available on request.

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