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1. FROM TRADITIONAL BUILDINGS TO NEARLY ZERO-ENERGY BUILDINGS

1.1. Background of Evaluation in a Building Sector

Climate change is becoming an increasingly serious concern, both in Europe and around the world. The effects of global warming are transforming our environment, increasing the intensity and frequency of extreme weather events. Scientific evidence shows that human-induced global warming has already reached 1°C above preindustrial levels and is increasing at a rate of about 0.2°C per decade. This means, that without accelerated and coordinated international climate action, as well as unprecedented political agreement, the global average temperature could rise by 2°C soon after 2060 (Di Foggia, 2018; EC 2018; Mishra et al. 2021). Nowadays, European Union (EU) policy promotes energy efficiency and renewable energy production in order to achieve climate neutrality of the continent by 2050. Following the European Green Deal (WEB–6), meeting such an ambitious goal requires maximizing energy efficiency and renewable production, especially in the building sector, which is responsible for up to 40% of total energy consumption and 36% of greenhouse emissions, and shows significant potential for reducing energy consumption (D'Agostino et al., 2021; Ionescu et al., 2015; WEB–5). Currently, the key role in this direction play nearly-zero energy buildings (nZEBs), which combine energy efficiency with the deployment of renewables (D'Agostino et al., 2021).

In order to understand new strategies and technologies improving the energy efficiency on the buildings, it is important to know the history of their development. It is also essential to better comprehend the changes made over time to optimize energy consumption and improve thermal comfort (Ionescu et al., 2015).

Beginning in the 1970s and continuing to the present day, European energy policy has evolved, both in terms of scope, ambition and scale. Initially, as a result of the oil crisis, legislation focused mainly on ensuring the security of energy supply in Europe. This was followed by general requirements for construction products (1989) (Council of the European Union, 1989) or boilers (1992) (Council of the European Union, 1992), to create over time a set of comprehensive energy standards and requirements for the energy performance of entire buildings (2002) (European Parliament, Council of the European Union, 2002) and 2010 (European Parliament, Council of the European Union, 2010). The next step was to strengthen these policies to meet climate change commitments under the UNFCCC (United Nations Framework Convention on Climate Change) and to improve the security of energy supply (Economidou et al., 2020). The adoption of more ambitious building standards and boiler requirements, has contributed to a decrease in heating energy consumption (WEB–3).

In the case of the last decade, it can be noticed that along with energy requirements, the concept of buildings has also changed. The shift from prescriptive requirements, such as U-values for building walls, to energy performance requirements enabled the introduction of cost optimization concepts in building codes and the implementation of some important definitions, such as: high performance buildings, zero emission buildings, zero carbon buildings, net zero energy buildings, and near zero energy buildings. Accordingly, nZEB became the new official EU definition (EPDB 2010 recast), which defined how buildings should consume near-zero energy and use renewable energy, adopt cost-optimal technological choices and guarantee a healthy and comfortable environment (Cao et al., 2016; Economidou et al., 2020).

The Energy Performance of Buildings Directive (EPBD) continues to be considered as the centerpiece of EU policy on improving the energy efficiency of buildings. According to it, a "nearly zero energy building" (nZEB) is a building that has very high energy performance and the required nearly zero or very low amount of energy, should be covered to a very significant extent by renewable energy sources (RES), including renewable energy generated on site or nearby (European Parliament, Council of the European Union, 2010). The Directive stipulated, that after 31 December 2020, all new buildings should meet nearly-zero energy buildings' requirements (Cao et al., 2016; Economidou et al., 2020).

As no specific numerical thresholds or ranges are defined in the EPBD, these requirements left room for interpretation and allowed the Member States the flexibility to define near-zero energy buildings, taking into account climatic conditions, ambition levels, primary energy factors, calculation methodologies, as well as country-specific building traditions (WEB–7). Therefore, Member States were required to develop nZEB definitions according to the above factors, as well as the primary energy consumption rate (in kWh/(m^2 year)). Furthermore, they had to implement targeted policies and provide funding to support the transition to nZEB by gradually increasing their number. In doing so, requirements were to be differentiated for different building categories (D'Agostino et al., 2021).

In addition to the financial instruments, policies and strategic measures implemented by approximately 70% of the Member States to facilitate the uptake of energy-efficient houses (European Commission, 2016), the 8th European Framework Programme for Research and Innovation – "Horizon 2020" (WEB–8) was launched by the EU. It promotes smart, sustainable, and inclusive growth in the scientific, industrial, and social sectors and includes several projects that aim to improve the skills and knowledge of designers in the field of construction and work toward the ultimate goal of creating new buildings or renovating existing ones with energy efficiency according to the standards of the nZEB (Magrini et al., 2020).

Observing how national requirements for the energy performance of buildings have evolved during the EPBD period (from 2006 to the beginning of 2021) (López-Ochoa et al., 2021a; López-Ochoa et al., 2021b; Vaquero, 2020), it can be seen that the minimum primary energy demand for buildings called nZEBs has decreased on average by about 67% (Economidou et al., 2020). This shows that significant improvements have been achieved in countries where the EPBD was in force. Important changes have also been observed in the tools and measures used in energy efficiency policy. While it is true that the SAVE Directive covered many thematic areas that are still relevant today, such as metering, billing, energy certificates, financing, etc., it was the legal framework set out in the 2002 EPBD, the 2006 ESD, and the 2012 EED that recommended the implementation of a wide range of policy instruments at the national level. The EPBD required member states to develop complete requirements in their building codes, while introducing information tools such as thermal system inspection programs and energy performance certification schemes, while the Energy Efficiency Directive mandated energy audits in industry, among others, introduced provisions for metering and billing, and urged the creation of energy efficiency funds. Despite some shortcomings, these measures, ranging from regulations and information tools to campaigns and training programs, to financial instruments, still form an important part of all national policy packages today (Economidou et al., 2020).

In addition to individual policy measures, comprehensive policy packages including clearly defined targets have played an extremely important role. Although no specific target has been set for the sector itself so far, looking at the goals for 1995, 2020, 2030 and 2050 (WEB–4), it can be seen that buildings have always played an important role in achieving energy efficiency (Economidou et al., 2020; European Commission, Directorate-General for Energy, 1997).

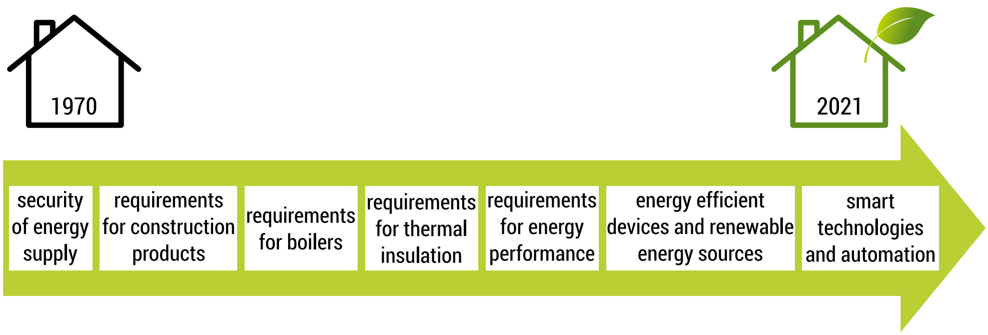

FIG. 1.1. Variability of building energy efficiency requirements over the years (Source: own elaboration)

The introduction of more recent national energy and climate plans through the adoption of the 2018 recast (European Parliament, Council of the European Union, 2018) of the Energy Performance of Building Directive, as well as the regulation “Governance of the Energy Union”, has strengthened the role that energy efficiency must play in the overall efforts to mitigate climate change and achieve the 2030 and 2050 goals, as well as allowing links between different policies, such as renewable energy and decarbonization policies (Economidou et al., 2020; Rosenow et al., 2017).

The aim of all these regulations and legislation in relation to buildings, was to implement solutions that would reduce energy waste and promote the idea of energy efficient houses. Unfortunately, about 35% of the buildings in Europe are still over 50 years old (Boemi et al., 2016).

Energy-efficient buildings, whether they are renovated to improve efficiency or built with energy efficiency in mind, have a significant number of benefits. They are less expensive to operate, more comfortable to live in, and more environmentally friendly. They also help reduce greenhouse gas (GHG) emissions [40] and realize two goals of sustainable development such as saving primary resources and reducing emissions to the environment (Di Foggia, 2018; Ionescu et al., 2015).

Based on many years of observation and research, as well as guidelines set by directives, standards, and regulations in the field of energy efficiency, the most important factors that affect the energy efficiency of buildings have been specified, along with the ways to increase it.

Thus, among the most relevant solutions are the following:

- using adequate insulation thickness of the building envelope, taking into account national and European standards,
- adapting the building to climatic conditions by using adequate building materials,
- removing the thermal bridges and leaks,
- proper orientation of the building,
- purchasing high-quality windows and doors (with low-emission coatings, gas fillings, efficient glazing, and frames made of eco-friendly materials),
- the use of high-efficiency HVAC systems and equipment (heat pumps, radiant ceiling heating/cooling systems, heat recovery ventilation, etc.),
- using high-efficiency lighting systems and full use of natural light,
- rational using of water resource (rain water collection, graywater treatment, water saving appliances),
- using an intelligent control and metering systems,
- using passive solar systems,
- monitoring and verifying performance, in order to inform occupants about their habits and encourage energy conservation measures (D'Agostino et al., 2021; WEB–2; Yi & Bing, 2017).

Also important for energy efficiency is the regulation of indoor temperature and the use of automatic control devices (WEB–2). Reducing the energy consumed for space heating and cooling is highly dependent on improving the performance of the building envelope (Yi & Bing, 2017). The problems of energy efficiency in residential buildings or their impact on the environment were outlined in (Attia et al., 2022; Baniassadi et al., 2022; Dakwale et al., 2011), while the factors that influence it were discussed by Chen (Chen et al., 2020). Figure 1.2 summarizes the most important elements affecting the energy efficiency of the building.

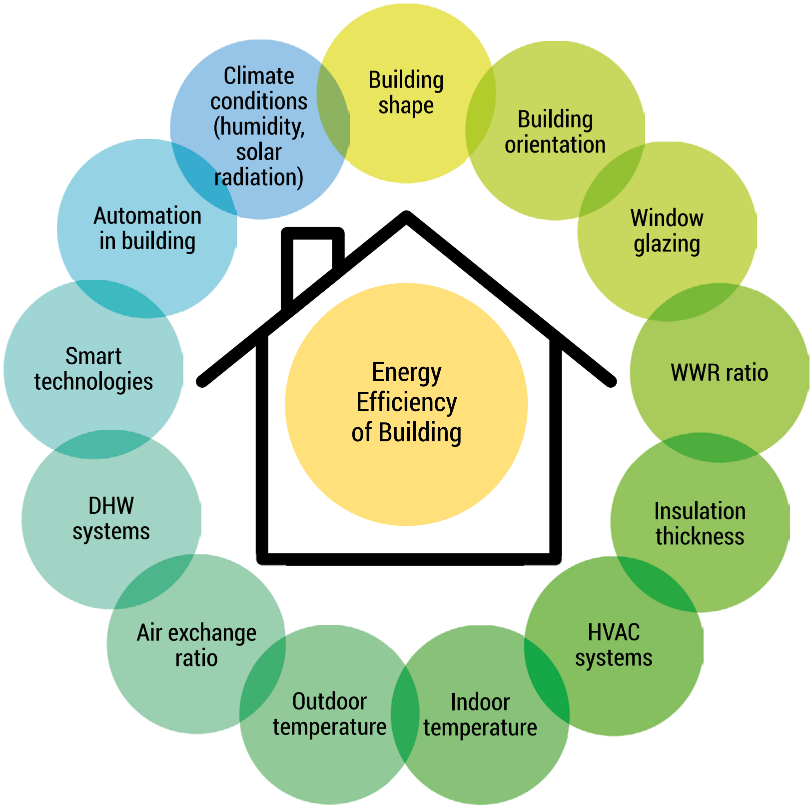

FIG. 1.2. Factors influencing energy efficiency of a building (Source: own elaboration based on Chen et al., 2020)

In the following section I will present details on how building energy efficiency policies, regulations, and laws have changed over the past 50 years, with special regard to the past 20 years, when the changes have been the most intense.

1.2. European Energy Policy

1.2.1. Beginnings

Initially, in the 1970s-80s, as a result of the oil embargo, energy policy emphasized primarily the security of energy supply. In the face of a sudden shortage of fuel, the priority became energy conservation and energy efficiency, which began to emerge as a policy response to the need for energy security, associated with the "security of oil supply". Moreover, the first and most drastic measure introduced in the 70's, relating directly to buildings, was the thermal insulation of their envelope. Next, a concept to focus on another energy sources evolved. Research on natural gas and renewable energy has been intensified (Economidou et al., 2020; WEB–10). In 1974 the European Council adopted a resolution (Council of the European Union, 1974) promoting energy saving which aimed at reducing the rate of energy consumption growth, i.e. reaching a level 15% lower than in 1973 by 1985. In 1980, the European Council implemented an energy intensity target and approved policies that included energy pricing measures. The Council Resolution of 1986, involved new Community targets for 1995 and emphasized the need to implement the "concept of Community solidarity", as well as the search for sustainable environmental and energy solutions, i.e. the use of the best available and economically viable technologies and the improvement of energy efficiency. The Council Resolution represented the first policy initiative of the European Union with the objective of greater energy efficiency in all sectors, as well as the use of various possibilities for saving energy. The Energy Efficiency (EE) target was defined as a minimum 20% improvement in efficiency of "final energy demand" by 1995. In 1987, the Commission published a communication entitled "Toward a Permanent Energy Efficiency Policy for the European Community" offering Member States fourteen energy efficiency measures to help achieve the 1995 target. In 1990, the issue of climate change began to emerge, and that same year the European Council of Environment and Energy Ministers agreed that total CO_2 emissions would stabilize at 1990 levels by the year 2000. According to the first report by the Intergovernmental Panel on Climate Change (IPCC), as well as the resolutions of the Rio Summit in 1992, the mitigation of climate change has become a key element of EU energy policy, along with the competitiveness of energy users and the security of energy supply. The concept of energy performance of buildings has varied considerably within Member States, especially in terms of assumed levels and standards, resulting in political actions at the European level. The first policies on energy efficiency of buildings were: "Construction Products Directive" in 1989, "Boiler Directive" in 1992 and "SAVE Directive" in 1993 (Economidou et al., 2020; Maltby, 2013; Papadopoulos, 2016).

1.2.2. Construction Products Directive

The Construction Products Directive (CPD) aimed at increasing the reliability of information on the performance of construction products used in buildings. It consisted of four main elements, including the CE marking of the products. The requirements introduced by CE marking included "energy conservation and heat retention", but the CPD itself did not explicitly refer to the energy performance of buildings. It merely directed that building structures and their cooling, heating, and ventilation systems be designed and built to ensure "low" energy consumption. The CPD was repealed and then replaced by the Con-struction Products Regulation (CPR 15) (Economidou et al., 2020).

1.2.3. Hot Water Boiler Directive

The first technical appliances to be covered by EU legislation were heating boilers and hot water heaters, specified in the Council Directive of 1978 on the efficiency of heat generators for space heating and the production of domestic hot water.

Due to the very low level of energy efficiency of boilers, in 1992 the Commission presented a legislative initiative on the energy efficiency of these devices. The document was called the Hot Water Boiler Directive (HWBD) and introduced common efficiency requirements for new hot-water boilers fired with liquid or gaseous fuels in all Member States. The directive was applicable to standard boilers, low-temperature boilers, and condensing boilers of 4 to 400 kW (Council of the European Union, 1992 ; Economidou et al., 2020).

A key objective of the HWBD was to use clear and consistent energy labels on boilers in all Member States, to make them easily comparable. A similar directive was adopted in 1996 and introduced efficiency requirements for domestic refrigerators and freezers. Both directives were predecessors to Directive 2005/32/EC that established efficiency requirements for energy-using products (Economidou et al., 2020).

1.2.4. Directive 93/76/EEC of 13 September 1993 to Limit Carbon Dioxide Emissions by Improving Energy Efficiency (SAVE)

The EU's first energy efficiency policy is considered to be the "SAVE" di-rective (Council of the European Union, 1993). Earlier policies, such as the 1976 and 1979 Council Recommendations, contained only policy suggestions for improving the efficiency of electrical devices, heating systems and thermal insulation, while the "SAVE" Directive obliged Member States not only to promote the rational use of energy, but also to develop and implement energy efficiency improvement programmes to reduce carbon dioxide emissions (Economidou et al., 2020).

At the time, EU and national policy makers believed that energy efficiency standards for buildings, expressed mainly as insulation requirements (such as "U" values) should be implemented at the national level. However, to counteract situations where some EU member states had already adopted mandatory building standards with different levels of restriction, whereas several European countries did not have building codes in force, the SAVE Directive required all member states to develop and implement programs to introduce unified regulations for thermal insulation in new buildings (Economidou et al., 2020).

The main building requirements included in the Directive are:

- building certification with a description of the energy performance;
- cost settlement of heating, air-conditioning and hot water needs to be calculated on the basis of actual consumption;
- thermal insulation of buildings;

regular inspection of heating systems with a capacity > 15 kW (Economidou et al., 2020; Sands & Galizzi, 2006).

The implementation of the SAVE Directive has not been as smooth and efficient as hoped, which has not allowed the aforementioned potential to be satisfactorily tapped. This was partly due to the fact that member states did not adopt efficiency requirements or standards in their countries or adopted lax national standards. This, in turn, has provided a rationale for increasing thermal insulation in existing buildings, extending certification or licensing, and installing energy-efficient equipment. The SAVE Directive was partially replaced by the Energy Performance of Buildings Directive in 2002 and the remaining articles were replaced by the Directive on Energy End-Use Efficiency and Energy Services in 2006 (European Parliament, Council of the European Union, 2006).

In 1998 the Commission presented a communication identifying a potential for energy efficiency improvements of 22% by 2010 compared to 1995 (Commission of the European Communities, 1998). The communication em-phasized the need for more action at the European, Member State, and Re-gional level, presented both the successes and failures of the policies, as well as analyzed the barriers to achieving this potential, reviewed the programmes adopted and proposed elements of strategy and priorities to realize it (Commission of the European Communities, 1998; Economidou et al., 2020).

Since 2000, the Commission has published several Energy Efficiency Action Plans, covering future strategies and actions such as new policies or strengthening existing measures.

Following the adoption of the Kyoto Protocol in 1997, the EU committed itself to a binding target of an 8% reduction in greenhouse gas (GHG) emissions between 2008 and 2012 compared to 1990 (European Parliament, Council of the European Union, 2006; Poulopoulos, 2016). This became the driving force for the implementation of stronger climate and energy policies. The Kyoto agreement on reducing greenhouse gas emissions reiterated the need to engage and promote energy efficiency in an even more proactive way. The 2000 Action Plan proposed several intensified actions, building on the provisions of the SAVE Directive. While recommending a more coordinated approach, it emphasized the freedom of Member States to set their own efficiency requirements. However, this Action Plan served as a key stimulus, shaping the policy cycle that led to EPBD in 2002 (Economidou et al., 2020).

1.2.5. Energy Performance of Buildings Directive

The Energy Performance of Buildings Directive (EPBD) implemented in 2002, was the first coherent European legislation on energy policy in buildings. This document, aimed at taping into the sector's high potential for cost-effective savings (specifically 22% over a 10-year period). The EPBD policy framework provided the background for, among other things, setting the minimum energy performance standards in the new or existing but renovated buildings (Economidou et al., 2020).

The assumption of minimum requirements for the energy performance of buildings, represented a major step forward. Under the provisions of the EPBD, the energy performance of a building was to be defined as the amount of energy calculated or consumed (monitored), usually measured in kWh/m^2, reflected in one or more numerical indicators, taking into account the following:

- external and internal climatic conditions;
- the orientation and location of the building;
- the thermal characteristics of the building envelope;
- the presence of passive solar systems and solar protection;
- the presence of natural ventilation and passive strategies;
- type of heating, domestic hot water, ventilation or cooling systems;
- type of lighting installations (especially for the nonresidential sector);
- energy generation for our own use (Economidou et al., 2020; European Parliament, Council of the European Union, 2002).

Furthermore, another important point in EPBD was the regular inspection and performance evaluation of boilers and air conditioning systems, both to ensure safety and to reduce energy consumption. According to the Directive, boilers with a rated output of more than 10 kW should be regularly inspected to improve their operating conditions. Similar measures had to be implemented for the first time also for cooling systems, in particular in larger service buildings (Economidou et al., 2020; European Parliament, Council of the European Union, 2002).

In 2006, the European Commission published the second Energy Efficiency Action Plan. Its contents included reducing and controlling energy needs and taking action to effectively save 20% of annual primary energy consumption by 2020, compared to baseline consumption forecasts. This meant achieving around 1.5% savings per year by 2020. The measures and policies in the 2006 Action Plan were developed on consultations initiated by the 2005 Green Paper on Energy Efficiency, which emphasized the need to build up the EU energy efficiency policy (Economidou et al., 2020).

The plan defines an energy savings potential of 27% compared to existing energy consumption in residential buildings and 30% in commercial buildings. It proposes an overall energy savings target of 20% to be achieved by 2020 through the development of existing policies and the use of new measures. The plan addresses the issue of lowering the EPBD threshold for mandatory energy efficiency improvements in existing buildings and mandating very low energy levels for new buildings. This resulted in a revision of the EPBD in 2010 (Economidou et al., 2020).

Following the 2006 Action Plan, in March 2007, the EU committed itself to becoming a highly energy-efficient part of continent with a low-carbon economy (Economidou et al., 2020). According to the 2007 Directive, objectives known as the ‘20-20-20’ targets, should be achieved by 2020, such as:

- 20% reduction in GHG emissions compared to 1990 levels;
- an increase in the share of energy from renewable energy sources to 20%;
- improving energy efficiency leading to 20% primary energy savings in the EU (D'Agostino & Mazzarella, 2019; Economidou et al., 2020; Ionescu et al., 2015).

In 2009, the European Commission presented a recast of the EPBD (in force from 2010) to improve some of the original regulations and achieve additional energy savings in line with the 2006 Action Plan. The main objective of the recast was to ensure that the national minimum energy performance requirements adopted by Member States had a similar level of restriction in terms of GHG reductions and energy savings. This was due to insufficiently ambitious and cost-effective standards adopted by some countries.

The Directive's therefore distinguished a cost-optimal methodology as a guiding principle for setting energy requirements for buildings. It also introduced the concept of "nearly zero energy buildings" (nZEBs), under which all new private buildings will have to meet nationally defined nZEB standards by January 2021.

Furthermore, the directive required all EU countries to specify how thermal bridges will be taken into account in the energy performance of a building, as well as introduced energy performance requirements for technical building systems (heating, domestic hot water, ventilation, cooling, and air condition-ing). The Energy Performance Certification (EPC) and inspection provisions for heating and air-conditioning systems have been strengthened especially to increase their effectiveness (Economidou et al., 2020; Papadopoulos, 2016).

In 2011, the new Commission presented a roadmap for achieving a low-carbon economy by 2050, which outlined far-reaching new energy and environmental targets. The target is to reduce greenhouse gas emissions by 40% by 2030, by 60% by 2040 and ultimately by 80-95% by 2050, compared to the 1990 levels.

In 2014, the EU implemented energy and climate targets for 2030. They also assumed a minimum of 27% share of energy from renewable energy sources (RES) and 27% energy savings. In 2018, as a result of discussions to establish the legal basis for the targets, they were modified in terms of RES to 32%, as well as energy savings to 32.5% (Economidou et al., 2020).

In February 2015, the Energy Union Strategy was adopted, namely "The Energy Union Package: A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy". The strategy emphasized the need to promote and provide greater support for secure, sustainable, competitive and affordable energy, focusing on five core issues.

1. security and solidarity;
2. a fully integrated internal energy market;
3. energy efficiency;
4. climate action, decarbonization of the economy;
5. research, innovation and competitiveness.

In order to implement the Energy Union Strategy and align the EED and EPBD with the new 2030 climate and energy targets, in 2016, the European Commission adopted a package of measures, the so-called "Winter Package". In proposing amendments to the EPBD as part of the "Winter Package", the Commission sought to simplify existing legislation and ensure consistency with other policy areas (i.e. the EED). The proposed changes addressed long-term renovation strategies, a vision for decarbonizing buildings by 2050, the introduction of a building intelligence indicator, and the mobilization of financial resources (Economidou et al., 2020).

In mid-2018, a new EPBD was published. The amendment implemented changes to accelerate cost-effective renovation of existing buildings, with the aim of decarbonizing the building stock by 2050, as well as strengthening smart technologies and systems and automation in buildings (including building controls and indoor temperature control devices) by implementing an assessment of buildings for their smart grid readiness capabilities (Witczak, 2018). An important point was also to increase the promotion of health and well-being of building occupants by paying more attention to air quality and ventilation systems.

On December 15, 2021, the European Commission published a proposal for substantial revisions (recast) to the Energy Performance of Buildings Directive (EPBD), as part of the "Fit for 55" package. The document consists of several legislative proposals aimed at meeting the EU's new goal of reducing green-house gas (GHG) emissions by a minimum of 55% by 2030 compared to 1990. The proposed changes will include the introduction of new energy per-formance standards for buildings, changes to the definitions of energy per-formance standards, changes to national building renovation plans, and new requirements for calculating emissions throughout the life cycle of new build-ings. There are also to be revised definitions of terms such as: "Zero-emission building", "Nearly-zero energy building", and "Deep renovation" (WEB–14, WEB–15).

New buildings will have to be zero-emission by 2030 (2027 for public build-ings), and the life cycle global warming potential (GWP) will be calculated for new large buildings starting in 2027, and for all new buildings by 2030. The calculations will take into account carbon emissions from the entire life cycle of a building - from production and construction, through use and decommis-sioning. Other regulations will introduce, among other things, building renova-tion passports and a smart readiness indicator, as well as will end all financial support for fossil fuel boilers, and promote building control or automation systems. The EPBD recast aims to accelerate the pace of building renovation, reduce energy consumption and greenhouse gas emissions, and promote the use of renewable energy (WEB–14, WEB–15).

1.2.6. Energy Efficiency Directive

At the end of 2012, the Energy Efficiency Directive (EED) (European Parliament, Council of the European Union, 2012; WEB–4) was adopted as part of the European energy and climate package. It set a target of a 20% reduction in primary and final energy consumption levels by 2020 and required member states to set their own energy efficiency challenges, as well as develop building energy efficiency strategies and implement energy efficiency obligation systems. In addition, Article 7. of the Directive required an annual reduction in the final energy consumption of 1.5% (Economidou et al., 2020; Rosenow, 2017). To provide a legal framework for the 2030 energy efficiency targets, the EED was updated in 2018.

One of the goals set out in the updated directive was the need to achieve an energy efficiency of 32.5% by 2030. It also stressed that strategies must facilitate the cost-effective transformation of existing buildings into nearly-zero energy buildings (Economidou et al., 2020).

Figure 1.3 shows the level of primary energy consumption in Europe, with reference to the targets set for 2020 and 2030, as an example of the effects of achieving the goals set by the directive.

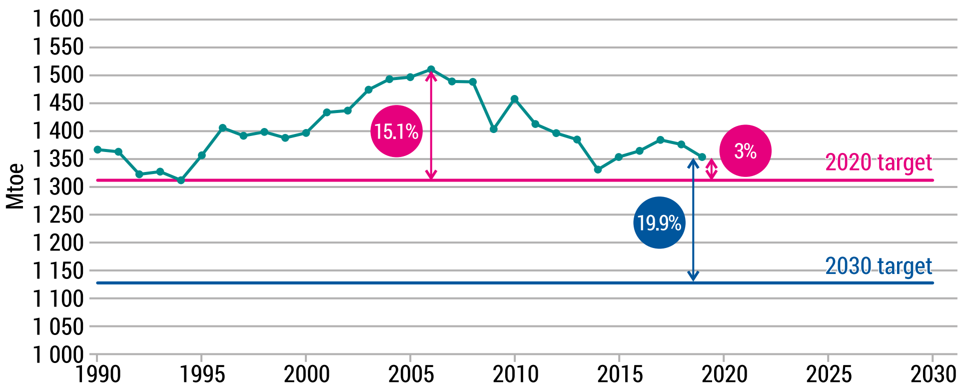

FIG. 1.3. Primary energy consumption in the EU, distance to 2020 and 2030 targets (Source: WEB–9)

To promote energy savings through behavioral change, the EED introduced a mandatory requirement for consumption-based billing for heating, cooling, and domestic hot water in multifamily buildings equipped with collective heating/cooling systems. The implementation of this legislation was intended to provide energy users with feedback on their consumption, which, in turn, was expected to reduce final energy consumption by up to 10% on average (Economidou et al., 2020).

Actions to limit global warming have been accelerated in recent years, and United Nations Climate Change Conferences (COPs) are considered the latest major milestones in global climate change debates (Economidou et al., 2020).

At the recent COP26 summit of world leaders, a new global agreement was reached – the Glasgow Climate Pact, whose main findings include reducing the use of coal (which accounts for 40% of annual CO_2 emissions), moving away from fossil fuels, limiting methane emissions by 30% by 2030 (compared to 2020), as well as the need to increase funding to help poor countries cope with the effects of climate change and switch to clean energy (WEB–1; WEB–11).

The development of energy efficiency requirements and policy instruments has also been discussed in (Geller et al., 2006; Reuter et al.; 2021; Shen et al., 2016).

As can be seen, none of the above-described European legal acts specified unambiguously precise and uniform requirements for all Member States regarding the internal systems or installations in buildings, as well as their structure (thickness of insulation, materials used). This happened and still happens because the energy efficiency of a building is influenced by various factors, depending among others on the location and climatic or social conditions of the country. The evolution of buildings over the years has been driven by the challenges of increasing energy efficiency or reducing atmospheric emissions, which in themselves have become the driving force for European countries to implement their own individual regulations tailored to the characteristics and possibilities of each country, in order to achieve their objectives. It is appropriate to apply the phrase that in the case of the development of energy-efficient buildings, "necessity is the mother of invention".

However, with increasing demands on energy efficiency and in parallel with rising indoor environmental quality standards, the building envelope has come to play a more important role in climate regulations. As a result, numerous requirements have been placed on them 2 The Figure 1.4 shows the variation of requirements concerning the heat transfer coefficient "U" of selected building partitions between 1983-2021, on the example of Poland.

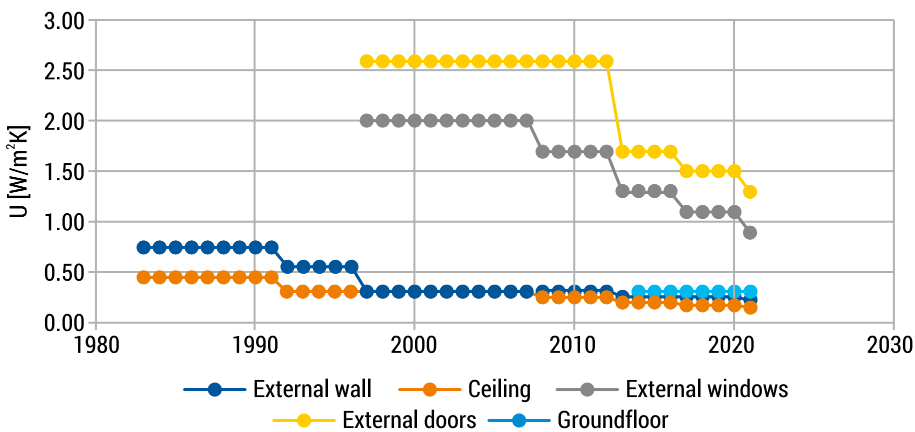

FIG. 1.4. Variability of heat transfer coefficient "U" requirements between 1983-2021 (Source: own elaboration based on Tatara et al., 2017)

It can be seen that in almost 30 years, the heat transfer coefficient requirements for external walls for new buildings have changed by as much as 73%, while for roofs and flat roofs – by about 67%, what indicates considerable progress.

1.3. Evolution of Buildings

The first energy efficiency regulations for buildings were not really aimed at reducing energy demand, but at providing adequate heating conditions. This was done by promoting the use of traditional architectural features that helped increase the thermal resistance of the envelope, such as a layer of air in the cavity of a double brick wall or in a two-layer wood floor (Papadopoulos, 2016).

The need to improve the energy efficiency of buildings emerged as a consequence of the oil crisis in the 1970s and was primarily expressed in the desire to reduce the energy demand of HVAC systems while improving indoor environmental performance. It has been a long way from those days to the zero or near-zero energy buildings required today. However, significant technological developments in buildings have been achieved through intensive, systematic deepening of interdisciplinary theoretical knowledge and regulatory frameworks such as directives and European standards (Papadopoulos, 2016). Successive and ever more stringent regulations have driven the development of efficient insulation materials and intelligent airtight buildings.

For many years, the greatest environmental importance was attributed to the building operation phase, as the longest period in its life cycle [3]. Therefore, people became more concerned with super-insulation, tightness of the building envelope, heat recovery from ventilation, the use of triple-glazed windows and passive technologies that relied on solar thermal energy. Definitions of "self-sufficient houses", "autonomous houses" and "green houses" were developed (Ionescu et al., 2015; Papadopoulos, 2016).

After the crisis, when the environmental consequences of the other phases of building began to grow (reduced reserves of raw materials, difficulties in managing and disposing of construction waste), a holistic approach was adopted, taking into account the impact of all stages of a building's "life". The building sector adopted the sustainability goals, as an innovative concept in structures, that began to be considered when defining new design strategies, creating new definition of "sustainable buildings" (Cao et al., 2016; Ionescu et al., 2015).

In 1974, research on the effect of air exchange on heat loss in buildings began. The concept of the "zero-energy house," which is very popular today, also emerged at that time (Ionescu et al., 2015).

With the dynamic development of technology in the building industry, the first "intelligent building" was developed in the early 1980s. During this time, Wolfgang Feist promoted the idea of the "Low Energy House" and, at the end of the 1980s, developed the concept of the "Passive House", combining all relevant design theories or algorithms. The first passive house was built in 1991 in Darmstadt (Germany) (Ionescu et al., 2015).

In 1992, the first autonomous energy house was developed, which was able to meet its own energy needs thanks to excellent insulation and solar energy technology (Ionescu et al., 2015).

In 1994, the first positive energy house designed by Rolf Disch and built in Freiburg was commissioned. It was the first house in which the amount of energy produced was greater than the amount consumed. All technologies used in it used only renewable energy (Ionescu et al., 2015).

In 1995, in turn, Wolfgang Feist developed the passive house standard on the basis of the experience gained. This was an important step in the evolution of buildings, as the idea of Passive Houses is popular up to the present day (Martinez-de-Alegria et al., 2021) and as shown in (Di Foggia, 2018) in the residential sector, currently the incremental costs of achieving Passive House standards range from 6% to 16% of the cost compared to standard constructions'.

Recent technological advances that affect the development of building techniques allow easy integration of energy-efficient ideas into building design, providing improvements in comfort, utility, energy efficiency, and even aesthetics. Environmental evaluation and analysis efforts also have been intensified. However, it must be remembered that 40 years after the first thermal insulation requirements were introduced and more than ten years after the first Energy Performance of Buildings Directive was established, thermal loads still account for almost two-thirds of building loads. Consequently, reducing them further is becoming an increasingly difficult task and requires increasingly advanced building materials and techniques, but also a more ambitious, integrated regulatory approach (Papadopoulos, 2016).

In recent decades, researchers in the field of low-energy house design are continually focused on creative solutions and thermal design principles, as well as ways to overcome barriers that prevent energy efficiency gains in buildings (Ionescu et al., 2015).

1.4. Energy Indicators of the nZEB

As mentioned, the concept of the nZEB is defined in the Directive EPBD 2010/31/UE as a building that has very high energy performance and in which the required nearly zero or very low amount of energy, should be covered to a very significant extent by renewable energy sources (RES) produced on-site or nearby. This concept must be differenced from other stricter concepts related to efficient buildings:

- Net Zero Energy Building (NZEB), where the energy consumed in the building is equal to the energy produced on-site;
- Positive Energy Building, that produces more energy than consumed;
- Net Zero Carbon Building (NZCB), when the amount of carbon emis-sion associated with the building operation during one year is zero

Nowadays, with the present technology, all the above criteria are not economically profitable. So, the EU has decided to set the nZEB concept in its Directives and recommendations.

The EU required from the Member States (MS) to stablish their nZEB requirements in their national regulations based on different factors: climate, heating system used, the building geometry, etc. It follows, therefore, that there is no common criterion and each state defines its own requirements.

In 2016, the Recommendations EU 2016/1318 considered 4 climatic zones (Mediterranean, Oceanic, Continental, and Nordic) and published the reference values for the primary energy consumption of the resident and non-residential buildings (Table 1.1) (European Commission, 2016). This means that the percentage of renewable energy ranges between 32 and 87%, depend-ing on the climatic zone.

TABLE 1.1. EU recommendations of the Primary Energy Consumptions [kWh/(m^2 year)] (Source: own elaboration based on European Commission, 2016)

	Residence Building			Offices		
	Total Primary Energy [kWh/(m^2 year)]	**Renewable Energy Source [kWh/(m^2 year)]**	**Net Primary Energy [kWh/(m^2 year)]**	**Total Primary Energy [kWh/(m^2 year)]**	**Renewable Energy Source [kWh/(m^2 year)]**	**Net Primary Energy [kWh/(m^2 year)]**
Medi-terranean	50-65	50	0-15	80-90	60	20-30
Oceanic	50-65	35	15-30	85-100	45	40-55
Con-tinental	50-70	30	20-40	85-100	45	40-55
Nordic	65-90	25	40-65	85-100	30	55-70

Recently, the European Commission published a draft of the revision of the Energy Performance of Building Directive to be approved in 2022 (European Commission, 2021). This revision is more oriented towards the Zero Emission Building than the current regulation. The new values of the proposed total primary energy use are given in Table 1.2. To avoid carbon emissions from fossil fuels, this energy should be fully covered, in an annual balance, by:

- renewable energy generated on-site;
- renewable energy provided from a renewable energy community;
- renewable or waste energy from an efficient district heating and cooling system.

Only in exceptional cases established at the national level may the primary energy consumption also be covered from the grid.

Table 1.3 presents the values used in some MS regulations for building energy performance (BPIE, 2021). Not all states consider the kWh/(m^2 year) in their regulations. This table shows the wide disparity in the way the EU directive about nZEB is implemented.

TABLE 1.2. Proposal Primary Energy Consumptions [kWh/(m^2 year)] in the draft of the new EU directive about the energy performance of building (Source: own elaboration based on European Commission, 2021)

EU Climatic Zone	Residence Building [kWh/(m^2 year)]	Offices	Other non-residential build-ing
Mediterranean	< 60	< 70	< NZEB requirements at national level
Oceanic	< 60	< 85	< NZEB requirements at national level
Continental	< 65	< 85	< NZEB requirements at national level
Nordic	< 75	< 90	< NZEB requirements at national level

TABLE 1.3. Total Primary Energy requirements [kWh/(m^2 year)] in the regulations of some EU Member States (Source: own elaboration based on data of BPIE, 2021)

	Residental Building [kWh/(m^2 year)]	Offices [kWh/(m^2 year)]
Denmark	27	33
Croatia	40	30
Ireland	42	66
France	50	50
Netherlands	50	40
Greece	53	125
Slovakia	54	61
Lithuania	60	80
Belgium	63	93
Spain	63	143
Poland	70	45
Sweden	70	50
Malta	73	290
Estonia	74	62
Slovenia	75	51
Bulgaria	95	140
Latvia	95	110
Cyprus	100	125
Hungary	100	90
Czechia	130	130
Finland	131	100
Romania	158	67

– More demand than EU recommendation

– Less demand than EU recommendation

The REHVA (Federation of European heating, Ventilation and Air Conditioning association) worked for a uniformed implementation of EPBD recast (Kurnitski, 2013). This common definition was based on the imported and exported primary energy according to EPBD recast and prEN 15603:2013. In these regulations, the Non-renewable Primary Energy ($E_{P,nRE}$) is defined as summatory for all energy types:

$$E_{P,nRE} = \Sigma_i (E_{i,imp} f_{i,imp.nRE} - E_{i,exp} f_{i,exp.nRE}) \quad (1.1)$$

where $E_{i,imp}$ and $E_{i,exp}$ are the annual imported and exported energies of type i on site or nearby, respectively, and $f_{i,imp.nRE}$ and $f_{i,exp.nRE}$ are the non-renewable imported and exported energy (type i) factors on site or nearby, respectively. If the national regulations do not define them otherwise, these factors can be considered similar.

The Energy Primary Indicator can be calculated by Eq. 1.1 and the useful floor area A_{net}, according to national definitions:

$$EP_p = \frac{E_{P,nRE}}{A_{net}} \quad (1.2)$$

This indicator uses the concept of *Primary Energy*, that can be defined as the energy that has not been subjected to any transformation. Subsequently, this energy must be managed by different energy chains before it is delivered to the building in the form of electricity, gas, heat (conversion, transport, etc.). These processes require additional energy consumption. The energy primary factor is the conversion factor that relates the delivery energy to the required primary energy.

The values of Primary Energy Factor are collected in the national standards of each Member State (MS). These values can vary from one standard to another because the transformation and transportation processes can be different in each country and different conventions can also be used for the estimation of these factors. Table 1.4 shows the range of values of the Primary Energy Factors of the EU states' standards (Hitchin, 2019).

TABLE 1.4. Range of the Primary Energy Factors in the EU states (Source: own elaboration based on data of Hitchin, 2019)

	Coal	Gas	Oil	Wood	Biomass	Grid Electricity	District heating
PEFs' range in EU states	1.00-1.46	1.00-1.26	1.00-1.23	0.01-1.26	0.01-1.12	1.50-3.45	0.15-1.50

Also, the EU calls for distinguishing between renewable and non-renewable energy with regard to energy consumption in buildings (see Eq. 1.2). So, PEFs for total and non-renewable factors are defined in the national standards.

Other indicator, that indicates the percentage of renewable energy shared, is the Renewable Energy Ratio (RER), that is the ratio of the net renewable energy consumed in the building to the total used energy. Using the energy flows shown in Fig 1.5, this indicator is defined by (Kurnitski, 2013):

$$RER = \frac{\Sigma_i [E_{i,RE} + (f_{i,imp.tot} - f_{i,imp.nRE})\, E_{i,imp}]}{\Sigma_i [E_{i,RE} + f_{i,imp.tot}\, E_{i,imp} - f_{i,exp.tot}\, E_{i,exp}]} \tag{1.3}$$

where $E_{i,RE}$ is the renewable energy of type i produced on site or nearby and $f_{i,imp,tot}$ and $f_{i,exp,tot}$ are the total primary energy factors for the imported and exported energy, respectively.

The definitions of Eqs. 1.1. and 1.3 include the concepts of 'on site' and 'nearby' to consider the possibility of energy production, for example an energy plant, near and linked to the building. Figure 1.5 shows an example of the energy flows considered in Eqs. 1.1 and 1.3).

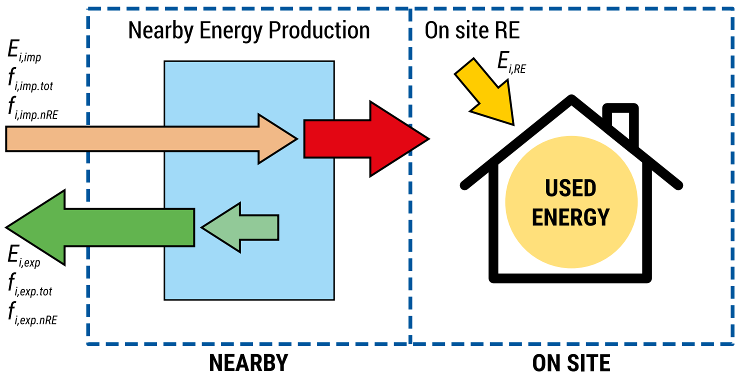

FIG. 1.5. Example of the energy flows of the equations 1.1 and 1.2 (Source: own elaboration)

Not all the countries have a requirement for renewable energy to contribute to the total primary energy demand. Table 1.5 shows the minimum renewable requirements in the countries that have implemented this condition.

TABLE 1.5. Minimum percentage of renewable energy in the regulations of some Member States of EU (Source: own elaboration based on data of BPIE, 2021)

Country	Minimum percentage of renewable energy [%]
Ireland	20
France	20-30
Hungary	25
Croatia	30

Country	Minimum percentage of renewable energy [%]
Netherlands	30-40
Lithuania	50
Portugal	50
Bulgaria	55
Austria	80% heating or hot water or 20% electricity from PV
Germany	15% solar energy (PV or solar thermal) 50% (geothermal, biomass and/or waste heat)
Portugal	50
Spain	60%–70% Domestic Hot Water DHW

1.5. Solutions of nZEBs

A proper design is crucial to reach the nZEB requirements. This design is based on a triple strategy:

- Passive solutions, oriented to reduce the energy demand of the building by architecture design. These solutions must be considered the priority in this design;
- Active solutions with the use of more efficient systems;
- The use of renewable systems meet most of the building's demand.

A priority scheme of these solutions in the design is shown in Figure 1.6.

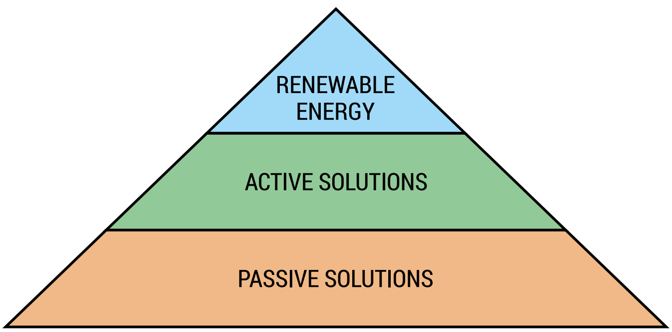

FIG. 1.6. Scheme of the triple strategy to nZEB design (Source: own elaboration)

A more detailed descriptions of these three solutions is given in this section.

Passive Solutions:
These types of solutions can reduce the heating and cooling energy consumption by about 90% compared to a conventional building. Some factors considered in this strategy are:

1. **Optimization of thermal insulation** of the building, with the selection of efficient material for wall, roof, etc.

2. **Selection of windows with high quality glazing.** Typically, these are tripple glazed windows. Also, the orientation of widows can have a positive effect. South-facing windows receive more direct radiation. Additionally, a canopy over the window pre-vents from overheating in hot season.
3. **Reduction of thermal bridges:** The thermal bridges produce the transmission of the heat from a part of the building to another. The reduction of thermal bridges in the building construction allows to reduce unnecessary energy losses.
4. **Natural ventilation** is also a good strategy for cooling in hot climate.

Other modern technologies for passive solutions of nZEBs are also being developed or are in the first stages of implementation. Some researchers are studying the application of nanomaterials, such as aerogels or Vacuum Insula-tion Panels, to improve the thermal insulation of the building with thinner lay-er dimensions. On the other hand, the Phase Change Materials (PCMs) are investigated for these purposes. These materials are paraffins or salts that al-low to store the solar radiation by phase changes from solid to liquid and vice versa. Their use in the external envelope leads to reduction of energy demand.

Special attention is also being paid to improving glazing. The study of "smart" glazing, with dynamic room darkening using different technologies: photo-chromic, thermo-chromatic, electrochromic, etc., allows to increase the win-dows-to-wall ratio (WWR) without reducing the building performance.

ZEBRA2020 project studied the strategies considered in 253 nZEBs in different countries located in three climate zones: Cold, Mild, and Warm climates (ZEBRA2020, 2016). The main characteristic of the passive solutions in these buildings are summarized in Table 1.6.

The stone wool and expanded polystyrene are the materials most commonly used for the walls of the building, which allow for isolation with an average thermal transmittance between 0.11 and 0.16 W/(m^2 K).

Triple glazed windows are used in more than 57% of the nZEB cases studied.

Sunshade, natural ventilation, and thermal mass are other passive systems commonly used.

TABLE 1.6. Most often used passive solutions in a selection of nZEBs (Source: own elaboration based on data of ZEB-RA2020, 2016)

	Cold Climate		Mild Climate		Warm Climate	
	Resident building	Offices	Resident building	Offices	Resident building	Offices
Average $U_{tramit.}$ of walls [W/m^{2}K]	0.18	0.14	0.14	0.14	0.17	0.14

	Cold Climate		Mild Climate		Warm Climate	
	Resident building	Offices	Resident building	Offices	Resident building	Offices
Typical wall material	expanded polystyrene in 27% of the nZBEs.	stone wool in 19% of the nZEBs.	expanded polystyrene in 27% of the nZBEs	stone wool in 28% of the nZEBs	expanded polystyrene in 25% of the nZBEs	stone wool in 19% of the nZEBs
Average $U_{tramit.}$ of roofs [W/m^{2}K]	0.11	0.16	0.13	0.12	0.24	0.15
Typical roof material	stone wool in 19% of the nZEBs.	stone wool in 14% of the nZEBs.	stone wool in 18% of the nZEBs.	expanded polystyrene in 28% of the nZBEs.	Wood fiber in 35% of the nZEBs.	expanded polystyrene in 14% of the nZBEs.
Average $U_{tramit.}$ of windows	0.84	0.85	0.99	0.87	1.16	1.17
Typical windows material	Triple glass in 57% of then ZEBs	Triple glass in 57% of then ZEBs	Triple glass in 57% of then ZEBs	Triple glass for 61% of then ZEBs	Triple glass in 47% of then ZEBs	Triple glass in 29% and doble glass in 29% of then ZEBs
Passive cooling	• sunshade (24%) • natural ventilation (16%) • thermal mass (16%) • night cooling (15%)	• sunshade (18%) • natural ventilation (8%) • evaporative cooling (4%) • night cooling (2%) • thermal mass (2%);	• sunshade (27%) • natural ventilation (23%) • thermal mass (20%)	• sunshade (17%) • night cooling (17%) • natural ventilation (11%) • thermal mass (11%)	• natural ventilation (55%) • sunshade (55%) • night cooling (49%) • thermal mass (47%)	• sunshade (50%) • natural ventilation (43%) • night cooling (36%) • thermal mass (36%)

Active Solutions:
These solutions aim to increase the energy efficiency of the building systems, such as lighting or HAVC systems.

The active energy efficiency solutions include:

- improving the lighting systems with low energy consumption lamp (LED), advanced lighting control (photoelectric cells, presence detec-tor), a daylight design;
- including ventilation systems: fan coils, displacement diffusers;
- increasing the efficiency of heating/cooling systems (HVAC and DWH), such as boilers (gas, biomass...), heat pumps, district heating, etc.;
- using automatic or manual shading devices.

The report ZEBRA2020 presents also the results of the most commonly used active solutions adopted in the studied nZEBs (ZEBRA2020, 2016). The summary of these results is presented in Table 1.7.

The air and water heat pump is the heating and cooling system most common-ly used, followed by district heating and condensing boiler.

For heating of DHW, the system is the same as the HVAC system in 50% of studied cases in the cold zones, the percentage decreases in warmer zones.

TABLE 1.7. Most often used active solutions in a selection of nZEBs (Source: own elaboration based on data of ZEBRA2020, 2016)

	Cold Climate		Mild Climate		Warm Climate	
	Residential building	**Offices**	**Residential building**	**Offices**	**Residential building**	**Offices**
Ventilation systems	Mechanical ventilation with heat recovery in 80% of the nZEBs	Mechanical ventilation with heat recovery in 80 % of the nZEBs	Mechanical ventilation with heat recovery in 86% of the nZEBs	Mechanical ventilation with heat recovery in 78% of the nZEBs	Mechanical ventilation with heat recovery in 90% of the nZEBs	Mechanical ventilation with heat recovery in 90% of the nZEBs
Heating systems	• heat pumps (31%) • district heating (21%) • condensing boiler (17%).	• heat pumps (32%) • district heating (27%) • condensing boiler (11%).	• heat pump (40%) • condensing boiler (20%) • stove (20%).	• heat pump (40%) • boiler (33%).	• heat pumps (57%) • boiler (15%).	• heat pumps (57%) • boiler (14%).
Domestic Hot Water	• 50% of nZEBs is the same system as HVAC	• 31% of nZEBs is the same system as HVAC.	• 40% nZEBs is the same system as HVAC (partly solar ther-mal energy)	• 44% nZEBs has separate system	• 31% nZEBs is the same system as HVAC (partly solar thermal energy)	• 36% of the nZEBs has separate system

	Cold Climate		Mild Climate		Warm Climate	
	Residential building	Offices	Residential building	Offices	Residential building	Offices
Cooling System					• 53% of the nZEBs use cooling systems: • air source heat pump (22%) • soil source heat pump (7%) • water source heat pump (7%)	• 79% of the nZEBs use cooling systems: • air source heat pump (36%) • soil source heat pump (21%) • water source heat pump (14%)

Use of Renewable Energy in nZEBs:

The incorporation of renewable energy in the nZEB designs is mandatory according to the Directive EPBD 2010/31/UE that encourages Member States to increase the RER in the building energy consumption.

The renewable energy solutions that are often used:

- for electricity production: photovoltaic panels integrated or non-integrated in the building, mini-wind turbines, co-generation.
- for thermal energy production (heating/cooling and domestic hot water) systems using solar thermal collectors, solar absorption machine, geothermal energy, biomass.

Table 1.8 shows the summary of the results obtained from the ZEBRA2020 project for the 253 studied nZEBs located in the three climates zones.

TABLE 1.8. Most often used renewable energies in a selection of nZEBs (Source: own elaboration based on data of ZEB-RA2020, 2016)

	Cold Climate		Mild Climate		Warm Climate	
	Residential building	Offices	Residential building	Offices	Residential building	Offices
PV system	Used in 30% of the nZEBs	Used in 27% of the nZEBs	Used in 33% of the nZEBs	Used in 44% of the nZEBs	Used in 55% of the nZEBs	Used in 43% of the nZEBs
Solar thermal system	Used in 31% of the nZEBs	Used in 24% of the nZEBs	Used in 44% of the nZEBs	Used in 22% of the nZEBs	Used in 44% of the nZEBs	Used in 29% of the nZEBs

The most commonly used technologies in nZEBs are PV and solar thermal, with similar percentages. The tendency is to increase the use of these technol-ogies in the climate zones where the solar radiation is higher. In general, the renewable energy is more often used in the residential building than in non-residential ones (offices).

1.6. Example of nZEB

In this section, three of examples of nZEB have been presented to show the strategies used in each case. The selected buildings are located in countries with different climate: cold, mild and warm. Special attention was paid to the performance of these nZEBs with the passive, active and renewable energy solutions selected in their designs. The primary energy indicator and RER are determined, in order to compare with national requirements in each country.

Cold Zone (Sandvika-NORWAY)

The example selected for cold zone is the *Powerhouse Kjørbo*, located in Sandvika (Norway) (Erhorn, 2014). This group of buildings is a retrofitting of four old office buildings adapted to produce energy (positive energy build-ing). The total area of these offices is 5200 m^2. The construction project is divided into in two stages. Nowadays, the first stage (2 buildings) has been completed (see Fig. 1.7).

FIG. 1.7. Photo of the Project *Powerhouse Kjørbo buildings* (Source: photo from 3D-view of Google Map)

Passive Solutions:

The old concrete structure of the walls is preserved, but its insulation properties are renovated. These concrete walls are covered with timber frames to reduce the thermal transmittance U= 0.13 W/(m^2K).

Triple glazing with aluminum frame is used in the windows with a U value equal to 0.80 W/(m^2K).

Natural light is optimized by a better design of the window arrangements.

Active Solutions

The heating, hot water and cooling energy is produced by a geothermal heat pump with the district heating network as an external supply.

A ventilation system with low pressure drop, heat recovery, and displacement diffuser was installed, which allows to increase its cooling efficiency.

Lighting is controlled by automatic system with presence sensor. And the ex-ternal sunscreens are also automated.

Renewable Energy Solutions

Solar PV panels placed in the roof surface (1400 m^2 per building) can produce 41 kWh/(m^2 year) electricity. This amount is enough to cover the electricity demand of building and to sell surplus electricity back to the grid.

As mentioned, geothermal heat pump with 10 wells is also used to supply energy for heating, hot water, and cooling.

The Building Energy Consumption

The electricity consumption of the building is dividing as following:

- lighting by efficient LED with sensors: 7.7 kWh/(m^2 year);
- heating supplied by the geothermal heat pump: 5.9 kWh/(m^2 year);
- ventilation: 2.3 kWh/(m^2 year);
- hot water supplied by the geothermal heat pump: 1.4 kWh/(m^2 year);
- cooling supplied by the geothermal heat pump: 1.3 kWh/(m^2 year);
- other household equipment: 0.8 kWh/(m^2 year).

The total electricity consumption is 19.4 kWh/(m^2 year).

The Energy Sources

The electricity produced by the PV system cover all the energy needs of these office buildings, including the energy necessary to operate the geothermal heat pump. The production capacity of this PV system is 41 kWh/(m^2 year).

Thus, a theoretical surplus electricity of 21.6 kWh/m^2 year can be obtained, which would be sold back to the Grid. Such building can then be considered an Energy-plus building.

An energy balance in the *Powerhouse Kjørbo* is shown in the figures 1.8:

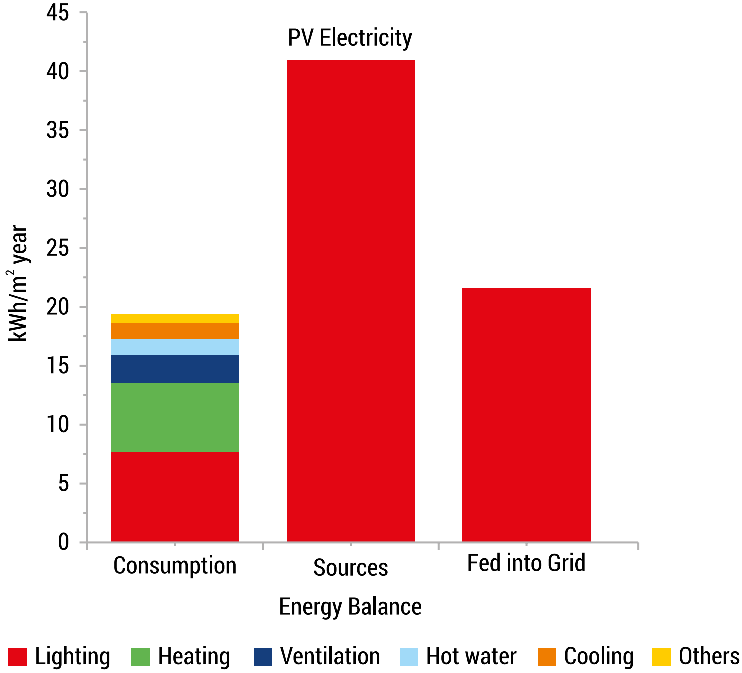

FIG. 1.8. Energy Balance in the *Powerhouse Kjørbo* (Source: own elaboration based on data of Erhorn, 2014)

The nZEB Indicators

The Primary Energy Indicators EP_P for this example can be calculated from Eqs. 1.1 and 1.2, considering the primary energy indicator of the national regulations. In Norway, there are not official values. An estimated value of this factor considering the contribution of renewable energy to the national energy mix is 1.46. Thus, the calculated EP_P is 28.3 kWh/(m^2 year).

Mild Zone (Berlin-GERMAN)

As example of nZEBs in Mild climate zone, *the Efficiency House Plus with E-mobility*, located in the Berlin city near Technical University of Berlin, is pre-sented (see Fig. 1.9). This is a prototype building built in 2011 with the aims to test its performance in real working conditions. It has an area of 150 m^2 and is design for a family of 4. This nZEB is a smart glass building with two floors that generate electricity for its own use and residents' vehicles (Erhorn, 2014; WEB–12).

FIG. 1.9. Photo of the building of the Project Efficiency House Plus with E-mobility in Berlin (Source: photo from https://www.solarwende-berlin.de/allgemein/masterplan-solarcity-berlin/wettbewerb-architektur Free License)

Passive Solutions:

The main envelope material was cellulose insulation. Timber panels 360-420 mm thick were used for the construction of walls, roof and floor. The thermal transmittances of this elements were similar about U=0.11 W/(m^{2}K).

A triple glazing was used for the windows with U=0.7 W/(m^{2}K).

Photovoltaic panels were covering the roof and façade.

The thermal bridges were reduced to avoid heat losses.

Active Solutions

The chosen heating system was an efficient heat pump with air-to-water heat source. The energy was distributed to the rooms by floor heating system.

A mechanical ventilation system with heat recovery of efficiency 80% was installed in the house.

All equipments are controlled by an automated system that monitors and manages its operation on-line.

Renewable Energy Solutions

As mentioned, the roof is cover by 98 m^2 of photovoltaic monocrystalline panels with an efficiency of 15%, and the façade is cover by 73 m^2 of thin-film panels with a efficiency of 12%. The total electricity production can reach 16 MWh that is it enough for the electricity consumption of the building and the electric vehicles.

The PV system is connected to a battery storage tank to store solar energy. A total of 7250 single second-hand car batteries with the capacity of 40 kWh was used to this purpose.

The Building Energy Consumption

All power equipment and systems require electricity. Beneath is a summary of the demand for electricity:

- heating supplied by a heat pump system: 20.8 kWh/(m^2 year);

- hot water supplied by a heat pump system: 8.1 kWh/(m^2 year);
- lighting by LED: 2.5 kWh/(m^2 year);
- ventilation: 15.3 kWh/(m^2 year);
- electrical household equipment: 14.3 kWh/(m^2 year).

Then the total annual energy consumption of the building is 61.1 kWh/(m^2 year). Additionally, the electrical automation can consume up to 19.6 kWh/(m^2 year).

The Energy Sources:
The solar PV panels covering the building is the main source of the energy, but the house is also connected to the grid from which energy is taken during the months when there is no radiation. The balance of the energy supply is as follow:

- Renewable PV energy: 65,6 kWh/(m^2 year). Part of this energy is used by the building itself, 32.3 kWh/(m^2 year), and the rest is fed into grid, 33,3 kWh/(m^2 year).
- Energy taken from the grid: 28.8 kWh/(m^2 year).

The figure 1.10 shows a scheme of the energy balance in this nZEB:

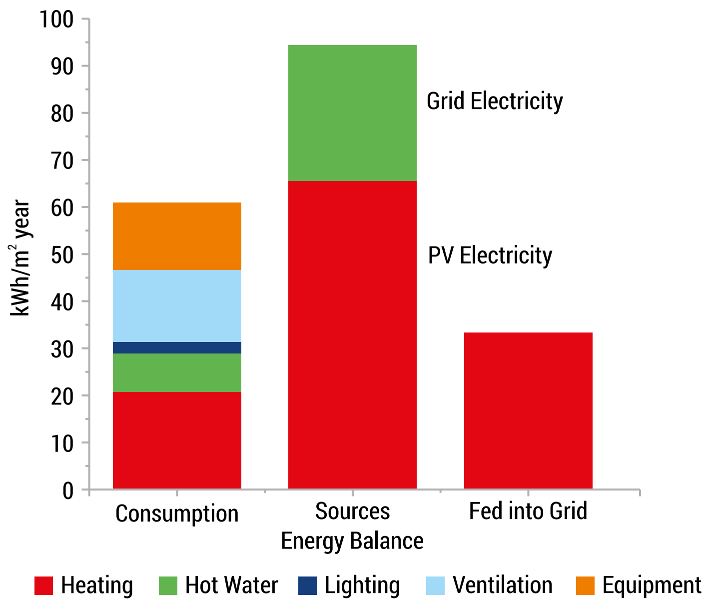

FIG. 1.10. Energy Balance in the Efficiency House Plus with E-mobility building in Berlin (Source: own elaboration based on data of Erhorn, 2014)

The net surplus energy produced by the renewable sources is 4.5 kWh/(m^2 year).

The nZEB Indicators
The Primary Energy Indicator, considering a primary energy factor of 2.5 for electricity, is: -24.1 kWh/(m^2 year).

The Renewable Energy Ratio is 1.07 (107%).

These data indicate that the building has an improvement of 78% above the national requirements.

Warm Zone (Valladolid-SPAIN)

The *LUCIA* building is advanced nZEB which belongs to the University of Valladolid (Rey-Hernández, 2018). With an area of 7500 m^2 (Figs. 1.11 a) and b)), it is used for research purposes, and it houses offices, laboratories, etc. This building has received one of the best ratings in the international rankings for efficient energy. It presents innovative passive and active solutions for the reduction of the energy consumption through the joint use of several different renewable energy sources.

a) b)

FIG. 1.11. Photos of the building of LUCIA in Valladolid (Spain). a) Source: photo by Rey-Hernández, 2018 with CC BY 4.0; b) Source: photo by D.Krawczyk

Passive Solutions:

The building presents different passive solutions that allow for the reduction of energy consumption by 50% compared to a standard building. The first is its orientation with south facing to increase the solar radiation in winter and to reduce it in summer. This effect is enhanced with a zigzag concrete structure in the external façade of the building, that causes a self-shading. Parts of the external wall and roof are also cover by PV panels with translucent glass that causes additional shading.

The walls are plastered with an internal insulation of thermal transmittance: $U = 0.157\ W/(m^2 K)$.

The windows are doble glazing filled with argon gas, $U = 1.2\ W/(m^2 K)$.

The building has also a natural ventilation with geothermal and heat recovery.

Active Solutions

The most innovative improvement of this design is the use of a biomass fueled combined heat and power system (CHP) to produce electricity and heat. The heating system is based on the heat generated by the CHP boiler with a nominal power of 328 kW and efficiency of 0.88. This system works in cooperation with heat recovery with efficiency of 61%.

There are two cooling systems. An absorption cooling system with the power of 176 kW and 232.7 kW conventional air system. A cooling tower located on the roof of the building is used to deliver the heat generated by the absorption system.

A triple ventilation system has been implemented. Free-cooling, heat recovery and earth-air heat exchanger with Canadian wells can work together or independently.

In terms of lighting, this building makes maximum use of the natural light. Big windows and tubular skylight aid the use of this light. For dark conditions, artificial light with efficient LEDs is used, which is controlled by automatic systems with presence detectors.

The control and regulation of the energy consumption of all building systems is another important issue of the building's energy efficiency. A connection protocol ModBus is used to this purpose.

Renewable Energy Solutions

As mentioned, two renewable energy sources are used: Biomass and solar energy.

Biomass is burnt in CHP boiler to produce heat. This heat is used for heating, hot water, and cooling. After a gasification process, the produced gas is com-busted in 5 modified engines to produce electricity, which is used for cooling, ventilation, and lighting.

Additionally, the solar PV panels located in the façade and roof allows to produce additional electricity.

The Building Energy Consumption

In this nZEB, there are two types of energies: thermal energy and electricity. Each of them is used as follows:

1. thermal Energy from the CHP system and heat recovery:
   - heating: 23.10 kWh/(m^2 year),
   - domestic Hot Water: 0.9 kWh/(m^2 year),
   - cooling Absorption: 4.56 kWh/(m^2 year),
2. Electricity from CHP system, PV panels and grid.
   - ventilation 9.2 kWh/(m^2 year),
   - lighting 10.42 kWh/(m^2 year),
   - cooling: 16.29 kWh/(m^2 year),
   - household equipment (Cooling tower, Flow system.): 23.27 kWh/(m^2 year).

Thus, the total annual energy consumption of the house is 28.56 kWh/(m^2 year) of thermal energy and 59.18 kWh/(m^2 year) of electricity.

The Energy Sources:

The thermal energy (heating, hot water and cooling) of LUCIA building is pro-duced by Biomass, 41.65 kWh/(m^2 year).

The electricity comes from the CHP system, the PV panels and the grid:

- heat from the CHP system (Biomass): 21.8 kWh/(m^2 year);
- PV panels: 2.97 kWh/(m^2 year);
- delivered by Grid: 34.4 kWh/(m^2 year).

Figures 1.12 a) and b) summarize the energy consumed by *LUCIA* building and the origin of the energy used to produce heat and electricity, respectively.

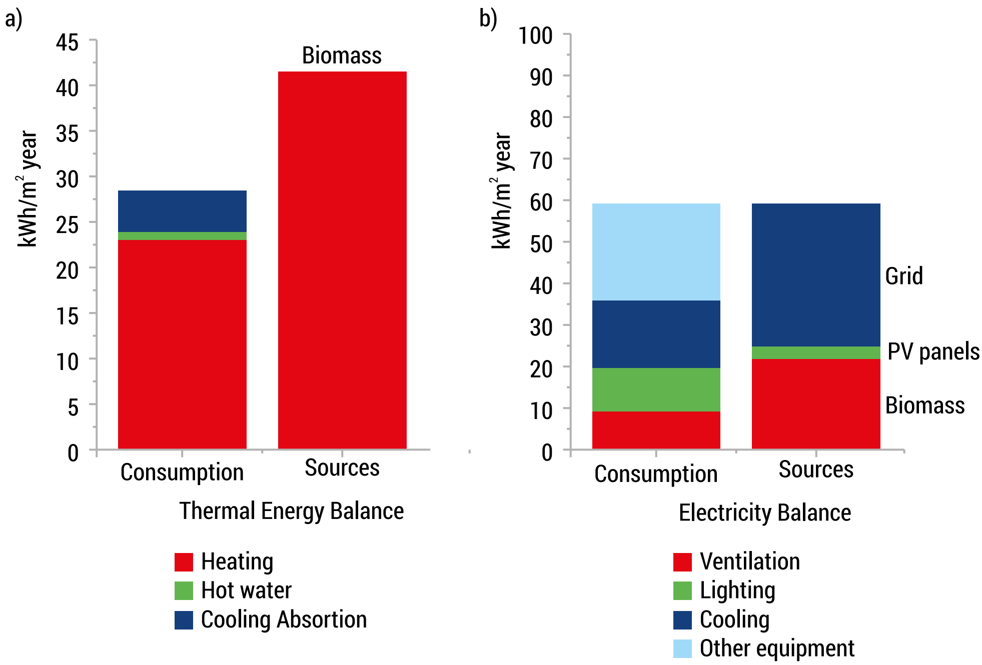

FIG. 1.12. Energy Balance in the LUCIA Building for a) heat and b) electricity (Source: own elaboration based on Rey-Hernández, 2018)

The nZEB Indicators

The Primary Energy Indicator can be calculated from Eqs. 1.1 and 1.2 using the primary energy factors defined in the national spanish regulation that are:

- for electricity from the Grid: $f_{i,nonRE} = 1.954$ and $f_{i,RE} = 0.414$;
- for electricity on-site: $f_{i,nonRE} = 0$ and $f_{i,RE} = 1$;
- for biomass on-site: $f_{i,nonRE} = 0$ and $f_{i,RE} = 1$.

The obtained values is:

$$EP_P = 67.2 \frac{\text{kWh}}{\text{m}^2\text{year}}$$

which is lower than the EU requirement for continental zone that is between 85-100 kWh/(m^2 year).

On the other hand, the renewable energy ratio RER is obtained from Eq. 1.2, with the contribution of the on-site renewable energy and the percentage of the renewable energy of the grid. The RER value for LUCIA building is 0.66 (66%).

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