Energy & Buildings 267 (2022) 112165

Contents lists available at ScienceDirect

Energy & Buildings

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

Overview and future challenges of nearly zero-energy building (nZEB) design in Eastern Europe

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ARTICLE INFO

Article history:
Received 1 March 2022
Revised 18 April 2022
Accepted 6 May 2022
Available online 11 May 2022

Keywords:
New construction
Buildings
Energy efficiency
EPBD
Construction quality
Cost-optimality

ABSTRACT

The European Unions' ambition for the construction sector is to be carbon neutral by 2030 for new construction. Since 2021, all new buildings in the EU should have been constructed as nearly zero-energy buildings (nZEB). However, Eastern European countries struggle to implement the 2018 Energy Performance of Building Directive recast requirements. Next to the economic challenges, equally essential factors hinder renovating the existing residential building stock and adding newly constructed high-performance buildings sourced primarily from renewable energy sources. Therefore, this study provides a cross-study to identify the barriers to nZEB implementation in ten Eastern European countries, including Bulgaria, Croatia, Czechia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, and Slovakia. The study was conducted between 2019 and 2021 and provides an overview of prospects for nZEB in Eastern Europe. The study examines the challenges of nZEB plans faced in those countries and provides constructive recommendations. The regulations and definitions regarding nZEB energy performance, cooling and heating energy demand, thermal comfort, onsite renewables, and construction quality were analyzed. Results show that most Eastern European countries are unprepared to comply with the EPBD guidelines and cost-optimality approach. The paper ranks each country and recommends specific measures to refine the nZEB definitions. The paper provides a thorough comparative assessment and benchmarking of select EU geography that can help shift the identified gaps into opportunities for the future development of climate-neutral high-performance buildings.

Abbreviations: AEC, Architectural Engineering, and Construction; AC, Air conditioning; ACH, Air change per hour; BPS, Building Performance Simulation; CEN, European Committee for Standardization; CDD, cooling degree days; DBT, Dry Bulb Temperature; DHW, Domestic Hot Water; EE, Eastern European; EPBD, Energy Performance of Building Directive; EPC, Energy Performance Certificate; EUI, Energy Use Intensity; EU, European Union; ETICS, External Thermal Insulation Composite Systems; FIT, Feed-in Tariff; GHG, Greenhouse Gas; HDD, heating degree days; HP, Heat Pump; HRV, Heat recovery ventilation; HVAC, Heating, Ventilation and Air Conditioning; IEA, International Energy Agency; IEE, Intelligent Energy Europe; IEQ, Indoor Environmental Quality, LCA, Life Cycle Assessment; MS, Member States; MVHR, Mechanical Ventilation with Heat Recovery; nZEB, nearly Zero Energy Buildings; NZEB, Net Zero Energy Buildings; OT, Operative Temperature; PE, Primary Energy; PEF, Primary Energy Factor; PH, Passive House; PMV, Predicted Mean Vote; PV, Photovoltaic; RES, Renewable Energy Systems; SCOP, Seasonal Coefficient of Performance; SEER, Seasonal Energy Efficiency Ratio; SRI, Smart Readiness Indicator; SHW, Solar Hot Water; SME, Small and Middle Enterprise; VRF, Variable refrigerant flow; WWR, Window to Wall Ratio.

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https://doi.org/10.1016/j.enbuild.2022.112165
0378-7788/

1. Introduction

The European Union's (EU) 2030 Climate Target called "Fit for 55" seeks to reach climate neutrality and 55% reduction of Greenhouse Gas (GHG) emissions by 2030 [21]. The Energy Performance of Building Directive (EPBD) recast of 2018 is the implementation tool to translate those targets and transform new and renovated buildings across the EU 27 member states. The revised Directive 2021/12/14EU (EPBD) at art. 9 indicates that EU Member States (MS) must reach a minimum 55% reduction in greenhouse gas (GHG) emissions by 2030 (compared with 1990 levels), thus setting the EU more firmly on the path towards meeting its ultimate goal of net-zero GHG emissions (climate neutrality) by 2050 [32]. Accordingly, most MS recently revised the existing rules, regulations, and guidelines and started to set up the means for increasing the penetration of high-performance buildings by setting up the nearly Zero Energy Buildings (nZEB) plans and requirements [6]. More importantly, all 27 EU member states must develop decarbonization roadmaps and trajectories to phase out fossil fuels and set carbon limits, as presented in Fig. 1. But the progress of nZEB implementation in Eastern Europe is slow. From one side, Northern and Western member states started earlier by formulating and implementing the nZEB concept [8]. Southern European countries are working on nZEB definitions and implementation plans taking into account summer overheating risks [7]. On the other side, Eastern MS are still trying to find adequate definitions and approaches to mass construct nZEB. Thus, there is a divide between the West and East in building energy efficiency and policy. Eastern Europe is emerging as an attractive renewables investment destination [67]. The International Renewable Energy Agency (IRENA) indicates the cost-competitive and vast renewables potential of East Europe [29]. The competition in Eastern Europe to spend public funds on renewable energy systems can create future problems with energy efficiency targets and demand reduction. Currently, nZEB needs to be mainstream across Eastern Europe.

The status of Eastern European countries reflects a severe problem of a joint nZEB definition adoption, benchmarking of national energy efficiency contributions, and, consequently, market uptake [32]. The housing stock in Eastern Europe consists mainly of multifamily houses located in blocks of flats and connected with district heating, in contrast to rural areas where single-family homes are dominant [14]. According to the EU Building Stock Observatory (BSO), a web tool that monitors the energy performance of buildings across Europe, the average energy need for heating of single-family houses built before World War II is between 175 and 310 kWh/m^2.a. Multifamily buildings built before World War II have an energy need for heating between 150 and 300 kWh/m^2.a. Therefore, EE countries are emerging as attractive energy efficiency and renewable investment destinations. Nevertheless, EE countries need to ratchet up building energy efficiency standards. The Emissions Trading System (ETS) and the EPBD drive EE countries to endorse the climate neutrality objective by 2050. The latest EPBD recast of 2021 requires the presence of two indicators for nZEB calculation methods that form the pillars of the definition [21]:

1) *A 'nearly zero-energy building' means a building that has a very high-energy performance. The nearly zero amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced onsite or nearby.*

2) *'primary energy' means 'energy from renewables and non-renewables sourced' that has not undergone a conversion or transformation process.*

Therefore, this paper aims to overview the technical and societal challenges of applying nZEB in Eastern Europe [15]. The overall aim is to understand nZEB and its market uptake barriers better. The cost of nZEB and the associated financial challenges are excluded in this study, as little has been published in this area. The study focuses on countries between latitudes 59°N and 41°N and includes a literature review of more than 60 publications on nZEB implementation in Eastern Europe. Ten countries are selected, namely Bulgaria, Croatia, Czechia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, and Slovakia. A screening of representative publications and available experts on nZEB narrowed the study scope to the ten selected countries. The selected countries are connected geographically with a significant population and building stock representing more than 19% of the European residential buildings stock [14] (see Fig. 2). The originality of the paper is twofold. First, the paper provides a comparative assessment of the challenges of nZEB, bringing insights from ten Eastern MS. Secondly, the paper identifies key supporting measures and climatic and socio-economic contexts recommendations. The low carbon transformation of the building sector in Eastern Europe is a hot topic within the current geopolitical context. With the EU's efforts to abandon fossil fuels and decarbonize heating in residential buildings, assessing the market transformation and providing insights and recommendations on state of the art is essential. Therefore, the paper characterized the current nZEB plans within

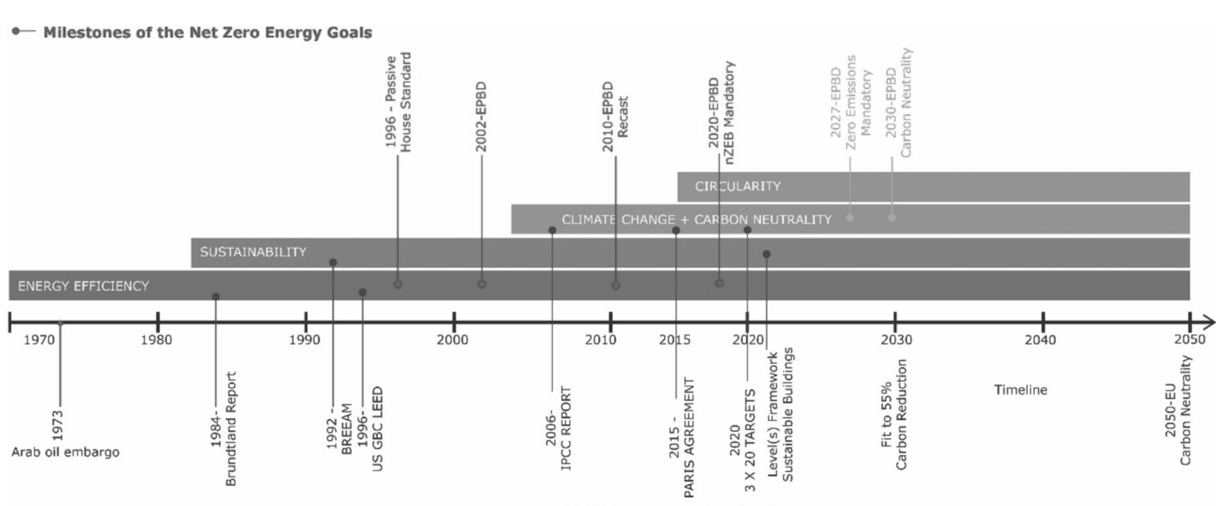

Fig. 1. Evolution of EPBD requirements from 2006 to 2050 and the milestones towards Net Zero Energy Buildings.

wider policy contexts in Eastern European countries to increase the nZEB market uptake. The main research questions are:

What is the state of nZEB plans in Eastern Europe?

What are the different approaches and barriers to implementing nZEB in Eastern Europe?

What are the recommendations to improve the residential building's energy efficiency in Eastern Europe towards nZEB and align with the EPBD 2050 targets?

The methodology used consists of reviewing the state-of-the-art 10 MS, similar to a previous work conducted by the primary author on Southern Europe [7]. The second step of the methodology is an experts-based questionnaire. An extensive dataset (Attia 2021) and fact sheets developed by 14 experts were created and analyzed to identify and understand the reality of the nZEB national plans in Eastern Europe. The market uptake of high-performance buildings, their associated technologies, and their potential were discussed. Finally, the analysis guides the challenges and constraints in each MS and provides a comprehensive list of recommendations and conclusions for nZEB in Eastern Europe.

1.1. Methodology

The research methodology is mainly qualitative, similar to the study conducted by Attia et al. [7]. The study combines literature reviews and a questionnaire shared with fourteen experts from Eastern Europe. The questionnaire was designed and answered during the Zero Energy and Low Carbon Buildings (ZERO) project between 2020 and 2022. The questionnaires were administered as a collective exercise in 2021. The literature review and questionnaires were conducted to evaluate the state-of-art and future trends in nZEB plans of residential buildings in Eastern Europe (EE). Both methods are described in detail below.

Firstly, a literature review was conducted to screen key publications and articles related to nZEB' and energy efficiency in residential buildings. Fig. 3 illustrates the keyword used as part of the inclusion criteria in the literature search. Google Scholar, Elsevier Engineering Village, and Web of Science databases searches were conducted in November 2021 to elaborate the review. Key publications from European institutions such as Eurostat, European Construction Sector Observatory (ECSO), Building Performance Institute Europe (BPIE), ODYSSEE database on energy efficiency indicators and energy consumption by end-use and their underlying drivers in the industry, transport, and buildings, and the national energy agencies in the ten investigated countries, were reviewed. The search included the proceedings of the European Council for an Energy-Efficient Economy conference. More than sixty references were collected, including articles and reports in 11 languages.

The literature review inclusion criteria included several terms related to the European Energy Performance of Buildings Directive (EPBD), such as 'certification,' 'cost-optimal,' 'nearly Zero Energy

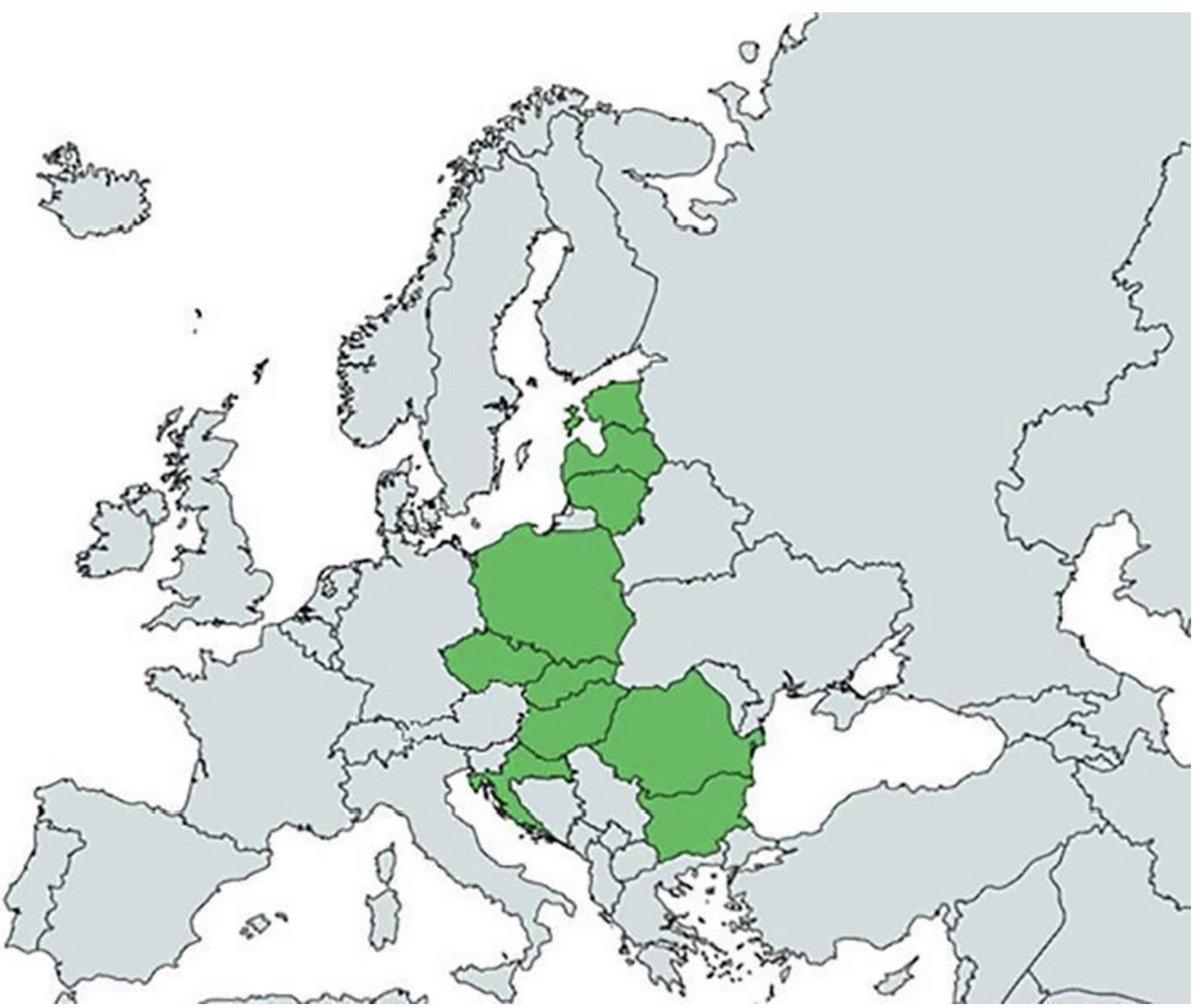

Fig. 2. The participating countries in the study on nearly Zero Energy Buildings status in Eastern Europe.

Fig. 3. Key elements influencing nZEB implementation in Eastern Europe.

Buildings (nZEB)' and 'Net Zero Energy Buildings (NZEB).' The references were sorted according to five main criteria, previously used in the study of [7], and that are relevant to nZEB, namely: 1) minimum energy efficiency threshold, 2) heating/cooling energy needs balance, 3) thermal comfort limits, 4) minimum renewables threshold, and 5) construction quality. Fig. 3 shows the key elements that significantly affect the building energy efficiency of the residential sector.

Secondly, a questionnaire was created to collect input from fourteen East European experts. Five key questions were proposed. A pilot study was carried out to identify relevant themes and concepts related to net-zero energy building regulations and implementation—the pilot study allowed testing and improving the questionnaire's consistency. The questionnaire focuses only on implementing the nZEB definition in the ten EE countries and the construction quality. Appendix I includes the questionnaire and details supporting the five main questions. Then, the recruitment of East European experts took place. nZEB experts were identified through their publications and snowball sampling. Individuals from the VBuilding Project on nZEB standards in Visegrad countries (Kosiński, 2021) were asked to name experts in Eastern Europe who are influential. All of the questioned experts represented civil and mechanical engineers working in universities. All interviewed experts had experiences ranging from 5 to 10 years and had worked on at least one project with an nZEB. The recruitment continued until saturation and heterogeneity were reached. The recruitment processes ended in the winter of 2021. Fourteen national experts from Bulgaria, Croatia, Czechia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, and Slovakia. The paper content focused on new and existing residential areas buildings. Experts were requested to consult and cite the official documents published by official agencies and ministries of each respective country. Several documents in the native language of the ten member states were cited in the reported questionnaire answers. Next, the content analysis took place for each response, and a dataset of tables was created.

2. Nearly zero-energy buildings in Eastern Europe

The literature review was based on an extensive list of references presented in Appendix II. The analysis grouped the key publications related to residential nZEB plans in the ten Eastern European (EE) countries. However, most of the reported findings below were mainly a result of the questionnaire responses of the 14 experts. The questionnaire answers in Appendix I allowed bringing in-depth insights into the state of nZEB implementation in Eastern Europe. The following paragraphs summarize the state of each country.

2.1. Bulgaria

- A continental climate in the north characterizes Bulgaria. In the South, the climate is classified as the Mediterranean. The South tends to be hot and dry in the summers and cool in winters. Nine climatic zones are used to calculate the energy efficiency of buildings.
- The national nZEB plan was adopted in 2015 by the councils of ministers. Minimum energy efficiency requirements for primary energy use intensity are 95 kWh/m^2.a for residential buildings and no minimum requirements for renewable energy share. Mechanical ventilation requirements are not defined.
- The cost optimality approach has not been used in the development process of nZEB, and no publications reported using this approach or formulating representative benchmark models.

2.2. Croatia

- Croatia is characterized by a rainy continental climate in the east and a moderately warm Mediterranean climate in the West. The Mediterranean region tends to be hot and humid in the summers and cool in winters. Two climatic zones are used to calculate the energy efficiency of buildings.
- The national nZEB plan was adopted in 2015. Minimum thresholds for primary energy range between 50 and 80 kWh/m^2.a, for final heating demands, are 50–75 and 25–60 kWh/m^2.a for final cooling demand in residential buildings.
- Renewable energy sources must cover at least 20% of the annual end energy used on site.
- There is an obligatory requirement to prove fulfilling air permeability. For the pressure difference of 50 Pa, the measured number of air exchanges must not exceed n50 = 3.0 h-1 in the case of buildings without mechanical ventilation systems or n50 = 1.5 h-1 in the case of buildings with mechanical ventilation systems.
- The use of heat pumps in the Croatian climate is highly effective when coupled with photovoltaic systems, especially for cooling and DHW during summer [64].
- Croatia has an active education plan for construction workers through the Croskills project [71]and has continued through Horizon 2020 projects Fit-to-NZEB [19]and Net-UBIEP [50], further through Erasmus + project BIMzeED [11], which the University of Zagreb conducted.

2.3. Czechia

- Czechia is characterized by a dominating climate, the continental climate, with warm summers and cold, cloudy, and snowy winters. Only one climatic zone is used to calculate the energy efficiency of buildings.
- A detailed national plan is available. Minimum thresholds for heating demand and cooling demand are compared with a reference building. The primary energy demand is estimated to be 30–90 kWh/m^2.a.
- The reference building is a hypothetical copy (same geometry, occupancy, climate...) of the designed building, with parameters mirroring limit values set in standard ČSN 730540–2 Thermal protection of buildings – Part 2: Requirements.

- Mechanical ventilation requirements are not obligatory.
- Seasonal heating and cooling energy demand variations are significant in nZEB family houses [44].
- Barriers to nZEB implementation problems include a lack of sophisticated organizational certification mechanisms and a shortage of qualified labor caused by mass migration to the West [57].
- The proliferation of nZEB single-family homes in rural areas is slow. Newly constructed rely on HP and PV. However, old buildings are old and rely on solid fuel heating systems with polluting emissions.
- Czechia developed a national cost optimum calculation completed in June 2017 based on the Energy Performance of Buildings Directive cost-optimality approach [35].

Estonia

- The Estonian climate is oceanic temperate, characterized by warm summers and fairly severe winters, reaching 5250 heating degree days (HDD) in Tallinn between 2015 and 2020. Only one climatic zone is used to calculate the energy efficiency of buildings.
- A detailed national plan is developed through the maxim allowed primary energy of 100–145 kWh/m^2.a uses in residential buildings, including appliances (small power plug loads) and lighting on the top of EPBD. The building performance calculation method is advanced and based on a dynamic simulation approach that considers the net floor area and linear thermal bridges.
- Since 2010 the cost optimality calculation approach has been used to define the nZEB requirements [39,54]. The cost-optimal requirements are mandatory and have been revised twice.
- Estonia has advanced building envelope air permeability requirements of 1.5 m^3/(h m^2) under 50 Pa of air pressure. The building air permeability must be verified through an air blower test.
- Estonia has the most significant number of heat pumps (air-to-water heat pumps) in households in Eastern Europe, reaching 35 heat pump units per 100 households (see Fig. 5) [53,56].

2.4. Hungary

- The Hungarian climate is continental, characterized by hot summers and fairly severe winters reaching 3000 heating degree days (HDD) and 500 cooling degree days (CDD) in Budapest between 2015 and 2020. Only one climatic zone is used to calculate the energy efficiency of buildings.
- A national plan is still not fully available, but some information is yet available. Minimum energy efficiency requirements for primary energy use intensity are 85–100 kWh/m^2.a for residential buildings and no minimum requirements for renewable energy share.
- Since 2016 the cost optimality calculation approach [59]has been used to define the nZEB requirements and TABULA benchmark models [28,30].
- Mechanical ventilation requirements are not obligatory.

2.5. Latvia

- The Latvian climate is oceanic temperate, characterized by warm summers and fairly severe winters, reaching 3846 heating degree days (HDD) in Riga between 2015 and 2020. Only one climatic zone is used to calculate the energy efficiency of buildings. The yearly average temperature is typically around + 6 °C.
- The national plan focuses on limiting the whole buildings' non-renewable primary energy and heat consumption [55]. Minimum energy efficiency requirements for primary energy use intensity vary from 95 kWh/m^2.a to 170 kWh/m^2.a. Minimal performance threshold heating demand varies in the range from 40 kWh/m^2.a to 60 kWh/m^2.a. Both values depend on the type and size of the building. Mechanical ventilation requirements are not obligatory.
- Latvia has advanced building envelope air permeability requirements of 1.5 m^3/(h m^2) under 50 Pa of air pressure for mechanically ventilated buildings.
- Few studies are available on the cost optimality calculation approach [70], and the cost-optimality approach was not used to define the nZEB requirements [63].
- The most common renewable onsite technologies for reaching net-zero energy goals are photovoltaic (PV) and solar thermal panels combined with ground source heat pumps [33].

2.6. Lithuania

- The Lithuanian climate is oceanic temperate, characterized by warm summers and fairly severe winters, reaching 4852 heating degree days (HDD) in Vilnius between 2015 and 2020. Only one climatic zone is used to calculate the energy efficiency of buildings.
- A national plan is in place. Minimum energy efficiency requirements for primary energy use intensity are 50–100 kWh/m^2.a in residential buildings. A minimum requirement of 50% of renewable energy share is mandated [61].
- The cost optimality approach has not been used in the development process of nZEB, and no publications reported the use of this approach or the formulation of representative benchmark models [72].
- Mechanical ventilation is not obligatory in residential nZEB.

2.7. Poland

- Poland has a cold climate with both maritime and continental elements.
- A national plan is in place. Minimum energy efficiency requirements for primary energy use intensity are 65–75 kWh/m^2.a in residential buildings. Mechanical ventilation requirements are not obligatory.
- Renewable energy must cover residual energy requirements in the housing construction equal to approximately 50 kWh/m^2.a.
- Renewable energy systems compete with energy efficiency in residential nZEB, and the preparedness for ensuring nZEB and NZEB is currently low [9].
- The cost-optimality approach in Poland is established, and the nZEB national plan requirements are based on it.
- EPC requirements and implementation process is inaccurate and is used inconsistently. EPCs in Poland for nZEB do not represent the expected energy efficiency performance [22].

2.8. Romania

- Romania has a temperate continental climate transitioning into an oceanic climate on the eastern coast.
- The nation plan considers nZEB to respect 93–217 kWh/m^2.a primary energy thresholds without requirements for minimum renewable energy share.
- The cost-optimality approach in Romania is established, and the nZEB national plan requirements are based on it [62].
- Mechanical ventilation requirements are not obligatory, and there are no requirements for nZEB envelope air permeability testing.

- EPC has no standardized templates, and there is a great diversity in certification. The EPC calculation methodology is not fully clear and detailed and, in some cases, provides room for diverse interpretation.

2.9. Slovakia

- Slovakia has a continental climate with warm, dry summers and cold winters, reaching 2964 heating degree days (HDD) in Bratislava between 2015 and 2020. Only one climatic zone is used to calculate the energy performance of buildings.
- The national regulation sets the lowest threshold among the ten compared countries of 32–54 kWh/m^2.a for primary energy and an obligation of mechanical ventilation and heat recovery system.
- RES should cover at least one of the energy use items, namely: heating and/or cooling energy demand, DHW energy demand, and electricity demand.
- nZEB is already a common practice in terms of Slovak regulation, from 2018 for newly constructed public buildings from 2021 for other and mainly residential buildings. However, they were also increasingly constructed before 2021 as well.
- In Slovakia, the construction sector of nZEB, including designers, developers, and builders, is considered well transformed. The market integrates new materials in mechanical ventilation systems, including heat recovery systems, smart meters, heat pumps, and RES.

3. Different approaches and barriers to implementing nZEB in Eastern Europe

The recast Energy Performance of Buildings (EPBD) requires the EU Member States to construct only nearly Zero Energy Buildings (nZEB) from 2021 for all new buildings. Acknowledging Eastern European countries' history and climate conditions, the status of national nZEB definitions and national plans reflecting on the six categories or topics were analyzed and presented below.

3.1. nZEB status

The progress of nZEB regarding policy development and implementation in the Eastern European construction sector witnesses a wide disparity. All ten states succeeded in developing national plans and a legislative framework for the newly constructed nZEB. The questionnaire undertaken on the new residential building stock and actual construction practice showed that the situation in the ten member states differs in many respects from Western Europe. The analysis and comparison of ten EE countries indicate a correlation between the advancement of nZEB regulations and construction concerning the economic strength of the investigated countries—EE countries with the highest GDP score high on good governance indicators and human capital education [10]. Consequently, their investment in the building energy efficiency and renewable energy sectors is the highest [43,58]. For example, the high GDP in Estonia and the Czech Republic positively influences this energy efficiency governance.

Table 1 presents an indicative summary of the evaluation based on the five major criteria explained in Sections 4.2–4.6. The somewhat developed countries regarding nZEB requirements are Estonia, Slovakia, Poland, and Croatia, followed by Romania, and Czechia, which are struggling with nZEB implementation. Bulgaria, Latvia, Hungary, and Lithuania are behind (Table 1). The detailed analysis is provided in the following section.

3.2. nZEB minimum requirements

In order to evaluate the minimum nZEB requirements and actual construction practice towards nZEB levels for each country, the analysis was categorized under two main themes, namely 'performance' and 'technology.'.

All ten states defined their nZEB requirements following a performance-based approach based on the first energy efficiency principle. Energy efficiency requirements for building envelopes and energy systems are expressed in primary energy demand as energy use intensity. The primary energy demand requirements are considered the key performance indicator for nZEB. Renewable energy use is integrated into the primary energy requirements too. As shown in Table 2, some member states indicate minimum final energy demand requirements for building services (i.e., heating, cooling, domestic hot water, ventilation, and auxiliary energy), including Croatia, Latvia, and Romania.

The results indicate that most countries developed their nZEB primary energy requirements for single-family residential buildings to reduce the heating energy demand. Most cities are heating-dominated and represent the different regional climates in the ten investigated climates. The absence of the requirement for integrating renewable energy in buildings and the low CDD values confirm this finding. However, the cooling energy needs in nZEB in Eastern Europe remain an underestimated factor. The base temperature values were chosen at 15.5 °C for 'Heating Degree Days' and 22 °C for 'Cooling Degree Days' to calculate and characterize the climate in the 23 EE cities. The cooling degree days reported in Table 2 reflect an increasing tendency of cooling degree days. Due to climate change [4], most of the cities located in Bulgaria, Croatia, Hungary, and Romania had significantly higher cooling degree days compared to the first five years at the beginning of the century (2000–2005).

Moreover, the assumption of a base temperature of 22 °C for 'Cooling Degree Days reported in Table 2 is not realistic. The questionnaire responses of the East European experts indicated that there would be a significant amount of heat in newly constructed residential nZEB in Eastern Europe. To avoid overheating, active cooling very often needs to be activated at 20 °C outdoor temperature or below. Thus, the base temperatures for the CDD calculation at 22 °C are not realistic and require lower, for example, 18 and 22 °C. Therefore, the cost-optimality approach should be adopted to define the primary energy use minimum requirements, emphasizing integrating renewables and avoiding discomfort. The current primary energy use requirements should be revised based on representative reference buildings and future climate scenarios.

Overall, Table 2 reports a significant disparity between requirements and the low requirements for single-family homes in some countries. As shown in Fig. 4, Bulgaria, Latvia, Romania, and Lithuania have nZEB standards that are less demanding than the EU Commissions' recommended benchmark and underdeliver on their energy efficiency potential. On the other hand, Slovakia and Croatia exceed the EU recommendations. It makes sense that Croatia, which has a milder climate than Estonia, will have lower net primary energy requirements. All countries had legislation for nZEB in place and used the numerical indicator of primary energy use expressed in kWh/m^2 per year. However, the results below should

Table 1
ranking of the 10 Eastern European countries regarding the nZEB national plans and construction practice.

Advanced	Fair	Struggling	Behind
None	Estonia, Poland, Slovakia, Croatia	Romania, Czech Republic,	Bulgaria, Latvia, Hungary, Lithuania

Table 2
nZEB performance threshold in Eastern European countries, mainly for single-family households (EEA, 2022).

Country	Climate Zone	Min. Energy Efficiency Energy need for Cooling	Energy need for Heating	Primary Energy	RES share	Summer Climate	2015–2020 CDD	HDD	Latitude	Altitude
		kWh/m^2.a	kWh/m^2.a	kWh/m2.a		Cities	22 °C	15.5 °C		
	1					Sofia	224	2285	42.65°N	550 *m*
BULGARIA	2	None	None	95	No	Plovdiv	390	1777	42.13°N	164 *m*
	3					Burgas	295	1596	42.50°N	30 *m*
	1	None	None		No	Zagreb	259	2076	48.51°N	122 *m*
CROATIA	2			50–80		Split	501	891	43.3°N	12 *m*
	1			30–90		Prague	105	2611	50.5°N	235 *m*
CZECHIA*	2	reference building			No	Brno	158	2396	49.11°N	237 *m*
	3					C. Budejovice	79	2444	48.58°N	381 *m*
ESTONIA**	1	None	None	46–90	No	Tallinn	41	3298	59.4°N	33 *m*
HUNGARY	1	None	None			Budapest	256	2254	47.49°N	98 *m*
	2			85–100	No	Pécs	243	2021	46.07°N	153 *m*
LATVIA	1	None	40–60	95–170	No	Riga	67	3092	56.94°N	2 *m*
LITHUANIA***	1		35–75	180–220	greater than50%	Vilnius	65	3185	54.6°N	156 *m*
	1					Warsaw	132	2548	52.2°N	99 *m*
	2					Olsztyn	90	2815	53.8°N	121 *m*
POLAND	3	None	None	65–75	No	Wroclaw	124	2342	51.1°N	131 *m*
	4					Gdansk	45	2805	54.3° N	8 *m*
	5					Suwalki	82	2713	54.1°N	170 *m*
ROMANIA	1	70	20	93–217	greater than30%	Bucharest	344	2029	44.4°N	77 *m*
	2					Cluj-Napoca	180	2482	46.7°N	380 *m*
	3					Brasov	84	3467	45.6°N	610 *m*
SLOVAKIA	1	None	None	32–54	No	Bratislava	212	2162	48.8°N	134 *m*
	2					Prešov	140	2720	49.0°N	250 *m*

Note: The baselines applied for the HDD, and CDD calculation is 15.5 °C, and 22 °C data from 2015 to 2020 was used. The hourly approach shows a significant CDD change regarding day/night variation compared to the HDD.
*CZECHIA: There are no particular values or thresholds according to ordinance no. 264/2020 Coll. A comparison with reference building is used. Energy need for heating: ≤ 1.0 * E_R (E_R = reference building) and – Primary Energy: ≤ 1.6 * E_R (E_R = reference building).
** ESTONIA: Estonian NZEB values including appliances and lighting are 100–145 kWh/m^{2}a.
***LITHUANIA: Energy need for heating: 100 m^2 – 75 kWh/m^2, 200 m2 – 57 kWh/m^2, 2000 m^2 – 35 kWh/m^2 – Primary Energy: 100 m^2 – 220 kWh/m^{2}a, 200 m^2 – 190kWh/m^{2}a, 2000 m^2 – 180 kWh/m^{2}a.

be indicative and interpreted within the ten states' broader context.

Unfortunately, none of the studied countries uses specific carbon dioxide emissions indicators or set thresholds for emissions on site. Carbon emissions are included in primary energy calculations based on conversion factors. However, Table 3 reports another wide variation for primary energy factors (PEF) calculations for different energy carriers, which is misleading. The variation of PEF values exceeds the purely physical primary energy content by as much as a factor of two or three. Also, the justification behind PEF calculations for EPBD purposes is not transparent in most investigated countries. Consequently, the reliability of primary energy savings or use in nZEB calculation is low in some countries. Future decarbonization efforts of heating in building heating, indicated by the Climate Action Plan (EC 2020), to deliver on the 2030 and 2050 targets will be complicated and slow under any future carbon pricing scheme.

As shown in Fig. 5, most Eastern European countries rely heavily on coal and nuclear energy and have a varying mix dominated by coal, nuclear, oil, and gas. Reducing housing sector emissions will be vital to achieving the following 2030 emissions targets in Europe. The remaining share of coal in power in Estonia, Bulgaria, Czechia, Poland, and Romania means that decarbonization of heating in most Eastern European countries is far from being achieved and jeopardizes the efforts to introduce nZEB. nZEB cannot taper emissions and energy use from buildings in this context because the nZEB national plan limits the primary energy use associated with carbon dioxide emissions. With the geopolitical insecurities regarding energy supply in this region, the transition to natural gas or renewables cannot be foreseen. Thus, the unambitious coal and fossil phase-out policies in Eastern Europe threaten the transition in the region towards low carbon economies.

3.3. nZEB design approach

A wide variation in the calculation methodology was found by analyzing the questionnaire outcomes. Although the climate is remarkably different in the North from Estonia to the South in Bulgaria, all the investigated counties remain heating-dominated. The calculation methods relied mainly on CEN 13,790 for the Energy performance of buildings [12]. Thermal comfort requirements are adopted from ISO 7730, CEN 15251, and CEN 16789. However, data on the cost-optimality method to define the nZEB requirements across the ten investigated countries was hardly found, except for Estonia. The study revealed that TABULA and EPISCOPE databases list reference buildings only for four described EE countries: Poland, Czechia, Hungary, and Bulgaria. But couldn't find any public document that links the nZEB requirements to the cost-optimality approach (Loga et al. 2016). The cost-optimality approach allows the definition of cost-effective energy efficiency measures and technologies to be integrated into national codes. The use of reference buildings and five-year revision cycles allows to constantly reduce the energy use demand (Karlsen et al. 2020). Thus, with the new nZEB national plan, there is a chance to achieve energy neutrality. However, most investigated regulations lacked transparency, did not share any insights on the reference buildings and suggested cost-optimality calculations for energy conservation measures.

Czechia is the only country that requires calculating the energy efficiency of nZEB based on a comparison with a reference building.

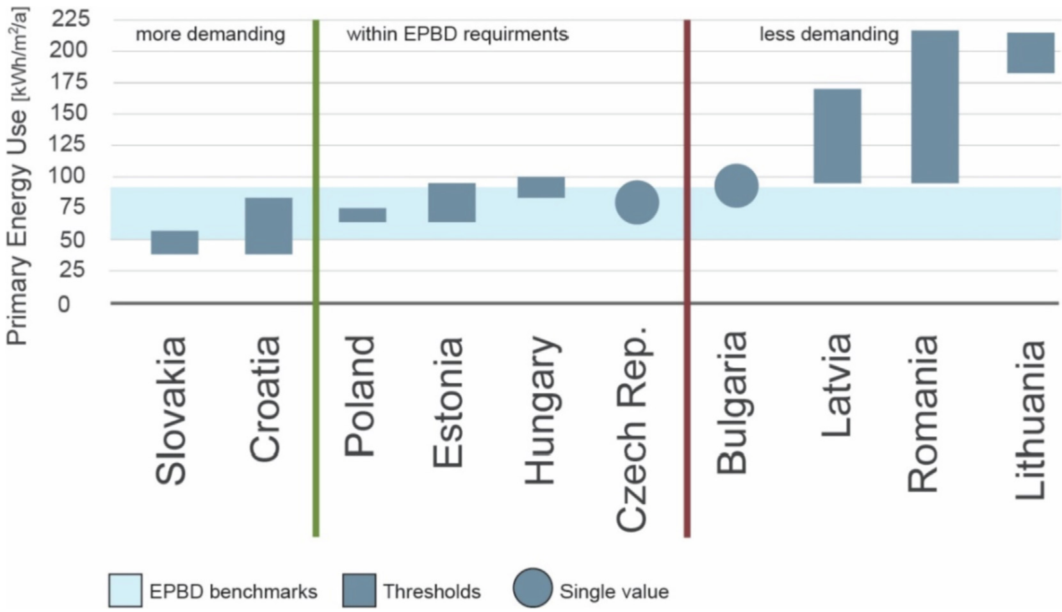

Fig. 4. Comparing the nZEB requirements in single-family residential buildings in the ten Eastern European countries.

All other countries set up prescriptive requirements for primary energy use or final energy use, as indicated in Table 2. Surprisingly none of the investigated calculation methods was identical. Every country developed its methodology to calculate energy performance. The comparison between the nZEB energy performance calculation methods shows that most of the calculation methods in many EE countries are complicated, despaired, and hard to apply. For example, Slovakia and Czechia use an overcomplicated calculation approach, as explained in detail in Appendix I. Although CEN 13,790 is the basis for all energy performance calculations for buildings [12], the investigated calculation methodologies in the ten EE countries lack uniformity and consistency.

On the other hand, all countries require building performance simulation to estimate the primary energy use intensity. As shown in Table 4, most countries require static or quasi-dynamic simulation software for energy performance calculation, except Slovakia. Czechia, Estonia, and Slovakia require a quasi-dynamic or dynamic energy modeling tool. More than half of the ten EE countries request a multizonal modeling approach. Croatia, Lithuania, Poland, and Romania require a single zone modeling approach. Building performance simulation tools are powerful for issuing energy performance certificates (EPC).

Independent control systems for EPCs have been formally established in the ten EE countries. EPC is a powerful mechanism to disclose the energy performance of nZEB. EPCs are an essential source of information for consumers planning to purchase or rent a property. They label nZEB as A. However, our study indicates the poor implementation of EPC regarding nZEB in most EE countries. For example, Czechia, Hungary, Bulgaria, Romania, and Poland do not oblige certifiers to perform a field inspection. The qualifications of the certifiers or accredited experts, the methodological calculation framework, software tools, and approach to collecting input data varied significantly in all ten EE countries. There are certification differences across regions in most countries, and the inaccuracy of the EPC issuing process.

Consequently, the comparability of EPC within each of the ten EE countries was considered low. Moreover, none of the investigated countries made their EPC databases available or accessible. Despite awareness about EPC construction stakeholders in EE countries, the effectiveness and credibility of EPC to assure nZEB high performance remain questionable among experts.

3.4. Thermal comfort

The continental climate covers most of the eastern part of Europe, including the ten investigated countries. The main characteristics of the climate are cold and long-lasting winters and predominantly hot summers. In high-altitude regions, there is usually snow during wintertime. However, countries approaching the Mediterranean or Black sea have a milder Mediterranean climate due to the influences from the sea.

Consequently, all nZEB definitions and requirements are developed for a heating-dominated building. All countries require highly insulated envelopes and airtight envelopes. Regarding thermal comfort, all nZEB requirements that comply with ISO 7730 comfort limits can be expressed by the PMV and the PPD indices, and some countries still rely on CEN 15,251 (e.g., Bulgaria, Croatia, Hungary, and Lithuania). Very few countries updated their indoor environmental quality requirements for nZEB to include CEN 16,798 (e.g., Estonia, Poland, and Romania) or allow for adaptive thermal as an alternative path to PMV/PPD thresholds. Some investigated nZEB documents reflected sensitivity to overheating risk. For example, Estonia has a unique overheating indicator with an upper threshold of 27 °C. However, the use of the adaptive thermal comfort path remains a weakness in the current nZEB regulations. Mainly, all experts confirmed the increasing need for active cooling in EE low-energy buildings.

Moreover, in the continental climate of the ten EE countries, high-performance mechanical ventilation with a centralized system is essential for nZEB [8]. Heat recovery systems (HRV) or mechanical ventilation with heat recovery MVHR supply air into the building through fans and extract the exhaust air. A heat exchanger is placed at the beginning of the air loop, where most of the heat energy is transferred from the extracted air into the incoming air stream. Results indicate a significant disparity in mechanical ventilation requirements in the ten countries, as previously reported in Section 3. Although mechanical ventilation is an integral system in nZEB, little is known about its design and technical installation in EE countries. Table 5 indicates that minimum requirements are set only for half of the investigated countries, and there is no consensus on national regulations and guidelines. Almost no country addresses the scope of inspections and commissioning for ventilation systems.

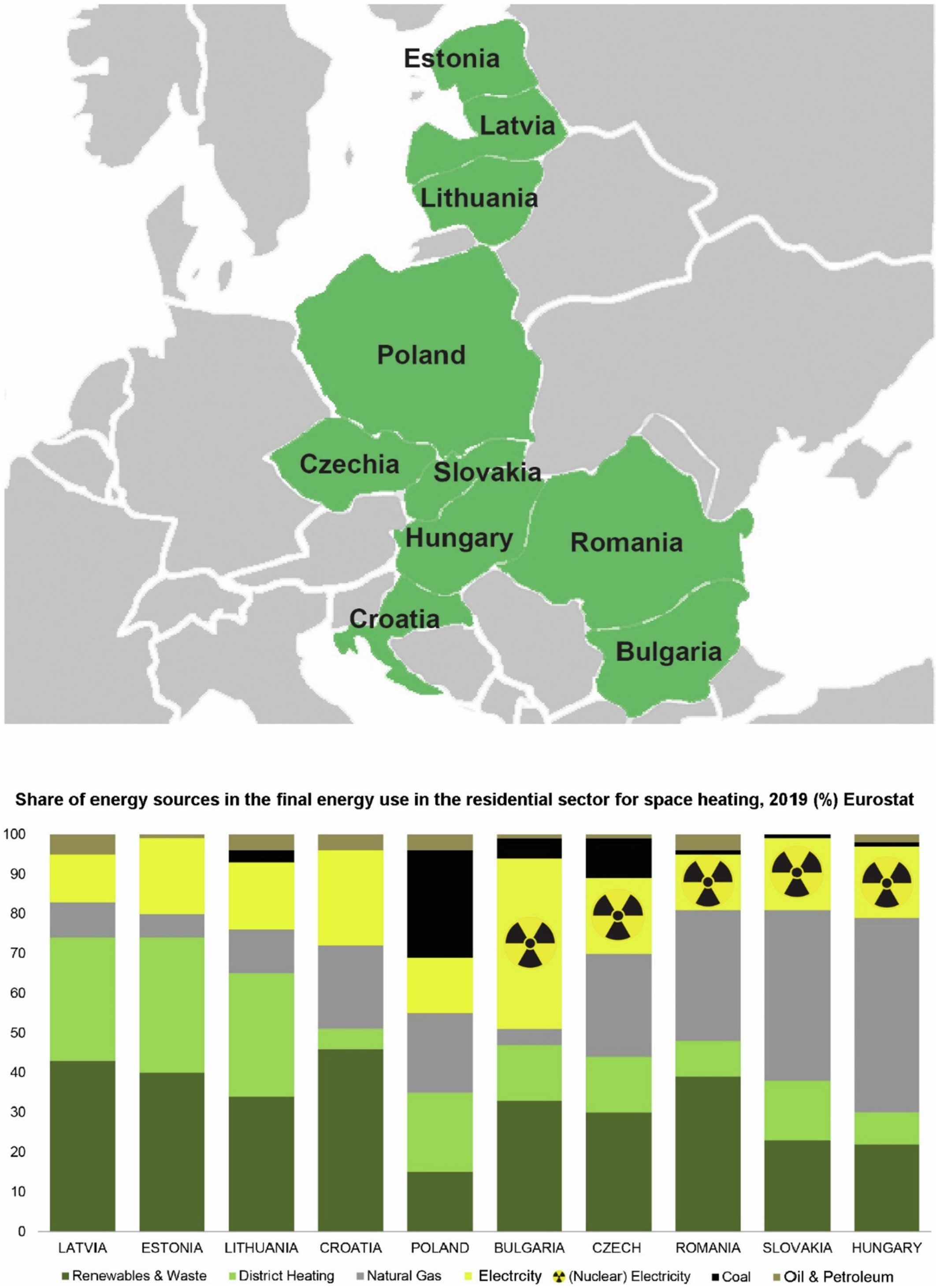

Fig. 5. Share of energy sources in the final energy use in the residential sector for space heating, 2019 (%) in ten EE countries, Source: Eurostat.

The obligation of mechanical ventilation is considered a new technical challenge in all 10 EE countries. Most existing standards did not introduce double flow mechanical ventilation requirements with heat recovery. Therefore, most nZEB requirements in the investigated national plan included mechanical ventilation systems as an optional approach with natural ventilation. For example, Poland and Latvia do not allow for natural ventilation for nZEB anymore, while Hungary, Bulgaria, and Romania do not specify any requirements for mechanical ventilation. Surprisingly, the technical requirements for heating systems focused on coal condensing boilers, gas condensing boilers, wood pellet boilers, and wood logs boilers. The options for air source heat pumps and ground collector brine heat pumps were not well described in most investigated standards.

3.5. Renewable thresholds

Table 2 indicates that eight EE countries' nZEB requirements lack renewable energy shares (Bulgaria, Croatia, Czechia, Estonia, Hungary, Latvia, Poland, and Slovakia). The integration of renew-

Table 3
Primary energy conversion factors in Eastern Europe's Member states for the year 2020 (Appendix I).

Country	BULGARIA	CROATIA	CZECHIA	ESTONIA	HUNGARY	LATVIA	LITHUANIA	POLAND	ROMANIA	SLOVAKIA
Fuel Oil	1.1	1.130	1.2	1.0	1.0	1.1	1.1	1.1	1.1	1.1
Natural Gas	1.1	1.095	1.0	1.0	1.0	1.1	1.1	1.1	1.17	1.1
Liquefied Gas	1.1	1.160	1.2	1.0	/	1.1	1.1	1.1	/	1.35
Hard Coal	1.2	1.038	1.2	1.0	1.0	1.1	1.2	1.1	1.2	1.1
Lignite (Brown Coal)	1.2	1.081	1.0	1.0	/	1.1	1.1	1.1	1.3	1.1
District heating	1.3	1.494	1.3	0.9	0,54–0,71	0.7 to 1.3 total 0.1–0.7 - non-renewable	1.25	1.2 (gas, oil)1.3 (coal)if cogeneration: 0.15 (biomass, biogas) to 0.8 (coal, gas)	/	1.3
Efficient district heating	/	/	≥ 80% share of renewables)0.9 (with < 80% share of renewables)	0.65	Renewable source 0,324–0,426	/	1.25	0.15 (biomass, biogas)	/	2.2
Electricity	3.0	1.614	2.6	2	regular: 2,5 (no peak load delivery time: 1,8)	2.5	2.5	3	2.62	2.2
Renewable Energy	/	0	0	0	0	1	1	0	1-solar therma systems 1.53 heat pump systems electrically driven 2.62 photovoltaic systems	0
Biomass	1.05	0.154	Wood pellets: 0.2 Wood / Wood chips: 0.1	0.65	0.6	1.2 nonrenewable 0.2	1.2	0.2	1.08	wood logd: 0.1 wood chips: 0.15 wood pellets: 0.2
Biofuel	/	/	/	0.65	0.6	1.5 - total 0.4 - non-renewable	1.2	/	/	/
District Cooling		/	/	0.4	/	should be calculated	/	/	/	/
Efficient district cooling	/	/	/	0.2	/	/	/	/	/	/

Table 4
The energy modeling approach used for the nZEB calculation in EE countries.

Country	BULGARIA	CROATIA	CZECHIA	ESTONIA	HUNGARY	LATVIA	LITHUANIA	POLAND	ROMANIA	SLOVAKIA
Simulation approach	Quasi Dynamic	Quasi Dynamic	Quasi Dynamic/ Dynamic	Quasi Dynamic/ Dynamic	Static	Static	Static	Quasi Dynamic	Static / Quasi Dynamic	Dynamic
Thermal zoning approach	Multizone	Single Zone	Multizone	Multizone	Multizone	Multizone	Single Zone	Single Zone	Single Zone	Single Zone / Multizone

able energy is considered part of the primary energy calculation in those countries. However, most requirements do not explicitly address integrating individual renewable energy measures in residential nZEB. Most newly constructed buildings in EE countries are apartment or multi-unit residential buildings connected to district heating and gas networks, which is well addressed. Only Croatia, Lithuania, and Romania require a minimum onsite renewable share ranging between 30 and 50% of the final annual energy demand. Heat pumps (mainly air source heat pumps) were not described in detail in most nZEB requirements, and most EE countries had proliferated calculation specifications for district heating systems with low energy conversion factors (see Table 2). Surprisingly, some nZEB definitions (e.g., Poland and Estonia) allow coal-fired boilers with low primary energy conversion factors.

On the other hand, the energy mix shown in Fig. 5 is considered a negative sign for relying on off-site renewable energy in EE. The energy mix in most EE countries is carbon-intensive, and therefore, increasing the onsite renewables is a better-decentralized choice. However, none of the investigated standards addressed storage or encouraged energy storage.

3.6. Construction skills and quality

One of the barriers that hamper the development of nZEB in EE countries is the lack of construction skills and quality assurance mechanisms. The questioned experts indicated several problems related to nZEB construction quality. Also, the European Construction Sector Observatory was consulted to draw a better picture of the construction quality and qualifications of professionals in the field of building energy efficiency and renewable energy. The analysis indicates several problems and challenges exist, such as builders' skills and competent inspection mechanisms. There is a lack of openness to innovation in the construction sector and low labor productivity. Green training programs for construction craftsmen, onsite workers, and construction managers are missing. The lack of education and the different construction approaches culture of building designers, including architects and engineers, impede small and middle-size enterprises (SMEs) from achieving high quality. Czechia, Poland, and Slovakia are trying to overcome the country's missing culture of continuing education. Moreover, an intergenerational gap between new and old generations exists specifically in the middle and senior levels of construction professionals. Also. The shrinking population in most EE countries and the constant immigration of skilled labor cause many shortages of national expertise.

nZEB requires high-tech solutions, components, and systems. The analysis results indicate that most of the new household construction in the ten countries are apartment buildings in urban agglomerations. As shown in Table 6, the average annual increase in housing units between 2015 and 2020 is around 1%. The compactness of the building geometry is not explicitly addressed as a separate measure. However, most standards consider the building form represented through a compactness factor when performing energy calculations. External Thermal Insulation Composite Systems (ETICS) is the most common envelope technology. Audit and quality control experts papered the fixation of ETICS and thermal-bridge-free joints as a recurring problem. National building codes require avoiding thermal bridges in envelope construction to reduce heat loss and the risk of condensation.

Consequently, specific constructive design requirements for balconies and facade connections need special attention. Our observations in the EE states indicate that thermal bridge solutions for cantilevered balconies are almost not implemented in newly constructed nZEB [9]. Thermal breaks around windows, windows, and building edges are reported frequently during building audits and EPC. Problems with windows fixation, windows alignment, and placement of window frames within the insulation plane are reported frequently. Applying airtightness tapes and films for envelope airtightness and leakages sealing is not a common practice. For example, the requirements for airtightness are missing in some countries like Czechia, Hungary, and Romania. As shown in Table 7, the requirements are medium to high in other countries. However, the blower door test is only requested in Estonia.

In general, limited attention is paid to high-quality building construction details during early designed states, besides the lack of coordination, organization, and flexibility during implementation. Without design and construction reviews, the low construction quality will impede nZEB market penetration. Local authorities and EPC certifiers or auditors are also part of the problem in many investigated countries. There are few reference cases of nZEB, and there are many wrong perceptions about how they should be designed, constructed, or operated. Without any requirements to monitor and enforce the implementation of nZEB, their construction quality will remain poor and complex. Despite the airtightness testing requirements in the Estonian nZEB, none of the ten countries formulated approaches to verify the accuracy of construction details or mechanical ventilation.

Table 5
Mechanical ventilation requirements for nZEB in the ten countries.

Country	BULGARIA	CROATIA	CZECHIA	ESTONIA	HUNGARY	LATVIA	LITHUANIA	POLAND	ROMANIA	SLOVAKIA
Mechanical ventilation is mandatory	No	No	No	Yes	No	No	No	No	No	No
Efficiency requirements for heat recovery?	/	/	/	80%	/	/	80%	/	/	80%

Table 6
Newly constructed households between 2015 and 2020 based on issued permits —source: Eurostat.

Country	BULGARIA	CROATIA	CZECHIA	ESTONIA	HUNGARY	LATVIA	LITHUANIA	POLAND	ROMANIA	SLOVAKIA
2015	2263	4249	28,886	3969	12,515	1658	6118	104,000	39,112	17,642 . . .
2016	2161 (-4 %)	5317 (+21%)	31,002 (+7%)	4732 (+17%)	31559 (+61%)	1536 (-8%)	7524 (+19%)	143,000 (+28%)	38,653 (-1%)	20,224 (+13%)
2017	2205 (+2 %)	6594 (+20%)	32,069 (+4%)	5890 (+20%)	37,997 (+17%)	2191(+30%)	7018 (-7%)	161,000 (+12%)	41,603 (+8%)	18,472 (-9 %)
2018	2324 (+6 %)	6635 (+0 %)	30,702 (+4%)	6472 (+9%)	36719 (-3 %)	2348 (+7%)	6941 (-1%)	183,000 (+13%)	42,694 (+3%)	20,574 (+11%)
2019	3052 (+24%)	7026 (+6 %)	31,606 (+3%)	7014 (+8%)	35123 (-4 %)	2511 (+7%)	7067 (+2%)	207,000 (+12%)	42,541 (+0%)	19,050 (-1%)
2020	3376 (+10%)	6775 (-4 %)	31,747 (+1%)	7579 (+8%)	22,556 (-55%)	2340 (+7%)	7619 (+8%)	222,000 (+7%)	41,311 (+2%)	20,385 (+7%)

Table 7
Airtightness requirements for nZEB in the ten EE countries:

Country	BULGARIA	CROATIA	CZECHIA	ESTONIA	HUNGARY	LATVIA	LITHUANIA	POLAND	ROMANIA	SLOVAKIA
Blowerdoor mandatory requirements	No	Yes	No	Yes/No	No	No	Yes	Yes	No	Yes
Airtightness under 50 Pa [M^3/m^2h]	<1	1.5–3	None	1.5	None	1.5	0.6–1	1.5–3	None	None

4. Discussion

In this study, ten Eastern European Countries (Bulgaria, Croatia, Czechia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, and Slovakia) were examined in-depth regarding the legislation requirements of nZEB. The study aims to increase the market uptake of nZEB and strengthen its implementation and standards. The key study findings and recommendations are presented based on the result analysis. The next step in the market development of nZEB in EE countries is to consolidate the existing standards before developing the nZEB renovation schemes [41]. The recommendations are discussed in future perspectives for policymakers, funding agencies, and building stakeholders. The following sections elaborate on the study's strengths, limitations, and future works.

4.1. Study findings

The study indicated that the most critical barriers to nZEB implementation are informational and organizational if the financial barriers are excluded. Despite introducing the second EPBD recast in April 2018, adopting its guidelines for promoting nZEB and best practices for all new buildings is in the infancy stage (Hogeling & Derjanecz 2018). The following issues were revealed during the analysis of questionnaires and study papers.

Many countries developed nZEB plans that are not ambitious enough. The preparedness for ensuring nZEB in Eastern Europe is currently low. nZEB implementation policies in Eastern Europe concentrate on short-term programs without stable and thorough frameworks to calculate and plan for energy and climate neutrality. nZEB definition in EE countries insufficiently reflects Europes' heating decarbonization objective and climate-neutral by 2050.

Limited progress regarding the development and implementation of nZEB in EE countries is reported. There is a lack of institutional support to educate professionals and implement nZEB. The somewhat developed countries regarding nZEB requirements are Estonia, Slovakia, Poland, and Croatia, followed by Romania, and Czechia, who are struggling with nZEB implementation. Bulgaria, Latvia, Hungary, and Lithuania are behind.

Many nZEB definitions and measures for heating systems fail to phase out fossil fuels. For example, in Poland, the recovery plan does not set a limit to support gas investments in household heating, while gas should only be allowed as a 'last resort' when renewable energy sources are not possible.

Many countries' primary energy demand thresholds are often insufficient, leading to misleading conversion energy carriers (Table 3). The primary energy factors (PEF) thresholds in some countries, such as Czechia, Estonia, or Romania, are too low for solid fuel or coal-based electricity. A consistent and harmonized approach is needed to determine the PEF values across Europe. The calculation methods refer to the outdated EPBD recast objectives with no mandatory requirements for renewable energy share.

The cost-optimal methodology, which is the foundation of national nZEB definitions, has not been fully adopted,. EE counties must paper on comparing the minimum energy performance requirements and calculated cost-optimal levels using the comparative methodology framework of EPBD. Moreover, the energy efficiency requirements in some countries such as Bulgaria, Hungary, and Romania are strongly driven by energy poverty concerns.

EPCs are so inaccurate and inconsistently used in EE countries resulting in more damage than good [40]. The 'smart metering' notion of energy meters is not addressed, and the inspection, commissioning, and onsite audits are missing regarding airtightness, insulation quality, or mechanical ventilation installation in all ten countries. The performance gap of nZEB in Eastern European countries is partly due to the weak EPC implementation [34]. The credibility of the EPC is low, and none of the countries provides open access to national EPC databases. Consequently, the legal compliance and technical control market are small, and the role of energy services companies (ESCO) is limited.

Electrification is another problem in existing nZEB definitions. Electricity use for heat pumps is penalized during the primary energy calculation and on the EPC scorecards, promoting gas boilers and polluting wood-based boilers. Most investigated nZEB national plans are not coupled with ambitious targets to install heat pumps and have a low market penetration (see Fig. 6). Power grids are not synchronized between the EE states.

Mechanical ventilation requirements are not consistent and lack clarity in many EE countries. For example, the Czech and Hungarian nZEB definition does not even include any requirements for mechanical ventilation.

Eastern European countries face a demographic challenge and increasing immigration of skilled professionals. The average working age in the building sector is high, and the labor markets' preparedness to implement high-performance buildings is low [63].

4.2. Study recommendations

In Eastern Europe, the challenge of strengthening nZEB requirements in the current and future is high. nZEB are not only concerned with the first principles of energy efficiency, but they

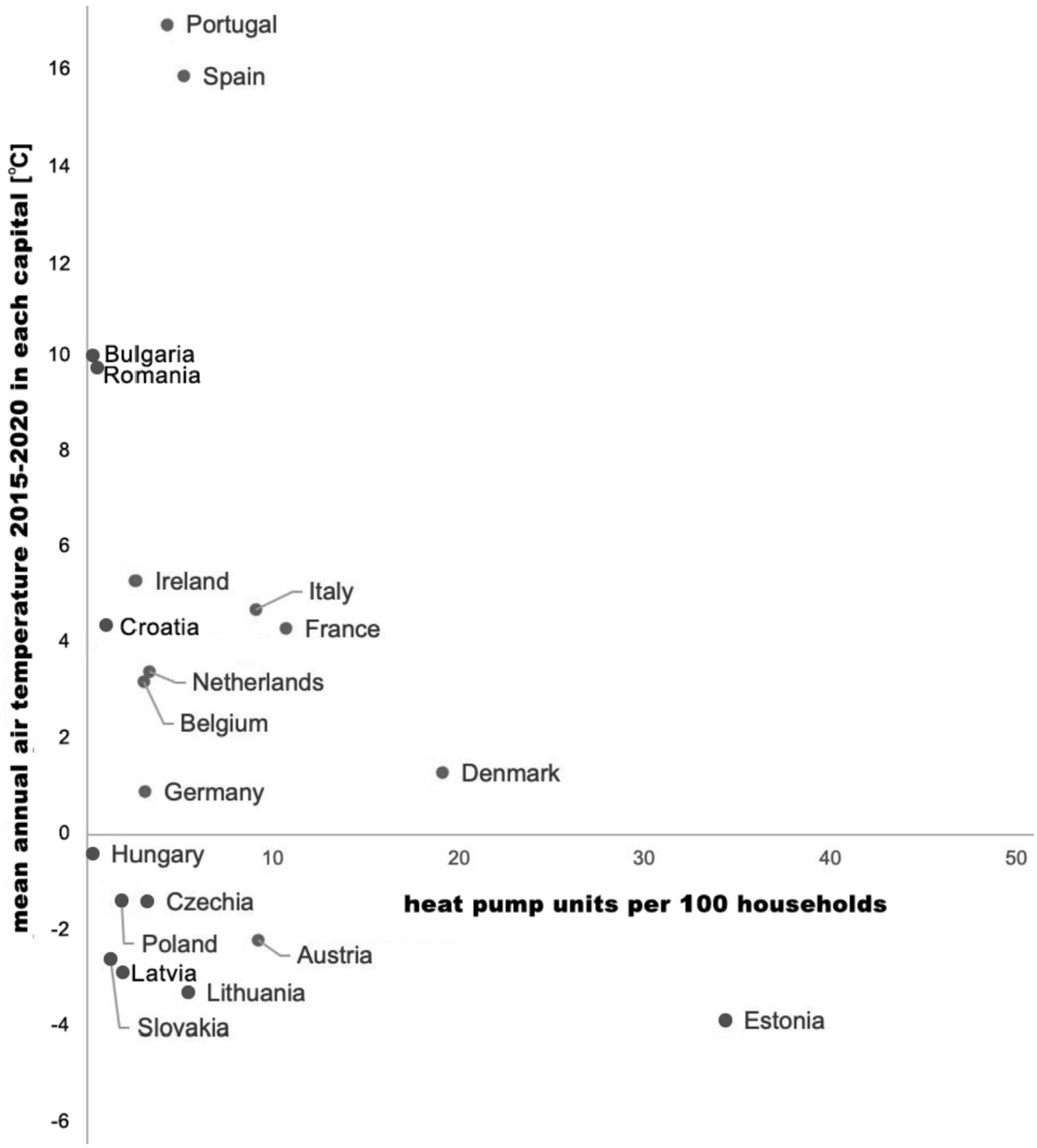

Fig. 6. Comparison of market penetration of heat pumps per household in the ten countries (. Source: [18]

require the improvement of IEQ, monitoring, and papering of performance, and highly specialized skills. As part of the papers' contribution, the recommendations are listed below:

Strengthening the nZEB standards in EE countries is the next step to seeking more ambitious performance thresholds for primary energy demand and decarbonization of building heating. It is strongly advised to ensure consistency with EPBD requirements in legislative revisions to meet carbon neutrality's Fit for 55 packages. Under the new EPBD recast, all construction would be net-zero emissions by 2030.

Enforce the implementation of the cost-optimality approaches [15]and use them for different archetypes and functions per country [51]. Countries like Croatia, Estonia, Latvia, Lithuania, Romania, and Slovakia must develop their reference buildings datasets and join the EPISCOPE and TABULA databases [30]. The cost-optimality approach should include impact assessments of the future nZEB national plans regarding market transformation risks, challenges, and cost-effective benefits.

Collaboration between the EE countries can be beneficial to harmonizing the approaches of energy performance calculation methods (CEN 13790) and PEF determination. There is a need to develop and coordinate new instruments and platforms regionally to ensure success. For example, Visegrad countries can create an observatory of high-performance buildings that promotes excellence and initiatives in the construction sector towards nZEB. The Visegrad cohesion funds for energy security are an excellent example of regional collaboration [52]. This political alliance can approach the building sector in the Visegrad countries and can similarly be conducted in Baltic countries to nZEB standards (Kosinski 2021).

Strengthen the rigorous implementation of nZEB standards to monitor and report on nZEB. The reliable quantifications of energy savings of nZEB are a must. Effective monitoring and control mechanisms of nZEB should be put in place and tackled on the micro-scale involving local government authorities and qualified certifiers [40]. EPC databases must be made accessible for better transparency. Liability and quality control of nZEB as performance-based buildings require a new legislative and insurance-based architecture.

Adopt CEN 16,798 in national regulation entirely and emphasize the performance requirements of MVHR. Specific actions should be taken to promote double-flow controlled mechanical ventilation systems. Overheating risk indicators must be developed to promote the adaptive thermal comfort path. Also, passive cooling solutions must be encouraged. In an aging region, the guidance on energy efficiency first principle should never become prioritized over indoor quality and occupants' health.

Integrate more renewable energy sources in buildings and set more ambitious minimum renewable shares obligations. The promotion of heat pumps or district renewable energy systems and storage capacity should be part of the future nZEB schemes. EE can capitalize on the district heating potential as a low-emission technology that integrates higher renewable energy shares.

Considerations are needed to adopt the Smart Readiness Indicator (SRI) to allow for rating the smart readiness of buildings, i.e., the capability of nZEB to adapt their operation to the occupant's needs. Also, the optimization of energy efficiency, overall performance, and adapting their operation in reaction to signals from the grid (energy flexibility).

Revise the EPC schemes, and standardize their calculation methods. EE'S current EPC schemes encourage photovoltaic panels and heat pumps without addressing the building envelope's energy efficiency. In many countries, they are used as an excuse to avoid improving energy efficiency and the reduction of energy use intensity. The current EPC schemes must be improved and enhanced to become more reliable and accurate (Attia 2020). Improved compliance and quality of the EPC issuing and auditing are essential. Public authorities' development of open access and a central EPC database is the only way to assure consistency and help authorities better-set carbon neutrality measures.

Support measures to improve designers' and builders' skills for nZEB implementation. Vocational education and training, including reskilling and upskilling the workforce, via targeted projects, at regional, national and local levels, must be provided [17]. Continuing professional development for architects and engineers is essential. Developing a new generation of building energy modelers and experienced certifiers goes hand in hand. Public administrations should integrate building energy modeling in the permit process and enforce energy performance contracting.

Study strengths and limitations.

Eastern Europe has a temperate-continental climate influenced by Scandinavian-Baltic weather in the Baltic countries and Poland, the Mediterranean in Croatia, and the oceanic climate of the Black Sea in Bulgaria and Romania. The similar climate conditions enable the possibility to extend the results of this study to other countries. The study on nZEB definitions and solutions can be transferred to other European countries with similar climatic conditions and economic characteristics such as energy costs and price of materials, and local labor for initial investment.

The research methodology involved questioning national experts from ten Eastern European countries. The study builds on existing literature [5,20] and provides a current overview on nZEB with a focus on EE. Active and well-known national experts were selected based on available publications on building energy efficiency. The review of the nZEB regulation lasted almost two years, which allowed for revising and refining the content and increasing its consistency. During the study period, four study visits were conducted in Poland and Czechia, and intensive contact with the four Visegrad countries regarding high-performance buildings occurred. Under any circumstance, the study cannot be representative, conclusive, or comprehensive. The literature review did not provide significant insights regarding the state of nZEB implementation in EE countries. Very little information is available in English. On the opposite, the most valuable information emerged from the experts' responses to the questionnaire. The responses provided by experts and the statistical information provided by official ministries and energy agencies in each respective country are made available in an open-access dataset (Appendix I). Therefore, the study is considered a new overview regarding nZEB implementation in Eastern European countries. The overview provided by experts is prospective, and the recommendations are practically based on experiences and learned lessons of nZEB implementation in EE countries during the last five years.

The paper's strength is the cross-comparison of the recent nZEB national plans in Bulgaria, Croatia, Czechia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, and Slovakia. Europe is in a sensitive ecological and energy security transition that requires strategic choices and future-proof concepts. Therefore, this paper provides a focused, critical overview of nZEB and its implementation barriers and potential in eastern Europe [32]. At the same time, the study suggests recommendations for nZEB performance improvement to help decision-making on the national, regional, and European levels. Thus, the study provides an opportunity to review the existing nZEB requirements, compare them, and improve them to prepare for the next renovation step. Without reviewing the nZEB plans and requirements for new constructions, any future renovation plans will lack the foundation to address serious challenges, including mechanical ventilation and heating decarbonization. Policymakers and funding agencies should adopt a holistic approach that includes the people who should implement this transition. Benchmarks for national energy efficiency contributions are needed. The public sector should set an exemplary role in implementing and promoting nZEB.

4.3. Implications for practice and future research

The overall number of newly built nZEB in Eastern Europe is low, and the overall annual construction rates are low. To put the reader in the picture and better understand the nZEB implementation plans in EE countries, one must recognize the influence of the geopolitical situation of Eastern European countries. The energy security problems associated with the transition from fuel and coal to gas can jeopardize many countries' sovereignty and autonomy. Many EE countries integrated nZEB definitions and regulations that allow onsite or off-site coal use. Countries such as Estonia, Latvia, and Poland that border Russia and can experience freezing winters prefer to keep coal as a viable energy source using highly efficient boilers or district heating stations for fuel security. Therefore, the evolution of nZEB plans in Eastern Europe cannot be influenced by Brussels' ambitions toward carbon neutrality by 2030.

However, climate change remains a pressing problem that all Eastern European countries must face. Studies on future climate impact on nZEB design and performance confirm the increase of cooling loads and the imminent overheating risk in the continental climate (D'Agostino et al., 2022). Therefore, national nZEB plans should tackle this issue and encourage onsite renewable energy as much as possible to encourage the building needs, assure thermal comfort and neutralize the carbon emissions associated with buildings construction and operation. The proposal of the new EPBD recast is ambitious on the decarbonization of heating and cooling systems in the EU's buildings and drastically improves the case for heat pumps. By ending financial incentives for fossil fuel boilers in 2027. Therefore, the exploration of the hydrogen path as an alternative for natural gas after 2030 and its influence on the buildings' associated carbon emissions and national energy mixes should be considered.

Moreover, the calls for insulation and rollout of heat pumps to 'get off gas' in Western Europe are not on the same level in Eastern Europe. Eastern Europe is in a state of transition from solid fuels to natural gas and renewable energies. The EU's plans to include gas and nuclear in the 'green' ranking leave policymakers and investors confused in Eastern Europe. Also, the shortage of construction materials, especially timber and bio-based materials, during the last two years is delaying the proliferation of nZEB and increasing their prices further. The abovementioned aspects are all considered hindering factors in developing consistent and long-term strategies for nZEB in Eastern Europe and further slowing the market uptake.

Therefore, future research should focus on nZEB case studies and cost-optimality studies in EE countries. The next challenge for Eastern European countries is to develop nZEB renovation plans and address embodied and operational carbon emissions [32]toward buildings' carbon neutrality road maps [42]and carbon taxation [63]. Other Eastern European countries such as Bosnia and Herzegovina, Serbia, and Slovenia should be added. The quality of the nZEB plan will deepen and strengthen the expertise of the construction sector to move towards nZEB renovation, integrating more renewable energy sources in buildings and circularly using resource-efficient materials. The current nZEB plans and requirements should be revised to open the door for pragmatic and ambitious plans for a building renovation wave across Eastern Europe.

5. Conclusion

The proliferation of nZEB in Eastern Europe is not happening fast enough. The current national plans for nZEB are generally insufficient. This paper reviewed and analyzed the regulations in ten EE countries under scrutiny regarding building energy efficiency, heating, and cooling energy demand requirements, thermal comfort, renewable energy shares, and construction quality. The review is based on the 2018 EPBD recast requirements to achieve carbon neutrality by 2050. Many nZEB definitions in EE countries and measures for heating systems fail to phase out fossil fuels. The EPBD cost-optimality approach is not fully adopted to define the nZEB performance targets. Also, the primary energy demand calculation refers to misleading energy carriers' conversion factors. Indoor environmental quality requirements regarding discomfort risk and mechanical ventilation are not well developed in most nZEB national plans. The paper provides technical recommendations, including revising the EPC schemes and standardizing their calculation methods. An improved compliance process and quality assurance of the nZEB design, construction, and operation are essential. The paper reports on the next steps that need to be taken by public authorities to develop open access and central nZEB implementation methods and databases. Following those recommendations can assure consistency and help authorities betterset carbon neutrality measures.

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.

Acknowledgment

This research was funded by the Belgian Wallonia Brussels International (WBI) and the Polish National Agency for Academic Exchange (NAWA), which gratefully acknowledged. This publication is part of 2020-2022: [ZERO] Zero Energy and Low Carbon Buildings in Belgium & Poland. We acknowledge the Sustainable Building Design Laboratory at the University of Liege for using the qualitative research protocols in this research and for valuable support during the questionnaire development and literature review analysis. Zsófia Deme Bélafi's work on this paper was supported by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences.

Data availability

Data are available within an enclosed Data in Brief paper (Attia, Kosiński, Laurent, Mihailov, Evstatiev, Krstić, et al. on Data on nearly zero energy building (nZEB) national plans in Eastern Europe, submitted).

Appendix I. . Supporting information

Attia, S., 2022, 'Data on residential nearly Zero Energy Buildings (nZEB) design in Eastern Europe', Harvard Dataverse, vol. 2, 2022, https://doi.org/10.7910/DVN/ZYVNLQ, Available from: https://dataverse.harvard.edu/dataset.xhtml?persistentId = https://doi.org/10.7910/DVN/ZYVNLQ.

Appendix II. . Literature review

Table AII, list of the Eastern European related articles reviewed and classified according to five thematic categories.

	Energy efficiency	Heating & cooling	Comfort & IEQ	Renewables	Construction quality
Bulgaria					
[16]	✓				
[26]		✓		✓	
Croatia					
[46]	✓				✓
[64]	✓	✓	✓		
[71]	✓	✓			✓
Czechia					
[68]	✓	✓			
[36]					✓
[3]	✓			✓	✓
[35]	✓	✓		✓	
[44]	✓	✓	✓	✓	
Estonia					
[2]	✓	✓		✓	
[69]	✓				

(continued on next page)

(*continued*)

	Energy efficiency	Heating & cooling	Comfort & IEQ	Renewables	Construction quality
[56]	✓	✓		✓	
[38,39]	✓	✓	✓	✓	
[54]	✓	✓		✓	
[1]				✓	
[53]	✓	✓		✓	
Hungary					
[28]	✓	✓		✓	✓
[59]	✓	✓			
[60]	✓	✓			
[45], p. 2)	✓	✓			✓
Latvia					
[33]	✓	✓		✓	
[63]	✓	✓			✓
[70]	✓	✓			
Lithuania					
[61]	✓	✓		✓	
[72]	✓	✓	✓		
[1]	✓	✓		✓	
Poland					
[9]	✓	✓	✓	✓	✓
[24,23,22]		✓	✓	✓	✓
[27]	✓	✓	✓		
Romania					
[62]	✓	✓		✓	
[49]	✓	✓		✓	✓
[47,48]	✓	✓		✓	
[25]	✓	✓	✓	✓	
[65,66]	✓	✓		✓	
Slovakia					
[37]		✓			
[13]	✓	✓		✓	
[31]	✓	✓	✓		

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