Readiness of Zero-Emission Buildings (ZEBs) implementation in the European Union

Carmen Maduta[1] and *Delia* D'Agostino[1*]

[1]European Commission, Joint Research Centre, Ispra (VA), Italy

Abstract. The building sector plays a central role in the reduction of greenhouse gas (GHG) emissions in the European Union (EU). The revision of the Energy Performance of Buildings Directive (EPBD) sets out ambitious requirements to make the EU building stock decarbonised by 2050. The proposal for a recast EPBD introduces Zero-Emission Building (ZEB) as the building target for all new buildings as of 2030. This paper offers insights into the concept of ZEB, analysing its key methodological aspects, with a focus on ambition, the role of energy efficiency, and the role of renewable energy. Additionally, the paper evaluates the performance levels of new buildings in EU Member States, highlighting the gaps between current Nearly Zero-Energy Buildings' performance levels and potential ZEB performance levels, specifically in terms of primary energy demand and renewable energy contribution. The findings emphasise the necessity to enhance initiatives aimed at improving energy efficiency and harnessing renewable energy sources to adopt the ambitious ZEB concept as of 2030. Additionally, the paper highlights the importance of addressing GHG emissions comprehensively, extending beyond the operational phase of a building to include embodied impacts, in order to achieve a life-cycle zero-emission building stock.

1 Introduction

Responsible for around 40% of energy consumed and 36% of energy-related greenhouse gas (GHG) emissions in the European Union (EU), the building sector is the core of EU energy and climate policies [1]. The European Green Deal, launched in 2019, set the ground for a holistic and cross-sectoral approach to achieve the EU-wide climate neutrality by 2050 [2].
The 'Fit for 55' package stressed the significance of building renovation and proposed measures the transition to green practices [3]. This includes supporting building renovations, adopting clean heating and cooling technologies, and integrating more renewable energy. The REPowerEU plan further emphasized the key role EU's buildings to reduce dependence on foreign energy sources [4].
The main legal pathways for a EU decarbonised building stock have been designed under the Energy Performance of Buildings Directive 2010/31/EU (EPBD) [5]. The Directive provides policies and measures to guide Member States in enacting legislation to enhance building energy performance. It frames requirements for new energy efficient buildings and the

* Corresponding author: delia.dagostino@ec.europa.eu

transformation of existing buildings. For new buildings, the EPBD requires Member States to ensure that all buildings from 2021 onward meet the Nearly Zero-Energy Building (NZEB) standard. NZEB is defined as a highly energy-efficient building where the nearly zero or very low amount of energy required is covered to a very significant extent by energy from renewable sources produced on-site or nearby [6].

In 2021, the European Commission (EC) proposed a recast EPBD to align with the EU's goal of a 55% GHG emission reduction by 2030 and the reinforced Directive will be published soon [7], [8]. The proposal aims for a decarbonised building stock by 2050, introducing inter alia, a definition for Zero-Emission Building (ZEB). A ZEB is defined as a building with a very high energy performance, requiring zero or a very low amount of energy, producing zero on-site carbon emissions from fossil fuels and producing zero or a very low amount of operational GHG emissions. The total annual primary energy use must be covered from on-site and near-by renewables, renewable energy communities, district heating and cooling systems or other energy from carbon free sources. In addition, the proposal requires Member States to introduce maximum thresholds for the total annual primary energy use of ZEBs that shall be at least 10% lower than of national NZEBs at the time of implementation. Also, the operational GHG emissions shall comply with a national maximum threshold. The primary objective at the EU level is for public-owned new buildings to be ZEBs as of 2028, with the broader goal that all new buildings meet the ZEB standard as of 2030.

Additionally, the proposal for a revised EPBD has incorporated a definition for deep renovation. Deep renovation means a renovation prioritizing energy efficiency and focusing on essential building elements. It entails transforming buildings into NZEBs before 2030 and ZEBs from 2030 onward. The ultimate target is to achieve a zero-emission EU building stock by 2050. A deep renovation may also be a prime opportunity to address various aspects, including indoor environmental quality, safety, and resilience against disasters.

Due to the climate and energy emergency we are facing, the ZEB contribution will be crucial to reach EU goals. The concept of ZEB must be properly received avoiding the delay that characterized the initial NZEB implementation. Accordingly, this paper provides an overview on ZEB, offering insights into challenges and future developments across the EU.

2 Methodological aspects of a ZEB

This section introduces key methodological aspects outlining a building with zero emissions, focusing on the overall ambition of zero emissions, the role of energy efficiency and the role of renewable energy. The concept of zero-emission building has gained global importance and application over the past two decades, emerging as a key strategy for decarbonising the building sector [9].

A worldwide consensus is that a building with zero emissions represents an innovative sustainability strategy, highly energy efficient and able to generate renewable energy in quantities sufficient to counterbalance its GHG emissions. Scientific terminology such as Zero Emission [10]–[12] or Net Zero Emission [13], [14], Zero Carbon [15], [16] or Zero Carbon Ready [17] collectively encompasses energy efficiency enhancements, the integration of renewable energy resources, and cautious carbon offsetting strategies.

2.1 Zero-emission ambition

A ZEB involves that one or more stages in the life-cycle of the building has absolute or net zero impacts in terms of GHG emissions. The level of ambition varies starting with the consideration of exclusively the operational stage and progressively broadening the assessment scope to encompass stages both preceding and succeeding the operational phase.

These stages include material production, transportation, construction, replacement, demolition, and recycling.
However, more commonly, the ambition is limited to the operational phase, with a specific focus on building-related energy use. In line with this, the proposed ZEB definition in the EU encompasses energy consumption for space heating, cooling, ventilation, domestic hot water preparation, lighting, and other technical building system energy uses (auxiliary energy).
In addition to considerations on assessment boundaries, another crucial methodological aspect relates to the ambition level of zero emissions. This centers on whether the overall balance over a specified calculation period is zero, denoted as net zero emissions, or whether the objective is absolute zero emissions. The latter scenario implies that a building has zero emissions linked to the consumption of fuel or electricity during its operational phase. Furthermore, when considering the entire life-cycle emissions, the building materials must originate from sources with zero emissions, and both the transportation of materials and the construction process must be characterized by zero emissions.
While the current proposed ZEB definition requires the status of absolute zero carbon emissions during building operation, the more ambitious absolute zero life-cycle emission represents the pathway towards climate neutrality of new buildings.

2.2 Energy efficiency role

The Energy Efficiency First Principle (EE1st) serves as a fundamental cornerstone for reaching climate objectives and reducing dependence on fossil fuels. Concretely, EE1st seeks to ensure that only necessary energy is produced, avoiding investments in stranded assets [18]. Attempting to achieve building with zero emissions without emphasizing energy efficiency would require substantial energy supplies from renewables, often proving impractical and cost-ineffective. Indeed, the proposed ZEB definition stresses the requirement for a very high energy performance in the first place and the low amount of energy still needed to be covered by renewable energy.
While energy efficiency measures can dramatically reduce a building's operational energy, attention to the entire life-cycle behavior is crucial to avoid potential increases in embodied energy. Highly energy efficient buildings need a greater consumption of materials, particularly thermal insulation materials [19]. Additionally, they may require the installation of diverse passive technologies (e.g. solar shadings), more complex technical systems as well as on-site renewable energy systems. In cases of renovation, the process involves the removal and treatment of old materials. Consequently, these measures contribute to higher embodied impacts in the construction and retrofitting of such buildings. Nevertheless, studies indicate that highly energy-efficient buildings outperform conventional ones over their life-cycle [20].

2.3 Renewable energy role

Adhering to the EE1st principle, a ZEB should minimize energy needs, and the low amount of energy needed should be covered by renewable energy production. However, not all buildings can generate enough on-site renewable energy, needing dependence on off-site sources. Therefore, the proposed ZEB definition allows for renewable energy from a renewable energy community, renewable energy and waste heat from an efficient district heating and cooling system and other energy from carbon free sources.
Renewable energy communities are based on open and voluntary participation of public, private and community actors in co-producing and distributing renewable energy and it is effectively controlled by its members [21]. Although such communities have received substantial policy support at EU level, the concept it is not widely known. There is a need for

increased dissemination of information about the structure and role of renewable energy communities to ensure better access for citizens, local administrations and stakeholders [22], [23]. To support the uptake of ZEB, renewable energy communities needs a rapid scaling up across the EU.

3 Current state of play

This section provides an overview of the current performance levels of new buildings in EU Member States and critically examines the challenges in achieving the potential performance levels outlined in the future building targets of ZEB. The key areas of focus include primary energy demand, the contribution of renewable energy, and GHG emissions.

3.1 Energy performance levels

The EPBD does not advocate a uniform approach for implementing the NZEB concept throughout the EU, leaving Member States to detail their NZEB definitions, accounting for the variety of building types and climates. A recent assessment of NZEB implementation in the EU reveals that NZEB are currently 70% more ambitious than 2006 national energy performance levels [24]. The common NZEB definition involves a year-long energy balance at building level, considering on-site renewables, using as indicator the primary energy demand for heating, cooling, ventilation, domestic hot water, built-in lighting and auxiliary energy. Some definitions cover additional energy uses like appliances, central services, and internal building mobility.

In 2016, the European Commission introduced guiding benchmarks for both total and non-renewable primary energy demand of NZEB [25]. Figure 1 compares the recommended NZEB benchmarks, the average NZEB performance level of new buildings, and the potential ZEB thresholds, in total primary energy demand. The ZEB thresholds are calculated as 10% lower than current averaged NZEB levels, as currently indicated in the proposal for recast EPBD. For comparison purposes, the Member States are divided into climatic zones as follows: (1) Cyprus, Croatia, Italy, Greece, Spain and Portugal in Mediterranean, (2) Belgium, Denmark, Ireland, Germany, France Luxembourg, and Netherlands in Oceanic, (3) Austria, Bulgaria, Czechia, Hungary, Poland, Romania, Slovenia, and Slovakia in Continental, and (4) Estonia, Finland, Latvia, Lithuania, and Sweden in Nordic. The average NZEB performance levels by climatic zones were calculated as explained in [26].

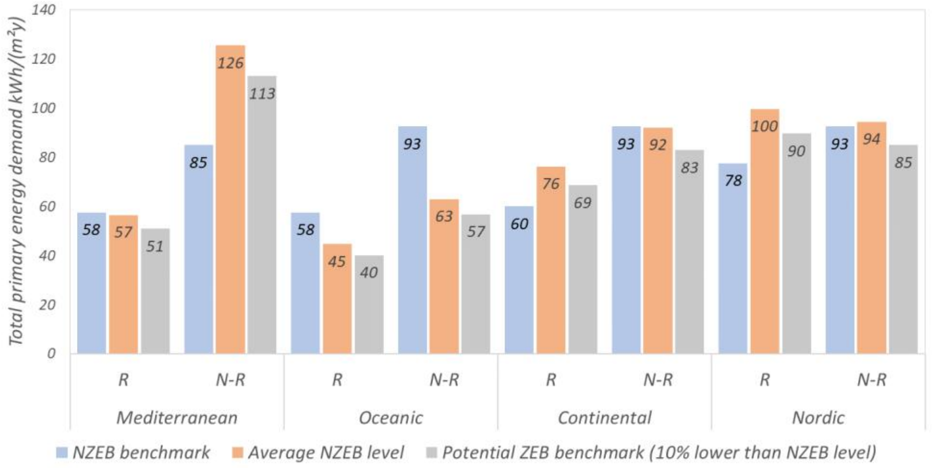

Fig 1. NZEB recommended thresholds, national NZEB performance level of new buildings averaged by climate zones, potential ZEB thresholds calculated as 10% lower than current NZEB levels, for residential and non-residential buildings, in total primary energy demand, by climate zones. Notes: R = Residential buildings; N-R = Non-residential buildings (offices)

The comparison reveals an uneven landscape. Residential buildings in Mediterranean and Oceanic climates are slightly more ambitious than recommended NZEB levels, whereas in Continental and Nordic climates, the average NZEB lags behind the thresholds. Regarding non-residential buildings, the situation is more optimistic, with the average total primary energy demand surpassing the NZEB threshold only in the Mediterranean climate, while values in Continental and Nordic climates align with the standards.

A ZEB that is 10% more ambitious than the current NZEB standards would enhance overall compliance; however, exceptions persist, particularly in residential buildings in Nordic and Continental climates and non-residential buildings in Mediterranean climates. Consequently, despite evident progresses, the majority of Member States will need to enhance the energy performance of their new buildings by more than 10% in the foreseeable future.

3.2 Renewable energy contribution

Another key factor influencing future national ZEB is the renewable energy obligation within national NZEB. Figure 2 provides an overview on how renewable energy is currently addressed in new NZEBs. It provides the lowest renewable energy contribution, the highest, and the averaged contribution across countries within the same climatic zone, in percentage (Member States division in climate zones as explained in Section 3.1). However, is important to note that not all countries have implemented a mandatory requirement for renewable energy contributions. In addition, some countries have distinct requirements depending on the building type, end-use covered, and technology [26].

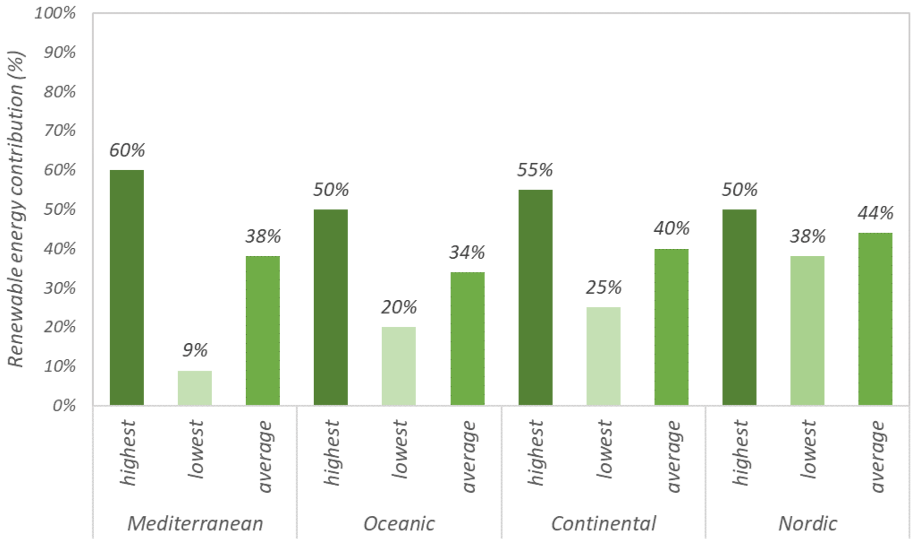

Fig. 2. Renewable energy share in the total primary energy demand in new buildings, lowest, highest and average contribution by climatic zone.

On average, renewable energy covers around 40% of the total primary energy demand of new NZEB. However, this figure is far from the proposed future requirement, which mandates that new buildings shall cause zero on-site carbon emissions and very low GHG emissions, thus heavily relying on renewable energy. Regarding the source of renewable energy, most countries rely on-site production from solar energy (photovoltaics and thermal collectors). Given this context, it is evident that Member States will need to further explore and exploit renewable options, including renewable energy communities and efficient district heating and cooling to realize the ambitious goals of ZEB.

3.3 GHG emission thresholds

While primary energy demand remains a key metric for future ZEBs in alignment with the EE1st principle, as society progresses towards decarbonisation, the proposal for a revised EPBD mandates Member States to establish maximum thresholds for operational GHG emissions of ZEBs. Additionally, the proposal entails the introduction of life-cycle Global Warming Potential (GWP) calculations for new buildings starting in 2030.
Member States have long implemented the calculation of GHG emissions within the methodology for calculating cost-optimal energy performance levels of buildings [27]. The macroeconomic perspective of the methodology allows countries to identify the packages of measures that bring the lowest operational emissions and benchmark their building standards accordingly. Recent assessment reveals that almost all Member States have performed the macroeconomic calculation, thus identifying the operational emissions impact [28]. Certainly, the methodology must be extensively applied to explore energy efficiency measures capable of maintaining energy demand within future benchmarks and to identify renewable options ensuring complete coverage of the ZEB demand.
Another tool indicating Member States' readiness for ZEBs, is the Energy Performance Certificate (EPC). Most national EPC schemes report the emissions (CO_2 or CO_2-eq) released during building operation. Additionally, five countries (Austria, France, Luxembourg, Romania, and Spain) include an emission class, complementary to the energy class, thus already benchmarking the operational GHG emissions of buildings [29].

4. Forward-looking perspectives and conclusions

The EU aims to lead the way in the global fight against climate change, ensuring a socially fair transition, which maintains and strengthens innovation and competitiveness. To align the requirements in the building sector with the ambitious goals of climate neutrality, a recast Energy Performance of Buildings Directive (EPBD) was proposed in 2021 and agreed at the end of 2023. The proposal introduces a definition for Zero-Emission Building (ZEB), focusing on achieving zero emissions during the operational phase of a building.
The progress in implementing Nearly Zero-Energy Buildings (NZEBs) suggests a certain readiness to embrace the ZEB in the EU Member States. However, current assessment reveals that average primary energy use in new buildings exceeds the recommended maximum benchmark for NZEBs in almost all climate zones. A potential 10% lower ZEB threshold would enhance overall compliance. However, finding suggests a need to enhance energy efficiency further to minimize demand, coupled with increased exploitation of renewable energy sources to deploy ZEB as of 2030. Currently, renewable energy contributes approximately 40% in new NZEBs, but there is a pressing need for an accelerated transition to achieve zero on-site carbon emissions in future ZEBs.
In light of the current climate and energy crisis, the contribution of ZEBs is pivotal for achieving EU goals. It is imperative that the concept of ZEB is embraced promptly, avoiding the delays that were evident in the NZEB implementation.
While operational impacts are being mitigated through NZEBs and ZEBs, embodied impacts are expected to dominate the life-cycle impacts of buildings. To address this, the recast EPBD proposes calculating the Global Warming Potential for all new buildings starting in 2030 and disclosing it through Energy Performance Certificates. While this marks a step toward considering life-cycle impacts by raising awareness, it may not automatically result in lower embodied impacts. Further improvements are crucial to more effectively address embodied impacts and move towards a life-cycle zero-emission building stock.

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