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Assessing Nearly Zero Energy Buildings (NZEBs) development in Europe

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ABSTRACT

Decarbonising the energy sector is crucial to reach future climate and energy goals. As established by the Energy Performance of Building Directive recast, Nearly Zero Energy Buildings (NZEBs) are the mandatory building target in Europe for all new buildings from 2021 onwards. In the light of the approaching deadline, this paper assesses the development of NZEBs in Europe based on the most recent collected data and information.

This paper provides an overview of the implementation of national definitions and energy performance values for new, existing, residential, and non-residential buildings in Member States. It evaluates the differences with the established European benchmark and cost-optimal levels. An overview of the most commonly implemented technologies in NZEBs is given together with costs and the relative projections over next decades. Finally, quantitative data on the NZEBs diffusion in Member States are given as recently assessed. The evolution of the NZEB concept and the future NZEBs role is also forecasted.

The results assume a strategic value in the light of future targets for the building sector, showing the progress made by Member States in relation to different NZEBs aspects. They provide a comprehensive analysis of the European NZEBs implementation depicting a positive overall progress improvement for NZEBs definitions, uptake, technology development, and energy performance levels. Next challenges and barriers are outlined and appear mainly related to NZEBs retrofit.

1. Introduction

The high energy consumption that characterizes the building sector, assessed at around 40%, is a worldwide concern. Several initiatives aim at reducing greenhouse gas emissions and the linked global temperature increase whose complex consequences threaten our environment and health [1–3].

European (EU) policies encourage energy efficiency and renewable production to achieve a climate neutral continent by 2050. As stated in the European Green Deal [4,5], this ambitious target requires to maximise energy efficiency and renewable production involving industry, mobility, economy and agriculture.

Combining energy efficiency with the deployment of renewables, NZEBs play a key role towards this direction [6]. The Energy Performance of Buildings Directive recast states that new buildings, occupied by public authorities and properties, have to be NZEBs by December 31, 2018, and all new buildings by December 31, 2020 [7]. A NZEB is defined as a building with a very high energy performance, where the nearly zero - or very low-amount of energy required should be covered as much as possible by renewable energy sources, produced on-site or nearby.

A uniform approach for implementing NZEBs is not established in the EPBD. Member States have to develop NZEBs definitions in line with national, regional or local conditions, and including a numerical indicator of primary energy use (in kWh/m^{2}y). Furthermore, they have to implement targeted policies and provide financing to foster the transition to NZEBs, progressively increasing the NZEBs number with targets differentiated for building categories.

Another important provision established in the EPBD relates cost-optimal levels of minimum energy performance requirements for new and existing buildings. These have to be met in compliance with a comparative methodology framework [8]. The methodology includes the establishment of reference buildings, the identification of energy efficiency and renewable measures to be implemented, the calculation of primary energy consumption and global costs. The cost-optimal level is found in the lower part of the graph that reports global costs (€/m^2) and energy consumption (kWh/m^{2}y) of each configuration [9].

A major concern remains related to existing buildings and the related

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high energy consumption. 35% of EU buildings are over 50 years old and 90% are built before 1990 [10]. Although the Renovation Wave [11] aims at boosting the current low renovation rate (between 0.4% and 1.2% in Member States), NZEBs renovation remains the hugest challenge for Europe. The high priority of the topic is also stressed in the 2018 amendment of the Directives EPBD and EED on energy efficiency [12], according to which Member States must establish a comprehensive strategy aimed at achieving a highly efficient decarbonised building stock by 2050 and cost-effective transformation of existing buildings into NZEBs. Indeed, NZEBs renovations are not defined in terms of a specific primary energy saving threshold, but according to official national NZEBs renovation definitions. This confirms the importance of having NZEBs definitions in place also for existing buildings.

Due to the variety of climates, market and local conditions throughout Europe, the implementation of NZEBs definitions has not been an easy task [13] and it is not yet fully assessed. Therefore, as the deadline for mandatory NZEBs has been recently reached, this paper aims to assess the progress of the NZEBs development in Europe, closing knowledge gaps such as that of comparing performance values among countries. The assessment is based on a comprehensive data collection and the most recent available information from Member States. It first evaluates the progress of NZEBs definitions in Member States. A comparison is then made between the NZEBs performance and benchmark levels (provided in the NZEBs Commission Recommendation [14] and cost-optimal levels (provided in national reports, as assessed by Ref. [15]). To provide a quantitative picture on the NZEBs development, the paper collects data on the number of NZEBs. Then, an overview is given on the main technologies implemented in NZEBs based on data extracted from European projects. Best practices are identified and cost projections are reported for the most diffused technologies. After a discussion that summaries the evolution of the NZEB concept, requirements, barriers, future challenges and trends, conclusions are drawn.

2. Methodology

The paper gives key knowledge on the progress of the NZEBs development in Europe through the:

- implementation of NZEBs national definitions, including energy class, U-values, renewable share and energy indicators. NZEBs energy performance values are provided for new and existing, residential and non-residential buildings, including obligatory renewable share and energy performance certificate, where available [16] (Section 3.1);
- comparison of NZEBs performance levels with benchmark [14] and cost-optimal levels [15,17] (Section 3.2);
- NZEB number, measures and uptake in Member States (Section 3.3);
- assessment of most commonly implemented technologies and related costs, including heating, cooling, ventilation, air conditioning, renewable sources, and lighting (Section 3.4).

The main source of information considered in this analysis are: the EPBD Concerted Action and complementary analyses carried out by Member States [18,19], Long Term Renovation Strategies and National Climate and Energy Plans submitted up to 2020 by Member States, available literature, national plans for NZEBs [20], information directly provided by Member States, recent EU funded projects on NZEBs [21–25] (last update dates back to Autumn 2020 when data were harmonized, cross checked and verified; continuos updates are in progress and may result in changes of some results presented within this manuscript).

3. Results

3.1. Updated NZEBs definitions in European Member States

Table 1 summarises the NZEB definitions progress as assessed in Member States (last update Autumn 2020).

Table 1 shows that 23[1] Member States have currently in force a NZEB definition, which is still under development in 2 Member States (Luxemburg[2], Spain), while in others (Czech Republic, Hungary, Belgium-Brussels, and UK) a previously adopted definition is currently under review. An Energy Class or Energy label equivalent to NZEB requirements is defined in 18 Member States. For half Member States, the required U-values are also provided, although in some cases the values are still in draft.

22 of the assessed definitions include also an energy indicator for both residential and non-residential buildings, such as an energy performance coefficient or the maximum primary energy demand (in kWh/m^{2}y) while 1 of them includes energy indicator only for residential buildings. 17 Member States include also an energy indicator for existing buildings. In 12 Member States the NZEBs definition includes a specific obligation to cover a minimum share of energy demand from renewable sources. In some cases this obligation is defined, however the exact share is not provided nor quantified.

Table 2 gives a comprehensive comparison among the last assessed NZEBs energy performance values for new and existing, residential and non-residential buildings.

Established NZEBs energy performance levels vary from 20 kWh/m^{2}y (Belgium Flanders) to 132 kWh/m^{2}y (Estonia) in new residential buildings, and 30 kWh/m^{2}y (Belgium Flanders) and 176 kWh/m^{2}y (Malta) in new non-residential buildings. In relation to existing buildings, NZEBs levels vary from 20 kWh/m^{2}y (Belgium Flanders) to 157 kWh/m^{2}y (Estonia) in existing residential buildings, and 21 kWh/m^{2}y (Croatia) and 176 kWh/m^{2}y (Malta) in existing non-residential buildings. In accordance with the EPBD principles, the reduction of energy demand through efficient measures and renewables to supply the remaining demand are a common agreement in the NZEBs implementation in Europe. In half Member States, U-values for walls, roofs, floors, windows and doors are also provided. However, a minimum share of energy demand from renewable sources is not always available.

3.2. Comparison of NZEBs performance levels with benchmark and cost-optimal levels

The NZEB benchmark levels of energy performance (kWh/m^{2}y) per building type, depending on the climatic zone, are reported in Table 3, as established by the Commission [14]. These benchmarks have been defined in terms of both total and net primary energy use, where the first one is obtained subtracting the primary energy associated to the total renewable energy generated on-site (both self-consumed and exported).

The last assessed NZEBs performance levels (Table 2) have been compared with the benchmark levels per Member State (Fig. 1). For the comparison, the central value of each interval provided in Table 3 has been chosen. The climate zones to be attributed to Member States for this comparison are provided by Ref. [26]. The different approaches adopted to establish NZEB definitions across Member States, the different methodologies in reporting, and the limited availability of data can possibly result in some inconsistencies in the comparison. To sort this out and have harmonized values, some adjustments have been applied, so that the comparison cover the same end-uses in all Member States. As example, a share of 15% has been removed where appliances were included in the reported values. Furthermore, the comparison was

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[1] Belgium is considered as one Member State here

[2] For Luxembourg NZEB definition for residential buildings has been in force since 2017, while for non-residential buildings was to enter in force in 2019.

Table 1
NZEB definitions summary.

	Definition/ requirements	Energy Class/label equivalent	U-VALUES	Energy Indicator (residential)	Energy Indicator (non-residential)	Energy Indicator (existing buildings)	Renewable share
AT	✓	X	✓	✓	✓	→	X
BE-BRU	≡	✓	X	✓	✓	✓	≡
BE-WA	✓	✓	✓	✓	✓	X	≡
BE-FLA	✓	X	✓	✓	✓	✓	✓
BG	✓	✓	X	✓	✓	✓	✓
HR	✓	✓	X	✓	✓	✓	✓
CY	✓	✓	✓	✓	✓	✓	✓
CZ	≡	X	✓	✓	✓	X	≡
DK	✓	✓	X	✓	✓	X	≡
EE	✓	✓	✓	✓	✓	✓	≡
FI	✓	✓	±	✓	✓	✓	≡
FR	✓	X	X	✓	✓	→	X
DE	✓	X	X	→	→	→	X
EL	✓	✓	X	✓	✓	✓	✓
HU	≡	✓	✓	✓	✓	✓	✓
IE	✓	✓	✓	✓	✓	✓	✓
IT	✓	X	✓	✓	✓	✓	✓
LV	✓	✓	X	✓	✓	✓	X
LT	✓	✓	✓	→	→	X	X
LU	±	✓	X	✓	→	✓	X
MT	✓	X	X	✓	✓	✓	→
NL	✓	X	X	✓	✓	X	✓
PL	✓	X	✓	✓	✓	✓	
PT	✓	✓	✓	→	→	→	✓
RO	✓	X	X	✓	✓	✓	✓
SK	✓	✓	✓	✓	✓	✓	≡
SI	✓	✓	±	✓	✓	✓	✓
ES	±	X	X	→	→	X	X
SE	✓	✓	X	✓	✓	X	X
UK	≡	X	X	→	→	X	X
±	under development	under development	draft				under development
→				calculated/assumed	calculated/assumed	calculated/assumed	calculated
X		no	not available	No/not available	No/not available	No/not available	not available
✓	yes/provided/to be approved	yes	yes	yes/provided (value or formula)	yes/provided (value or formula)	yes/provided (value or formula)	yes/provided
≡	under revision						not quantified/non obligatory

assessed for net primary use values (on-site renewables excluded).

*RES required but specific value not available.

**Value from Cost-optimal analysis or from EPBD report.

FR: values for existing building taken from EPBD report. The compared values correspond to the reported by MSs values including the AC use.

HR, EL, IT: the compared values correspond to the average of the reported by MS climatic zones of the country.

FI: the compared values correspond to the average of reported by the MS values for different types of detached houses.

RO: the compared values correspond to the most representative climatic zone of the country according to the MS report.

DK: The values have been calculated based on the following formula: Dwellings: $(30 + 1000/A)$ kWh/m^2 per year.

Other buildings than dwellings: $(41 + 1000/A)$ kWh/m^2 per year.

A is the floor area.

Residential: $A = 145.72$ m^2 (average floor area of single family dwellings in Denmark, 2018, source: Odyssee database.

Non-residential: $A = 100$ m^2

HU: values for residential do not include lighting, values for non-residential include lighting.

PL: The values have been calculated based on the following formula: $EP = EPH + W + \Delta EPC + \Delta EPL$.

A share of 15% has been removed in the final graphs where appliances were included in the reported values.

In Fig. 1 it is possible to observe that NZEBs values in most Member States are higher than the benchmark values in both residential and non-residential, new and existing buildings. In more details, the assessed NZEB level exceeds the benchmark level for more than 10% in 24 Member States. Excluding Netherlands, Belgium-Flanders and Lithuania in relation to single-family houses, the benchmark level is more demanding than the NZEBs level (a maximum absolute difference of 67 kWh/m^2y is observed in Estonia's new buildings). In relation to office buildings, only Belgium-Flanders, Denmark, Croatia, Ireland, Netherlands, Romania, Slovenia, and Sweden present NZEBs levels lower than the benchmark level. In the other Member States, the benchmark level is lower than the NZEBs level (a maximum absolute difference of 146 kWh/m^2y is observed in Malta's new and existing building).

However, the requirements in terms of energy performance level show heterogeneity and reflect different calculation methodologies of energy flows. Key NZEBs definition parameters, like the boundary, can lead to differences in the assessed levels. Furthermore, different climatic zones across Member States also prevent a full direct comparison. This also can explain why, apart from a few exceptions, the assessed NZEBs level appear less demanding than benchmarks established by the Commission.

Another important comparison is made between the NZEBs performance levels and cost-optimal levels derived by Member States for several types of buildings (new/existing residential/non-residential) in

Table 2

Comparison among Member States for NZEB energy performance levels in residential and non-residential, new and existing buildings (Source: [15,18], plus clarifications from Member States contact points; Long Term renovation strategies; National Climate and Energy Plans; Country sheets for EU28 reflecting progress in implementing the EPBD 2018, data subject to updates).

MS	NEW BUILDINGS Non-renewable primary energy (kwh/m²y)		EXISTING BUILDINGS Non-renewable primary energy (kwh/m²y)		RES	EPC
	residential	Non-residential	residential	Non-residential		
AT	41	84	68			
BE-BRU	45	85	55	100		
BE-FLA	20	30	20		15 kWh/m2/year (residential), 20 kWh/m2/year (non-residential)	
BE-WA	85	Relative requirement				A
BG	43	63	43	63	55%	A+
CY	75	94	75	94	25%	A
CZ	80	80				
DE	40	75	65			
DK[a]	37	51				A 2015
EE	132	85	157	136		ENERGY CLASS A-B (new residential), A (new non-residential), C (existing)
EL[b]	37	92	75	138	15–60% depending on building type	A for new, B+ for existing A for new, B+ for existing
ES	50	100				
FI[c]	94	85	94	85		B
FR	60	110	100	150		
HR[d]	28	21	28	21	30%	A+
HU[e]	100	90	100	90	25%	BB
IE	33	35	100	99	20% (new residential)	A2 (new residential), A3 (new non-residential), B2 (existing residential)
IT[f]	35	117	35	117	50%	
LT	60	80			50%	A++
LU	45	60	45	60		
LV	95	95	95	95		A
MT	56	176	56	176	25% residential 20% non-residential	
NL	30	28			30–50%	
PL[g]	75	107.5	75	107.5		
PT	35	130	55	140	50% (residential)	A
RO[h]	78	40	78	40	30%	
SE	90	70				A-C
SI	70	55	95	65	50%	A1, A2, or B1
SK	54	61	54	61		A0
UK	45	150				

[a] The values are calculated based on the following formula: Dwellings: (30 + 1000/A) kWh/m2 per year Other buildings than dwellings: (41 + 1000/A) kWh/m2 per year.A is the floor area.Residential: A=145.72 m2 (average floor area of single family dwellings in Denmark, 2018, source: Odyssee database Non-residential:A=100 m2

[b] Values are the average of different climatic zones values

[c] Residential: Average of different types of detached houses

[d] Average of continental-coastal

[e] Residential: without lighting, non-residential: with lighting

[f] Average of 6 different climatic zones of IT

[g] EP = EPH+W + ΔEPC + ΔEPL, where:EPH+W – maximum values for parts of the energy performance index for heating, ventilation and domestic hot water ΔEPC – maximum values for parts of the energy performance index for cooling ΔEPL – maximum values for parts of the energy performance index for built-in lighting Af,i – floor area heated or cooled of i-part of unified utility function of building

[h] Values for the most representative climatic zone of RO

Table 3

NZEBs benchmark levels of energy performance (kWh/m^{2}y) per building type according to the climatic zone (data derived from Ref. [14]).

Climate zone	Building type	NZEBs Benchmark level		NZEB targets (kWh/m^{2}y)
		Net primary use (on-site RES excluded) (kWh/m^{2}y)	Total primary use (kWh/m^{2}y)	
Mediterranean (e.g. Catania, Athens, Larnaca, Luga, Seville, Palermo)	residential	40–55	85–100	35–100
	non-residential	20–30	80–90	60–175
Oceanic (e.g. Paris, Amsterdam, Berlin, Brussels, Copenhagen,	residential	15–30	50–65	15–70
	non-residential	40–55	85–100	40–150
Continental (e.g. Budapest, Bratislava, Ljubljana, Milan, Vienna)	residential	20–40	50–70	20–125
	non-residential	40–55	85–100	25–125
Nordic (e.g. Stockholm, Helsinki, Riga, Stockholm, Gdansk, Tovarene)	residential	40–65	65–90	65–95
	non-residential	55–70	85–100	95–110

both 2013 and 2018 (Article 5, EPBD Recast).

The analysis of the latest reports [15] highlighted that only a few Member States (Belgium Wallonia, Denmark, Estonia, France, Hungary, Lithuania, Poland and Spain) provided a comparison analysis of the cost-optimal and NZEB levels. However, where not available, the levels from the 2013 cost-optimal reports were selected. In many cases, the cost-optimal levels were derived by averaging the values obtained for different sub-categories of the same building type.

Figs. 2 and 3 reports the gaps between cost-optimal and NZEBs levels for new and existing buildings, respectively. A negative value means that the NZEB net primary energy is lower than the cost-optimal one, so the green area can be a considered as the dominium of acceptable gap.

The graphs in Figs. 2 and 3 allow to depict a quite positive picture. For new buildings, the gaps between NZEBs and cost-optimal levels overcome 15% only in the 20% of cases. For existing buildings, this happens in the 18% of cases, but less data are available for this comparison. The Member States who should mostly verify the ambition of their NZEB definitions are Malta, Slovakia.

A good number of Member States are introducing NZEB requirements substantially lower (about −50%) compared to cost-optimal levels. From these observations, it is possible to conclude that a good number of Member States referred to the cost-optimal approach to define the NZEBs requirements.

3.3. NZEBs uptake

The NZEBs and high performing buildings number in Europe increased significantly from 2012 to 2016. A total of 1,238,184 buildings were built or renovated to NZEBs levels during this period [11]. Most of them (the 22%) were built in 2014. The share of NZEBs in the total construction market increased during the period from 2012 to 2016 (from 14% in 2012 to 20% in 2016 on average) (Fig. 4).

Residential buildings represent the largest share (95.6%) over the total NZEBs (Fig. 4a). Interestingly, the number of new and existing non-residential NZEBs per year increased by 63% from 2012 to 2016. The 52% of NZEBs from 2012 to 2016 were the result of new constructions, while 48% of renovation (Fig. 4b). Most both renovations and new constructions took place in 2014. This data demonstrate a tangible increase in the NZEBs uptake in the EU compared to previous assessments that showed NZEBs spread only at a demonstration project level, mainly for research purposes [27,28].

Most Member States adopted a number of measures to increase the NZEBs number (Fig. 5):

- Regulatory (e.g. energy standards, definition of NZEB requirements, adoption of regulation and laws);
- Financial (e.g. subsidies, renovation grants, operational programmes, fiscal incentives);
- Informative (e.g. information campaigns, leaflets, websites);
- Educational (e.g. training courses for engineers and architects, guidelines);
- Strategic (e.g. national plans, renovation strategies);
- Market-based (eg: ESCOs);
- Research (e.g. implementation of NZEB pilot projects).

Fig. 5 shows that the 33% of the NZEBs measures are regulatory, the 23% financial and fiscal. The 18% of reported measures are informative, followed by educational (13%) and strategic measures (8%). Research (4%) or market-based (1%) are a smaller share of total measures.

Fig. 6 shows the NZEBs distribution and the NZEBs square meters by Member State (2016).

The largest share of renovated or constructed NZEBs in 2016 occurred in France (30% of total EU NZEBs), followed by Germany (16%) and the UK (10%). The 79% of NZEBs were constructed or renovated in 7 Member States (France, Germany, UK, Italy, Austria, the Netherlands and Spain), while the other 21 Member States accounted for the 21% of total NZEBs (Fig. 6a). In relation to the NZEB square meters, the largest share was registered in France (20%), followed by Germany (18%), and Italy (8%). The 60% of the total EU NZEBs square meters occurred in 5 Member States (France, Germany, Italy, UK and Poland), while the other 23 Member States accounted for the remaining 40% (Fig. 6b.

An important indicator to assess the NZEBs development is the share of NZEBs within the total construction market. This share increased during the period from 2012 to 2016 in Europe (from 14% in 2012 to 20% in 2016) (Fig. 7).

Among Member States, Luxemburg, Austria and Cyprus registered the largest shares in 2016 (43%, 40% and 37% respectively). On the contrary, Poland, Sweden and Romania registered the lowest shares (8%, 11% and 13% respectively), as shown in Fig. 7a. Regarding the share of square meters in NZEBs standard within the total construction market, Luxemburg, Latvia and Lithuania registered the largest share among Member States in 2016 (57%, 50% and 35% respectively), as shown in Fig. 7b. The Member States that registered the lowest NZEBs share are Hungary, Finland and Poland (8%, 9% and 10% respectively). The respective EU average share went from 10% in 2012 to 16% in 2016.

Fig. 8 shows the NZEBs distribution in 2016 in new residential and non-residential, existing residential and non-residential buildings per Member State.

The highest percentage of non-residential renovation to NZEB levels in total NZEBs (74%) was registered in Latvia, while Italy registered the highest percentage of residential renovation to NZEB levels in total NZEBs (78%). The NZEBs added in Estonia in 2016 were mostly new residential buildings (84%), while the 31% of total NZEBs added in 2016 in Lithuania were new non-residential buildings. 20 Member States registered the largest shares in new residential constructions.

The major challenge appears a widespread NZEBs retrofit implementation. The current renovation rate has been assessed between 0.5% and 2.5% per year with buildings dating between 1945 and 1980 having the largest energy demand [29]. Moreover, the existing stock is characterized by a high heterogeneity in terms of uses, climatic areas, construction traditions and systems.

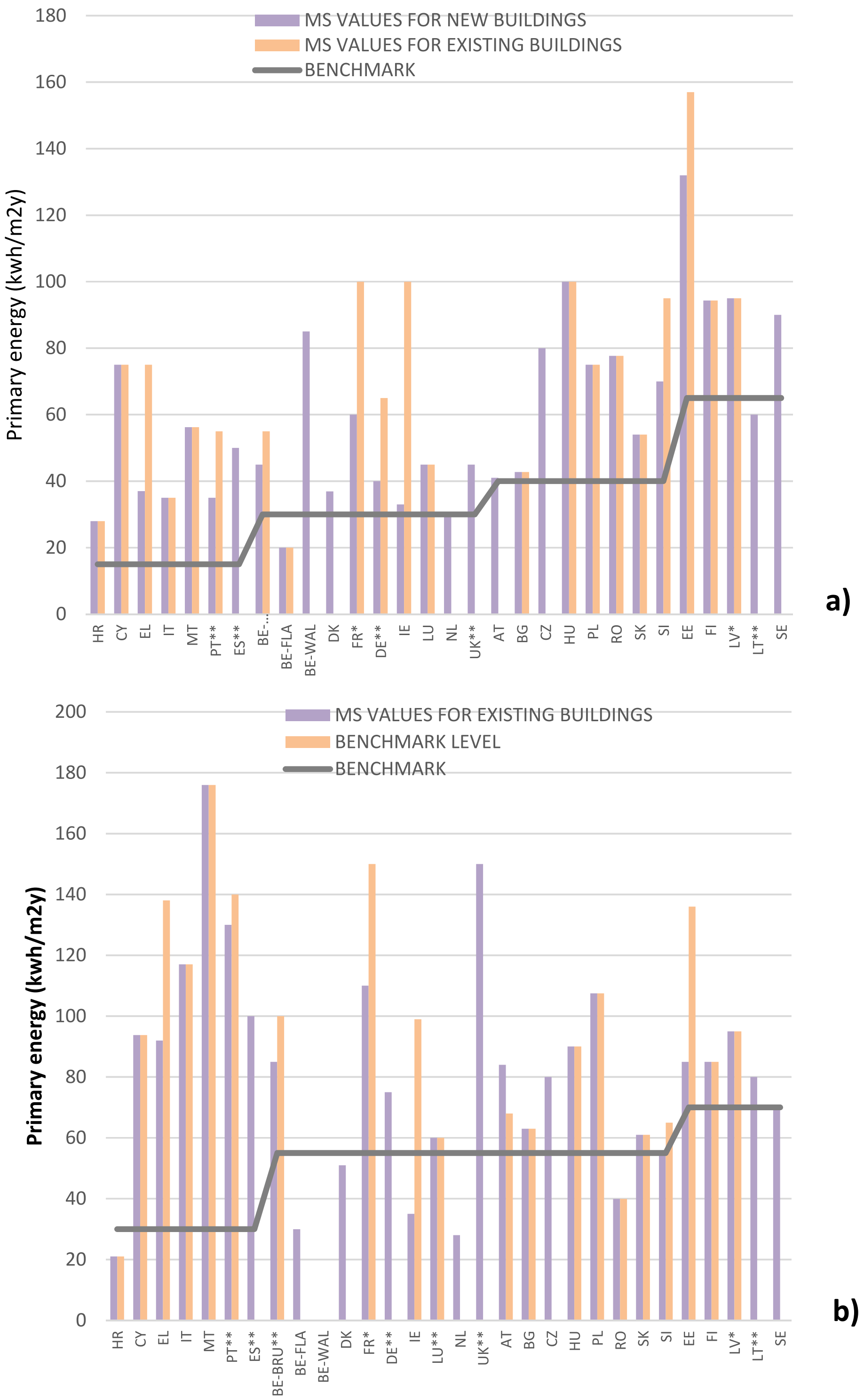


Fig. 1. Comparison between benchmark and NZEBs performance levels in a) single-family houses and b) offices.

3.4. NZEBs technologies

The NZEB target can be achieved using appropriate technologies and best practices [30]. High efficient solutions minimise the energy needs while renewables (PV, solar thermal, wind power, heat pumps) supply the remaining demand to a large extend. A critical role, not yet fully addressed, is played by occupant's behaviour [31]. Different studies optimize the NZEBs design and technologies, but the need of reference models related to human behavioural issues persist.

The main solutions for space heating, cooling, lighting and other equipment can be distinguished between active and passive [32]. A distinction can be also made between solutions for new or renovated NZEBs. Common main solutions are reported in Table 4 as extracted from Ref. [21].

Generally, a proper building geometry which facilitates natural lighting and ventilation, the implementation of energy saving techniques and storage systems, together with renewable energies, can lead to the achievement of NZEBs [30].

Most frequently implemented technologies are now summarised. Best practices examples are also identified as extracted from Ref. [19]

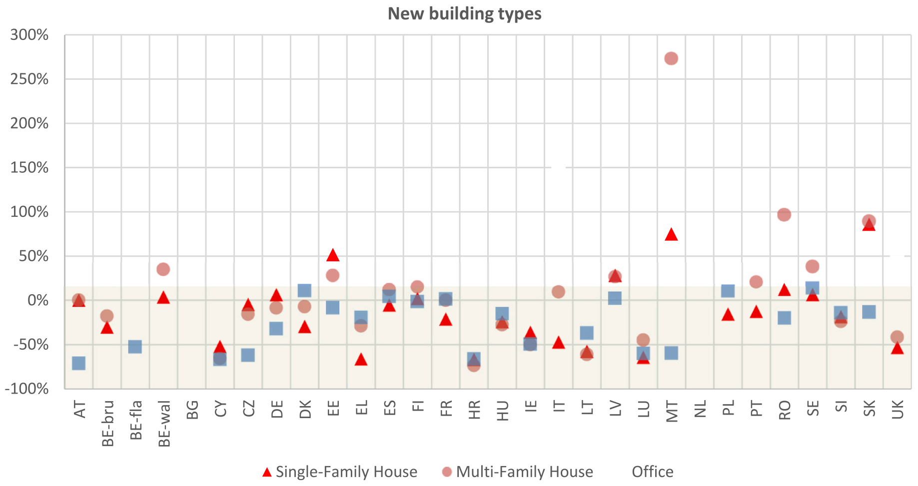


Fig. 2. Gap between cost-optimal and NZEB net primary energy levels for new buildings.

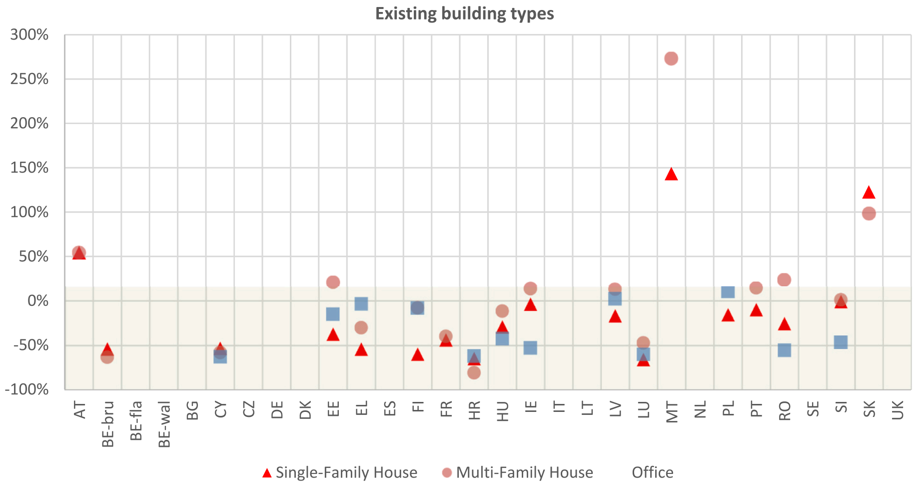


Fig. 3. Gap between cost-optimal and NZEB net primary energy levels for existing buildings.

and EU funded projects on NZEBs [21–25]. All the data of the collected NZEBs best practices are available in Ref. [33].

Active solutions for space heating and domestic hot water include heat pumps, boilers and district heating or decentralised heating. Passive technologies for space heating are based on thermal insulation to store energy.

Fig. 9 presents the most widely used space heating and domestic hot water systems in NZEBs best practices [18,19,21–25].

There are various types of boilers based on the fuel to produce space heating (e.g. gas boilers, oil boilers or biomass boilers). Among them, oil boilers are expected to decrease in the following years due to their high level of emissions [34]. Gas boilers are the most used heating technology in Europe, with a share of 40% in the heating technology stock [21,35]. However, a further decrease is expected until 2050 (by 5–11% compared to 2016) [21]. Biomass boilers are also an efficient technology solution for NZEBs as they are based on renewable energy and produce fewer emissions. Some Member States implemented policies to give incentives for a wider use of biomass [25].

In relation to implemented technologies, 49% of NZEBs best practices buildings have heat pumps, making them the most popular active heating system in NZEBs. These are also used for domestic hot water, where the 23% of buildings have opted for heat pumps while among the RES, PV is the most commonly used technology (presented in the 69% of the buildings). They can be classified based on the kind of energy that they use (e.g. ground-source or geothermal heat pumps, ambient air heat pumps or water heat pumps). Nowadays, heat pumps are the cheapest renewable technology for kW installed in the market to generate heating, cooling and hot water [25].

Regarding the trends and the objectives for heat pumps, some Member States have set targets or have adopted financial or fiscal measures to favour the use of heat pumps. This may lead in increase in number of heat pump installations in the following years and in an important reduction of heat pumps costs in Europe until 2050.

Ventilation is very important in NZEBs as it improves air quality. Central or decentralised mechanical ventilation is often used in NZEBs with heat recovery systems as natural ventilation could not be sufficient. Natural ventilation can be achieved mainly through windows and it is usually complementary or it is used only during summer. Mechanical ventilation could offer a more precise operational control of air conditions and it is not dependent on the outdoor climate [21]. It can include fans, ceiling fans, exhaust air systems, heat exchangers, VRV system (variable refrigerant volume), heat recovery units.

In relation to cooling, active solutions include heat pumps, air-conditioning, underfloor cooling, district cooling and ceiling fans. Passive technologies for cooling include building shading, night cooling, natural ventilation and green roofs. Natural cooling can reduce significantly the total energy demand of a building. In the collected NZEBs best practices [33], 20% of the buildings uses exclusively or mainly natural cooling solutions, while 18% mechanical cooling solutions. In some buildings there are both technology types, while in others there are no

Fig. 4. a) NZEBs in Europe by building use (2012–2016); b) NZEBs in Europe (2012–2016) (new and renovated) (Data elaborated from: [11]).

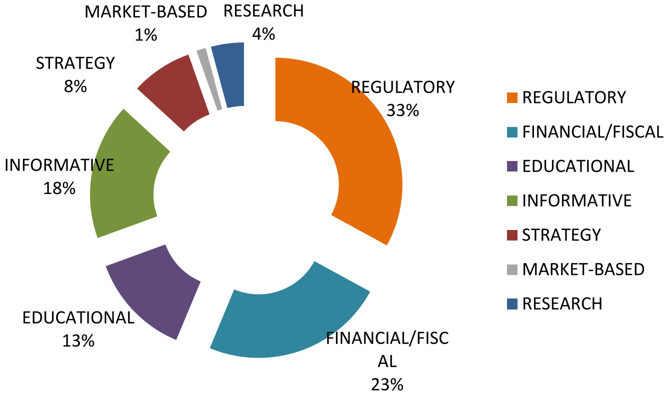


Fig. 5. NZEBs measures by type (Data source [18,19]: plus NZEB Action Plans, Information provided by MSs).

available data for the implemented cooling solutions. However, recent forecasts [36] predict that cooling will be much more important in buildings due to foreseen climate change scenarios of temperature increase [37].

Renewables could be on building site or close to the building site. Table 5 shows the main renewable energy generation options for NZEBs [modified from: [38]].

Most used renewable technologies in NZEBs are PV, solar thermal, geothermal and biomass (Fig. 10a). The NZEBs legislation defines as requirement a minimum share of primary energy demand to be covered by renewables in some Member States. The minimum RES contribution varies per Member State and the NZEB buildings in Europe present a wide range of RES shares and technologies. The majority of collected NZEBs best practice use one or more renewable technologies for their

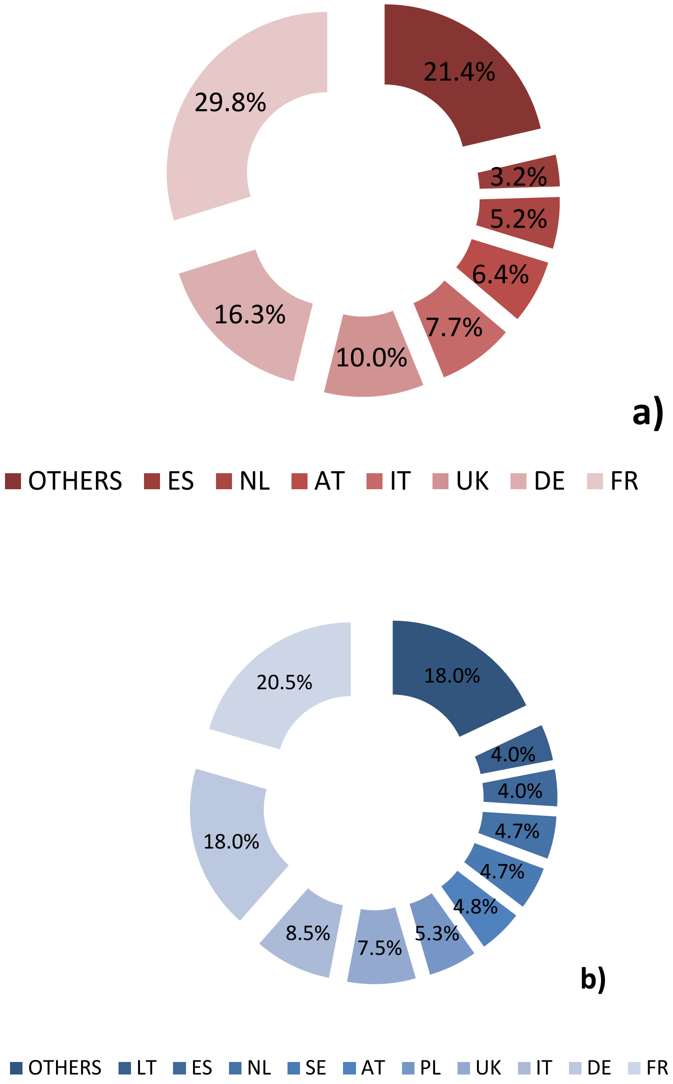


Fig. 6. a) Number of NZEBs by Member State (2016); b) Square meters of NZEB by Member State (2016) (Data elaborated from: [11]).

energy needs. They can achieve a reduction in their energy supply as well as in the total CO_2 emissions. In Fig. 10b, the average renewable contribution in best practices NZEBs per country is shown.

Solar thermal is a widely used renewable technology for space heating and hot water, whose efficiency depends strongly on weather and climate conditions. The energy is absorbed and collected through the solar thermal collectors (e.g. unglazed, flat-plate, evacuated flat-plate and vacuum tube, tracked concentrating).

Photovoltaics are one of the main renewable technologies used in the buildings sector. Having many advantages, it is present on the highest NZEBs number in Europe. PV systems can be classified in stand-alone systems and grid connected [25]. The electricity generated can be self-consumed ore exported to the grid. Operational and maintenance cost of photovoltaics are relatively low. Building integrated photovoltaics (BIPV) systems are also a promising solution [39]. However, to boost its cost-competitiveness, the production and installation of BIPV should be scaled up. Advantages and disadvantages can be found in Ref. [40].

Stationary battery systems are becoming increasingly important, especially in combination with renewable electricity generation from PV and wind. Wind energy and PV are likely to spread in future, more electrical storage devices will also be required. It is expected that the use in buildings will become financially attractive.

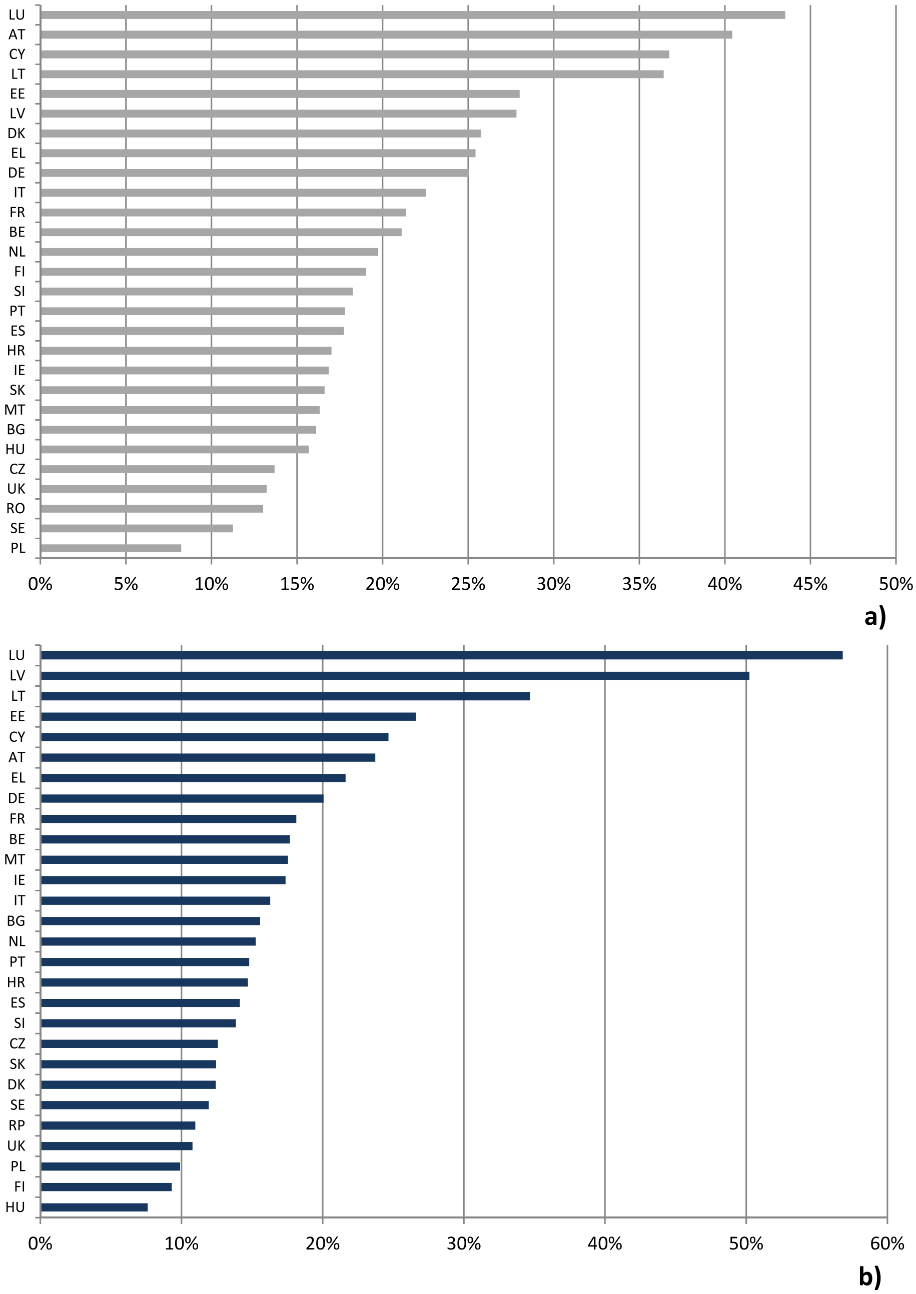


Fig. 7. a) Share of NZEBs in the total construction market of Member States; b) Share of square meter of NZEBs in total construction market by Member State [Data elaborated from: [11]].

Energy savings in lighting can be achieved increasing an efficient use of daylight as well as by installing smart systems. Automation systems, such as the presence and the daylight detectors, can also produce energy savings. LED and energy savings lamps are also commonly used. Finally, Compact Fluorescent Light Bulbs and T5 bulbs are used in several NZEB buildings manually or in combination with presence detectors (Fig. 11). To note that for the most of the building projects, the lighting system is not available.

Costs of main technologies are reported per Member State in Tables 6 and 7, as extracted from Ref. [21].

The technologies cost reduction potential ranges for the analysed heating technologies and renewable energies systems are summarised in Table 8.

The highest potential reduction is expected for PV, followed by solar thermal and aerothermal heat pumps. In contrast, oil boilers is expected to be reduced almost negligibly for their cost while the reduction potential for gas boilers is also relatively low. It is expected that solar thermal collectors cost will register a reduction by 22–51% from 2016 to 2050 [21]. Biomass boilers can potentially reduce their cost by 10–18% in the period 2016–2050. Heat pumps cost reductions could be between 11 and 44% in comparison to 2016 for aerothermal pumps, and between 8 and 34% for ground source heat pumps. Stationary batteries have a substantial cost reduction potential of around 64% until 2050, which is the highest of all analysed technologies. The specific costs fall from 863 €/kWh to 298 €/kWh. The cost range in 2050 is between 193 €/kWh and 449 €/kWh, corresponding to a cost reduction between 48% and 78%. Regarding cost predictions of ventilation systems, it is expected that they will be reduced by 40%–62% for decentralised and by 35%–55% for centralised systems by 2050 compared to 2016.

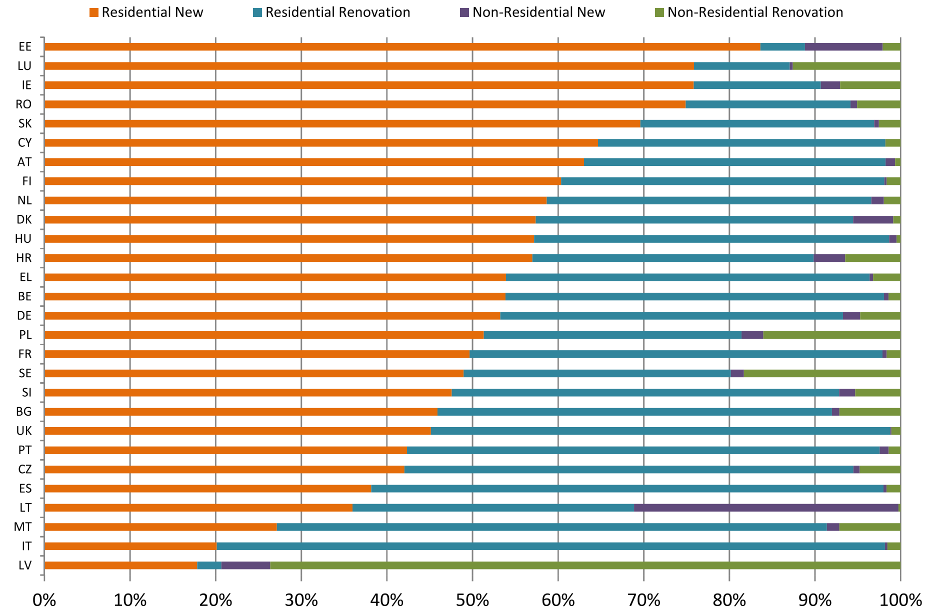


Fig. 8. NZEBs in 2016 in new residential and non-residential, existing residential and non-residential buildings per Member State.

Table 4
Main NZEB technical solutions [21].

	New NZEBs	Renovated NZEBs
Passive solutions	Thermal insulation[a]. Windows: Triple glazing; approx. 0.85–1.0 W/(m^{2}K). Passive cooling solutions: sunshade (use of solar energy in winter, minimization in summer or warm climate regions), natural ventilation and lighting, thermal mass, night cooling.	Thermal insulation[b]. Windows: Triple glazing; approx. 0.9–1.15 W/(m^{2}K). Passive cooling solutions: sunshade use of solar energy in winter, minimization in summer or warm climate regions), natural ventilation and lighting, thermal mass, night cooling.
Active solutions	Mechanical ventilation with heat recovery. Heating: Heat pumps or district heating. Hot water: same system for heating and hot water in cold climates, otherwise dedicated hot water generation, which is also partially depending on solar thermal. If cooling, also heat pump is used Efficient lighting and appliances.	Mechanical ventilation with heat recovery. Heating: Condensing boiler (often gas) or district heating; heat pumps only play minor role compared to new buildings. Hot water: same system for heating and hot water in cold climates, dedicated hot water generation not as wide-spread as in new NZEBs; partially depending on solar thermal. If cooling, also heat pump is used. Efficient lighting and appliances.
Renewables	PV, Solar thermal.	PV, Solar thermal.

[a] U-values:Wall: 0.15 – 0.20 W/(m2K), Roof: 0.10 – 0.25 W/(m2K

[b] U-values: Wall: 0.10 – 0.20 W/(m2K), Roof: 0.10 – 0.20 W/(m2K)

4. Discussion

NZEBs requirements are currently 70% lower than national minimum energy performance requirements in 2006. This was obtained progressivity, with at least four legislative steps introduced over the last 15 years [41]. Results show the main regulatory steps for some key countries in terms of maximum primary energy demand for the average residential building (per type, dimension and climate).

Despite the fragmented, conservative and high technical building sector, policies are effectively contributing to mitigate the energy demand and boost NZEBs implementation. Measures can target the envelope (thermal insulation, glazing, thermal bridges) or heating/cooling generation and distribution systems. Recently, measures targeting smart metering and control systems are spreading to better control supplied services, giving information to the occupants and their behaviour to encourage conservation measures. Additional measures address air conditioning, ventilation, hot water and lighting. To further increase energy savings, apart from the progress in energy efficiency, the inclusion of social-economical and human dimensions will be crucial.

Along with energy requirements, also the building concept has also continuously evolved over the last decade. Starting from high performing buildings, the NZEBs marked the EU official definition (EPDB 2010 recast). Since then, the NZEBs concept evolved as schematized in Fig. 12.

NZEBs present a reduced energy demand through the deployment of energy efficiency measures and covering the remaining demand from renewables. The cost-optimal concept has to be integrated. However, the envisaged match between cost-optimal and NZEBs energy performance level remains debated, Especially for existing buildings, studies investigating the possible energy/financial performance gaps between the two levels can inform policy-makers about how demanding the forthcoming market transition towards an energy efficient building stock will be [42].

The drop in PV cost and the introduction of battery storage will allow demand management in a way not achievable before. However, battery storages do not yet appear a cost-effective measure [43]. Specific measures are needed towards this direction.

Apart from on-site energy storage, the implementation of smart technologies and the internet of things, the new generation of NZEBs will include electric vehicles charging, economic viability, consideration of climate change [44].

During the last decade, substantial developments have been made in the field of building energy saving through recovering waste to energy and utilising various energy conservation measures. In order to shift towards a restorative and regenerative design (Fig. 12), less emphasis needs to be placed on an isolated element or building and more on a design process that focuses on the evolution of the whole system.

Among the promising technologies currently under investigation and development there are: nanotechnologies, phase change materials, prefabricated modules, 3D printing, vacuum insulated panels, ventilated facades with PV panels, electrochromic windows, integrated heating, ventilation, air conditioning along with electricity, ICT, renewables

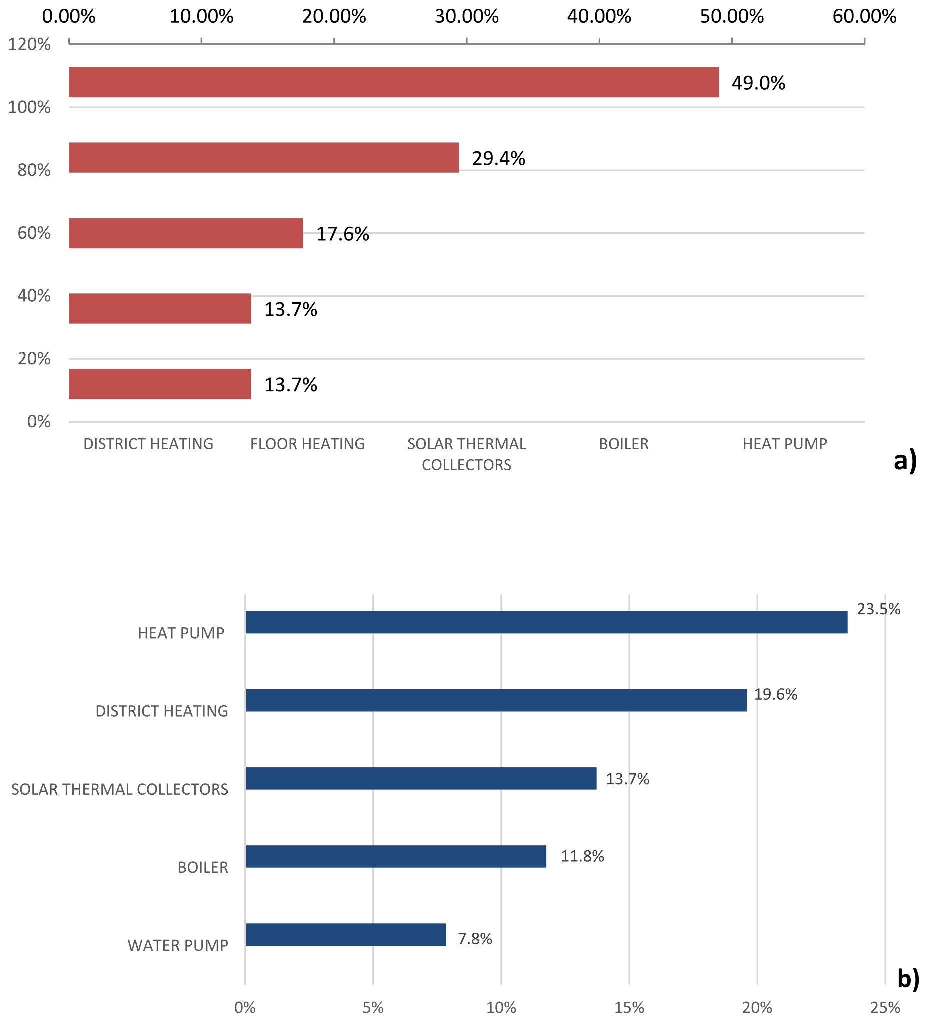
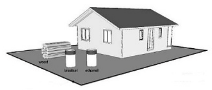
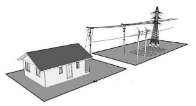


Fig. 9. Most commonly used systems for: a) space heating and b) DHW in exemplary NZEB buildings across EU (Source: [18,19,21–25]).

Table 5
Main renewable energy generation options for NZEBs [modified from: [38]].

Renewable location	Example scheme
Renewable energy within the building footprint	
Renewable energy within the boundary of the building site	
Off-site renewable energy to provide energy (e.g wood pellets, biodiesel, ethanol)	
Purchase renewable energy generate off-site.	

[45].

It appears clear that NZEBs will have a stronger role in alleviating environmental, social or ethical issues [46]. The future generations of NZEB will be scaled-up and integrated to a district level, shifting the focus from the single building to the district scale, creating Net Zero-Energy District (NZED). At city scale, this concept includes a wider vision of urban sustainability that foresees innovative solutions for street lighting, urban mobility, waste, and public safety [47]. A cluster of private and public units is formed and the energy demand is met by renewable energy self-produced within the neighbourhood.

The higher consideration of the impacts on the natural environment appears crucial in future NZEBs that will also incorporate regenerative energy strategies. These include considering vertical green, rainwater storage and treatment, waste management.

Building retrofit can be seen as an opportunity to produce and regenerate an interaction between the building and its environment.

Different barriers can be identified towards NZEBs renovation: technical, financial, social, political and institutional (Table 9). There is also a lack of workforce in the construction and renovation sectors as well as of qualified workforce to renovate buildings to NZEBs, and to roll out smart building technologies and infrastructure for e-mobility. Other barriers together with main benefits that derive from NZEB implementation are schematized in Table 9.

It is frequent that existing structures limit the choice of the technical solutions that can be used, especially in buildings of architectural value. Furthermore, technical solutions may be expensive and request a high investment. A limited access to investments and the non-adequacy of financial models of micro-credit institutes are other open issues. The payback period for renovation may take between 15 and 30 years, and often residents do not benefit from it [50]. Recently, the importance of

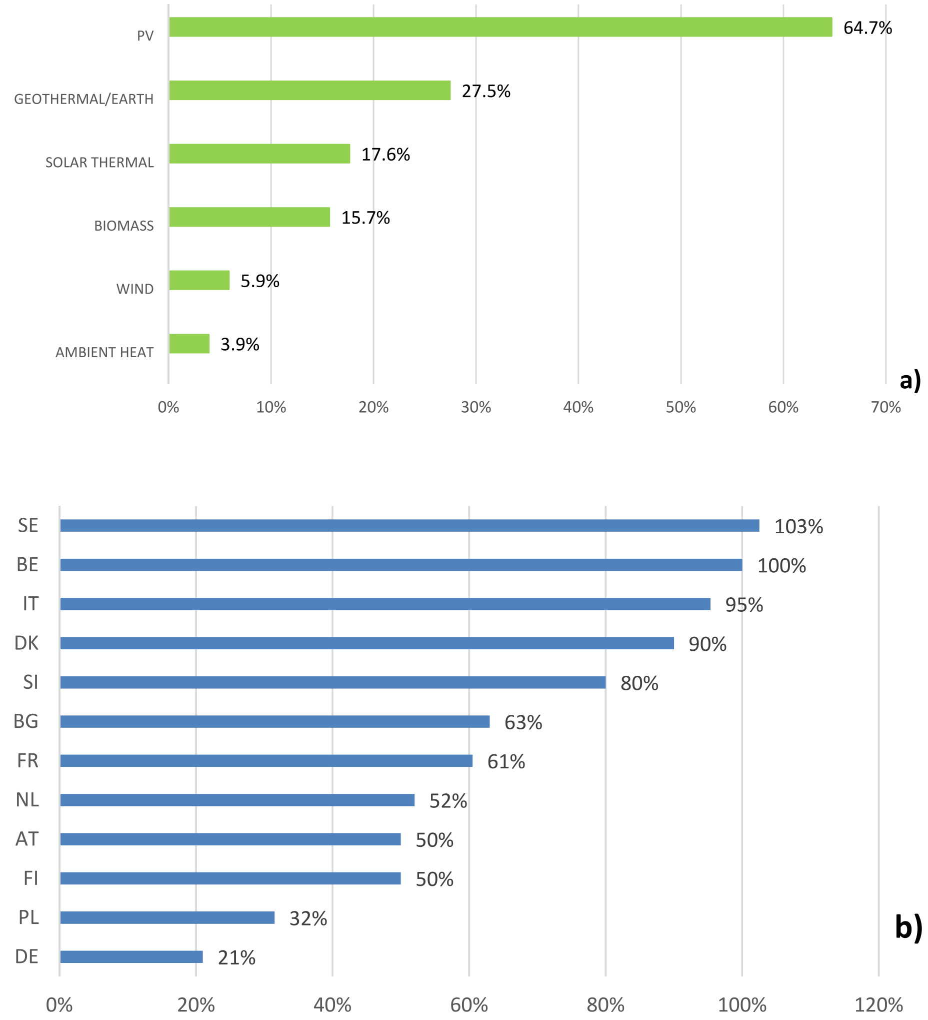


Fig. 10. a) Most commonly used RES in exemplary NZEB buildings across EU (Source: [18,21–25]); b) Average RES share in best practice NZEBs buildings by MS (Source: [18,21]).

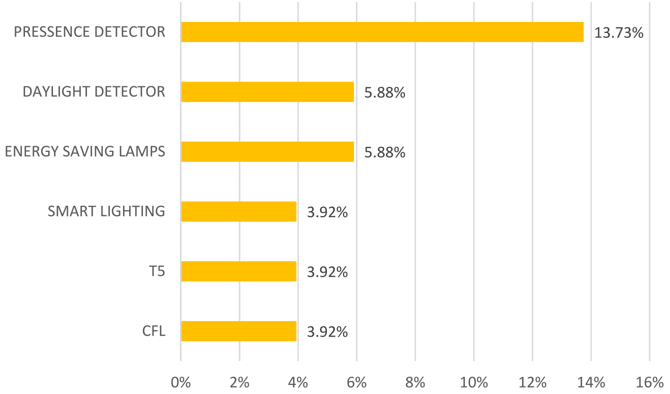


Fig. 11. Most commonly used systems for lighting in exemplary NZEB buildings across EU (Source: [18,21–25]).

social barriers has risen [48]. Communication of best practices and end-user behaviour are other aspects to be considered towards a wide NZEB retrofit implementation.

The following aspects appear important to overcome barriers:

- Stimulate NZEBs from regulatory and non-regulatory policy instruments;
- Industrialise the process of NZEBs renovation;
- Scale up private investments;
- Better use and easier access to EU funds;
- Tackle energy poverty, social housing, low income households;
- Public sector as leading example;
- Drive smart technologies and digital data;
- Explore innovative financing instruments and approaches;
- Involve and train citizen and local authorities;
- Harmonise policy instruments, which need to be concrete, coherent, ambitious;
- Address building integrated renewables and efficient systems.

NZEBs also play a rose be in tackling energy poverty. Among the projects towards this direction, there is the Transition Zero project [49]. It aims to increase the diffusion of NZEBs across Europe, targeting especially the NZEB refurbishment in social housing. Taking experience from the success of *Energiesprong* in the Netherlands, the Transition Zero is expanding in the UK and France, using the social housing sector as a catalyst. *Energiesprong* delivers fully integrated refurbishment packages with long-term guarantees that make the solution commercially financeable and scalable. Transition Zero contributes to the alleviation of energy poverty but it also applies to non-energy-poor housing stock. Its business model offers viable solutions whereby social housing companies can alleviate problems of affordable housing and energy poverty.

Table 6

Average NZEBs technology costs per Member State (Source: [21]).

MS	Average PV system rooftop cost (€/kWp)	Average Solar Thermal Cost (€/m^2)	Average Heating Costs (€/kWth)				Average Cooling cost (€/kWth)		Average Mechanical ventilation cost €/(m^3/h)	Average Mechanical ventilation with heat recovery cost €/(m^3/h)	Average Heat pump specific cost (€/kWth)			
	Capacity <25 kWp	Flate plate collector (20–80) m^2	Gas condensing boiler (Capacity 50–200 kWth)	Biomass boiler pellets (Capacity 50–200 kWth)	District heating compact station for indirect operation (Capacity 50–200 kWth)	Gas CHP (Capacity 50–200 kWth)	Compressor chiller	Split air-conditioning - cold only - in buildings	Capacity class <10000 m^3/h	Capacity class <10000 m^3/h	Air-water heat pump reversible (Nominal capacity 50–200 kWth)	Air-water heat pump non reversible (Nominal capacity 50–200 kWth)	Water-water heat pump reversible (Nominal capacity 50–200 kWth)	Water-water heat pump non reversible (Nominal capacity 50–200 kWth)
Austria	1540	533	160	420	96	1453	592	585	2.8	16.1	4890	2107	1513	454
Belgium	1366	473	142	372	86	1289	525	448	2.5	14.3	4338	1869	1342	404
Bulgaria	745	258	77	203	47	703	287	244	1.4	16.8	2365	1019	732	220
Croatia	841	291	87	229	53	794	324	276	1.6	8.8	2672	1151	827	249
Cyprus	922	319	96	251	58	870	355	302	1.7	9.6	2929	1262	906	273
Czech Republic	935	500	97	255	59	882	360	306	1.7	9.8	2969	1279	919	276
Denmark	2223	770	231	606	139	2099	856	729	4.1	23.2	7062	3043	2185	657
Estonia	907	314	94	247	57	857	349	297	1.7	9.5	2882	1242	892	268
Finland	1744	604	181	476	109	1646	671	572	3.2	18.2	5540	2387	1714	516
France	1589	550	165	433	99	1500	611	521	2.9	16.6	5046	2174	5161	470
Germany	1478	512	153	403	93	1395	569	484	2.7	15.4	4694	2022	1452	437
Greece	971	336	101	265	61	916	373	318	1.8	10.1	3083	1328	954	287
Hungary	814	282	85	222	51	769	313	267	1.5	8.5	2586	1114	800	241
Ireland	1211	419	126	330	76	1143	466	397	2.2	12.7	3846	1657	1190	358
Italy	1432	496	149	390	90	1352	551	469	2.7	15	4548	1960	1408	423
Latvia	885	307	92	241	55	836	341	290	1.6	9.3	2813	1212	870	262
Lithuania	898	311	93	245	56	848	346	294	1.7	9.4	2853	1229	883	266
Luxemburg	1502	502	156	410	94	1418	578	492	2.8	15.7	4771	2056	1476	444
Malta	1217	422	126	332	76	1149	468	399	2.3	12.7	3866	1666	1196	360
Netherlands	1254	434	130	342	79	1184	529	411	2.3	13.1	3983	1716	1233	371
Poland	1003	348	104	274	63	947	386	329	1.9	10.4	3187	1373	986	297
Portugal	770	267	80	210	48	727	296	252	1.4	8	2445	1053	757	228
Romania	710	246	74	194	44	670	273	233	1.3	7.4	2254	971	698	210
Slovakia	790	274	82	216	50	746	304	259	1.5	8.3	2511	1082	777	234
Slovenia	1223	424	127	334	77	1155	471	401	2.3	12.8	3886	1674	1203	362
Spain	1078	374	112	294	68	1018	415	353	2	11.3	3426	1476	1060	319
Sweden	2052	711	213	560	129	1937	790	673	3.8	21.4	6518	2808	2017	607

Table 7
Average envelope costs per Member State (Source: [21]).

NZEB Technology costs	Average Envelope costs (€/m^2)				
	Roof (15–25 cm thickness)	External wall (15–25 cm thickness)	Basement (15–25 cm thickness)	Double glazing	Triple glazing
Austria	118	118	56	439	581
Belgium	105	104	49	389	515
Bulgaria	57	57	27	212	281
Croatia	65	64	30	240	317
Cyprus	71	70	33	263	348
Czech Republic	72	71	34	266	352
Denmark	171	170	80	633	838
Estonia	70	69	33	258	342
Finland	134	133	63	497	658
France	122	121	57	453	599
Germany	113	113	53	421	557
Greece	74	74	35	276	367
Hungary	62	62	29	232	307
Ireland	93	93	44	345	457
Italy	110	109	52	408	540
Latvia	68	68	32	252	334
Lithuania	69	69	32	256	339
Luxemburg	115	115	54	428	556
Malta	93	93	44	347	459
Netherlands	96	96	45	357	473
Poland	77	77	36	286	378
Portugal	59	59	28	219	290
Romania	54	54	26	202	268
Slovakia	61	60	29	225	298
Slovenia	94	94	44	349	461
Spain	83	82	39	307	407
Sweden	157	157	74	585	774

Table 8
Cost reduction potential range for the main heating technologies and renewables, towards 2030 and 2050 (Source: [21]).

Technology	Potential range until 2030 (%)	Potential range until 2050 (%)
PV	20.0–29.0	41.0–55.5
Solar thermal	9.1–23.9	22.0–50.8
Gas boiler	4.1–9.2	4.9–11.1
Oil boiler	0.3–0.7	0.8–1.9
Biomass boiler	7.2–13.4	9.6–17.8
Aerothermal HP	4.8–21.6	11.0–43.9
Ground source HP	5.9–25.8	7.9–33.4
Thermal storage	9.5–26.9	15.7–41.4
Electrical storage	34.9–62.7	47.9–77.7
Air conditioner	9.3–25.2	17.8–44.3
Decentralised ventilation	30.3–49.3	40.4–62.2
Centralised Ventilation	24.4–41.0%	34.6–55.1

5. Conclusions

Achieving a decarbonised building stock by 2050 require an effective mobilisation of public and private finance. Estimated additional investment needs to reach EU 2030 energy and climate targets is around 325 billion annually, with approximately EUR 250 billion for residential and EUR 75 billion for public buildings. Similar magnitude of annual investment is needed to reach climate neutrality by 2050 [10]. Renovated and new NZEBs can give an important contribution towards a decarbonized building stock helping the reduction of energy consumption in buildings to reach future climate and energy targets. According to the last assessment, different aspects in relation to the NZEBs development in Europe can be outlined:

- There is a considerable increase of NZEBs definitions in place: 23[3] Member States have in force a definition, in 2 the definition is under development, in 4 a previously adopted definition is under review. NZEBs definitions adapt to national conditions, with most common choices demand/generation as energy balance, performed over a year at single building level, using on-site renewables. For more 18 Member States, an Energy Class or Energy label equivalent to NZEBs requirements is now defined.
- NZEBs performance levels in most Member States are less demanding than NZEBs benchmark levels provided by the European Commission, apart from 3 (in relation to single family houses) and 8 (in relation to office buildings) Member States. This can be due to different calculation methodologies of energy flows, different accounted boundaries, and accounted climate zones.
- NZEBs performance levels are lower (about −50%) of cost-optimal levels, implying that Member States may refer to the cost-optimal approach to define the NZEB requirements.
- The NZEBs requirements are currently 70% lower than the national minimum energy performance requirements in 2006, showing a consistent trend in increasing energy efficiency and a gradual move towards NZEBs. This was obtained progressively, thanks to at least four legislative steps introduced over the last 15 years.
- National energy policies evolved with technical regulatory measures to define and increase NZEBs. The measures to stimulate the NZEBs diffusion are mainly regulatory, financial and fiscal. Most target the envelope and heating systems. Measures targeting smart metering and control systems can be promoted, favouring a conscious occupant behaviour that can energy performance and thermal comfort. Behavioural and public awareness involving citizen and local authorities may be useful to increase a responsible use of energy.
- NZEBs have a role in alleviating environmental, social, and ethical discrepancies. As testified by specific projects targeting social housing, NZEBs also have the potentiality to tackle and fight energy poverty, especially at retrofit level.
- Quantitative evidence about the NZEBs uptake show how currently the concept has been translated in concrete examples. In summary, almost 1.25 million of buildings were built or renovated to NZEBs (or similar) levels from 2012 to 2016, mostly residential. The share of NZEB in the total construction market has increased during the period 2012–2016 in Europe (from 14% in 2012 to 20% in 2016, in average).
- Most NZEBs implemented technologies are passive (sunshade, natural ventilation and lighting, thermal mass, night cooling), and active (mechanical ventilation with heat recovery, heat pumps or district heating), in combination with efficient lighting and appliances. Most U-values are found between 0.15 and 0.20 W/m^2K (walls), 0.10–0.25 W/m^2K (roofs), 0.9–1.1 (windows).
- For renewables, PV and solar thermal are commonly implemented. Cost projections indicate that PV cost will decrease between 41% and 56% towards 2050, solar thermal between 22% and 51%. PV will probably be the pillar to decarbonise our power supply in next decade. Energy storage will be more and more important in NZEBs. The cost of stationary batteries will drop around 65% in next decades. Specific measures are needed to support this technology.
- Apart from the implementation of smart technologies, smart readiness indicator, digitalization, automation, and the internet of things, the new generation of NZEBs will include electric vehicles charging, economic viability, recovering waste to energy, occupant involvement, comfort, health, consideration of climate change and embodied energy.

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[3] Belgium is considered as one MS here.

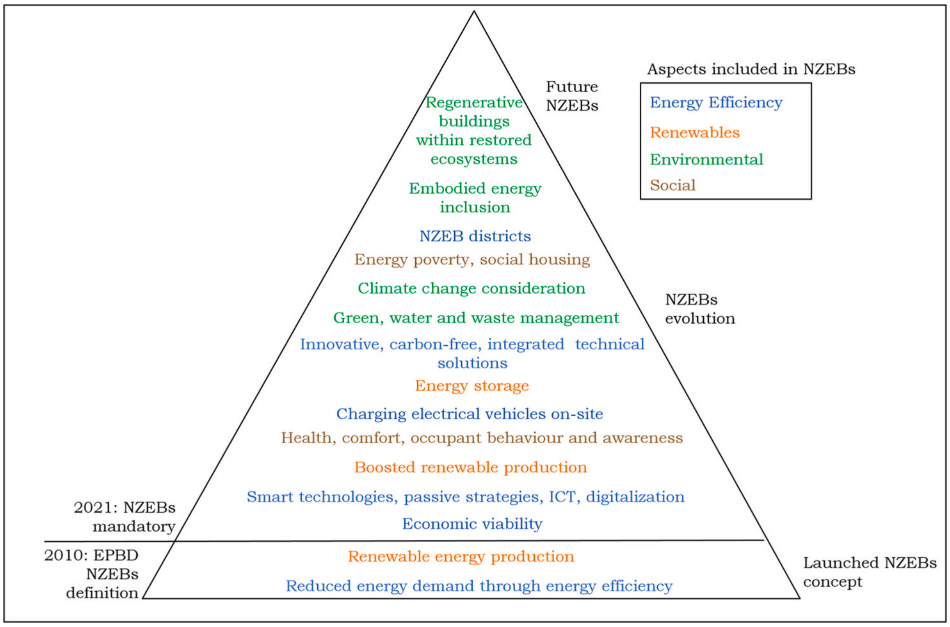

Fig. 12. Evolution of aspects included in the NZEB concept.

Table 9
Barriers and benefits identified for NZEBs retrofit.

Barrier	Description
Financial	Costs of renovation, access to finance, energy price, insufficient attractive financial products, limited use of mechanisms that leverage public capital to attract private investment.
Regulatory	Varying level of NZEB performance requirements and local climatic variations preventing standardised approaches.
Technical	Lack of knowledge of construction industry, costs of technical solutions, limited uptake of energy efficiency, renewable and smart technologies.
Process	Fragmentation of supply chain, burdening of home owners, complex permit procedures.
Awareness	Lack of understanding of building energy use and potential energy savings, poor data on buildings, lack of awareness of the benefits.
Structural	Characteristics of the building sector, small-scale nature of renovation projects which obstruct cost effectiveness, long lifetime of buildings, limited industrialisation, need for engaging with citizens directly or via local or other intermediaries.
Lack of expertise	Lack of provider's expertise, insufficient work force, need of trainings and digital skills.
Information	Insufficient knowledge of the scope of financing programmes and products available, need for intensified technical assistance, capacity building and support to home owners, project promoters, intermediaries and local and national administrations.
Benefit	Description
Environmental	Increase energy savings, decrease GHG emissions, decrease material and fossil use deployment.
Economic	Employment, GDP, innovation, productivity, sectoral modernization, decrease energy bills, increase property value.
Social	Energy security, health, well-being, comfort, decrease energy poverty.

- Future NZEB will be scaled-up and integrated to a district level, shifting the focus from the single building to the district scale (NZED) and to city scale. Also, new technologies are emerging will be part of future NZEBs (such as nanotechnologies, phase change materials, prefabricated modules, 3D printing, ventilated facades with PV panels, electrochromic windows, integrated heating, air conditioning along with electricity, ICT, renewables, smart devices).

Although the diffusion of NZEB retrofit considerably increased over last years, a widespread NZEBs retrofit implementation is still a challenge to be overcome in the light of the need of further boosting renovation (at least doubled). Building refurbishment to NZEBs requires specific innovative tools and incentive mechanisms able to make investment more attractive, beside an appropriate combination of efficient technologies, systems and envelope solutions depending on location, legislation and market conditions. Dedicated planning goals as well as mid- and long-term plans are also useful instruments for upgrading to NZEBs levels. As Member States present a wide range of building types and technologies, climatic, and financial conditions, there is the need for more targeted measures and guidance to stimulate a large-scale NZEBs retrofit diffusion. Coordinated policies to combine energy efficiency and renewable energy use to achieve NZEBs appear essential to be encouraged.

A widespread NZEBs implementation can provide massive benefits. While decreasing greenhouse gas emissions, dependence on energy supply, and energy poverty, NZEBs will increase jobs, energy security, and economic growth in Member States, contributing to overcome the epidemiological crisis we are facing.

Declaration of competing interest

The authors Delia D'Agostino, Sofia Tsemekidi Tzeiranaki, Paolo Zangheri, Paolo Bertoldi declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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List of abbreviations

NZEBs	Nearly zero energy buildings
MS	Member States
RES	Renewable Energy Sources
PED	Primary Energy Demand
EU	European Union
EPBD	Energy Performance of Building Directive
EPC	Energy performance certificate
LTRS	Long term renovation strategy
c-o	Cost-optimal
AT	Austria
BE-BRU	Belgium-Brussels region
BE-FLA	Belgium- Flemish region
BE-WA	Belgium- Wallonia
BG	Bulgaria
CY	Cyprus
CZ	Czech Republic
DE	Germany
DK	Denmark
EE	Estonia
EL	Greece
ES	Spain
FI	Finland
FR	France
HR	Croatia
HU	Hungary
IE	Ireland
IT	Italy
LT	Lithuania
LU	Luxemburg
LV	Latvia
MT	Malta
NL	Netherlands
PL	Poland
PT	Portugal
RO	Romania
SE	Sweden
SI	Slovenia
SK	Slovakia
UK	United Kingdom

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