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The Transition to Integrated Renewable Energy: A Framework for Low Energy Building Design

* Ph.D. Candidate. **Amal KIRATI** [1], Ph.D. Candidate. **Zineb MEDJELDI** [2], Dr. **Assoule DECHAICHA** [3] and Pr. **Djamel ALKAMA** [4]
University 8 Mai 1945, Department of Architecture, Guelma, Algeria [1,2,4]
university of Mohammed boudiaf, urban planning department, M'sila, Algeria [3]
E-mail [1]: kiratiamal@gmail.com , E-mail [2]: zinebmedjeldi1@gmail.com ,
E-mail [3]: assoudech@gmail.com , E-mail [4]: dj.alkama@gmail.com

Abstract
Following the Paris Agreement in 2015, global attention to global warming countermeasures has intensified, as climate change is a major threat to human societies, fundamentally linked to energy consumption and greenhouse gas emissions. Given the huge impact of buildings on energy consumption, changes must take place towards a sustainable energy transition by using renewable energies such as solar energy in order to push buildings to near zero energy consumption. In this context, our work consists of clarifying the nearly zero energy building (NZEB) concept and of reviewing research articles focusing on the use of renewable energy sources (RES) in an efficient way, based on solar energy.
Keywords: Energy Consumption; Greenhouse Gas Emissions; Impact of Buildings; Renewable Energies; Solar Energy; Nearly Zero Energy Building.

1. Introduction

The world's population is expected to consume 50% more energy by 2035 (compared to 1990) due to rapid population growth (Ghosh, 2020). Nearly 50% of the world's population currently lives in cities and by 2030, this number will increase to 80%. The fact that cities are energy intensive, accounting for over 70% of global CO2 emissions (Vassiliades et al., 2022), is significant (Savvides et al., 2019). Most areas of human activity should be reviewed in order to reduce these emissions. Specifically, the building sector is one of the main activities responsible (Santos-Herrero et al., 2021), playing an important role in global warming and climate change, resulting in sea level rise due to melting ice caps and ocean acidification. The vision of the global community has been set to achieve zero net carbon emissions by 2050, to keep the global temperature increase below 1.5°C, in order to achieve at least a sustainable position in relation to the target of the COP26 (the United Nations Climate Change Conference, 2021) (Basher et al., 2022).

Today, new environmental and energy requirements are forcing us to rethink the way we consume and use urban resources, especially energy, which is becoming increasingly scarce due to climate change (Amen, 2021; Aziz Amen, 2022; Fenni, 2022), so it is necessary to follow a very strict energy policy to achieve sustainable growth in a responsible way (Senouci et al., 2022). In this case, innovative and sustainable building infrastructure can be one of the best alternatives to ensure on-site renewable energy production to increase energy supply (Amen & Nia, 2020; Basher et al., 2022; Amen et al., 2023). Among the various renewable energies, research on the use of solar energy is being actively carried out due to its unlimited energy source, convenient system installation, and good maintainability (Choi, 2022). In this regard, the European Energy Performance of Buildings Directive (EPBD 2010/31/EU) requires all new buildings to be NZEB (Nearly Zero Energy Buildings) from 2021 and aims to achieve a highly decarbonized building stock for existing and new buildings by 2050 ("Sustainability Insights on Emerging Solar District Heating Technologies to Boost the Nearly Zero Energy Building Concept," 2021)

Nomenclature		**COP26**	the United Nations Climate Change Conference, 2021	**Net ZEB**	Net Zero Energy Building
		EPBD	European Energy Performance of Buildings Directive	**RE**	Renewable Energy
nZEB	Nearly Zero Energy Building	**GHS**	Greenhouse Gas Emissions	**BIPV**	Building Integrated Photovoltaics
RES	Renewable energy sources	**MS**	Member States	**HVAC**	Heating, Ventilation, Air Conditioning
DHW	Domestic Hot Water	**LCA**	Life Cycle Assessment	**BEPS**	Building Energy Performance Simulation

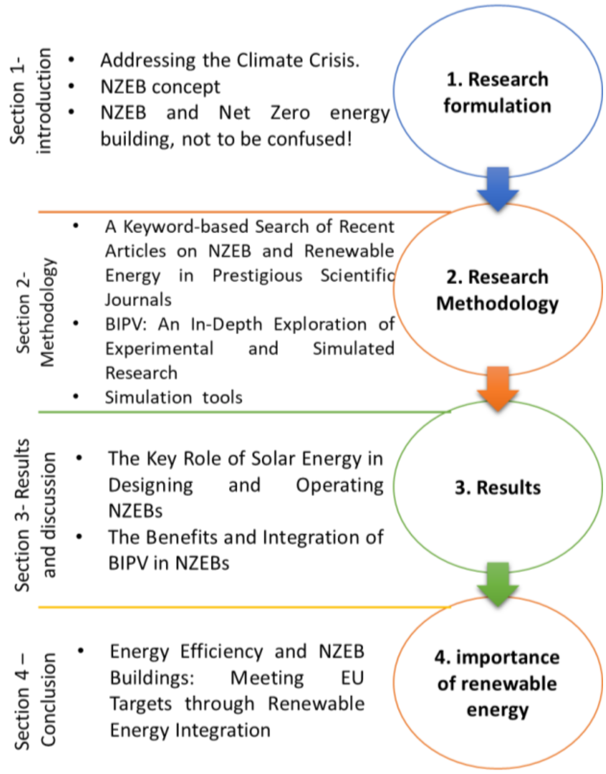

Figure 1. Structure of the Study (Developed by Author).

1.1. NZEB concept

The European Commission officially defines NZEBs (Article 02) as extremely energy-efficient buildings. The near-zero or very low energy requirement should be largely supplied by renewable energy sources, including those from on-site or nearby production ("New Buildings & NZEBs," n.d.). They are seen as an integrated solution to solve the problems of energy saving, environmental protection, and CO2 emission reduction in the building section (Deng et al., 2014).

the introduction of the NZEB objective in the design of buildings will promote a decrease in the amount of energy required, thus abandoning fossil fuels. A graphical interpretation of the NZEB energy balance is shown in the following diagram (Fig. 2) (Magrini et al., 2020)

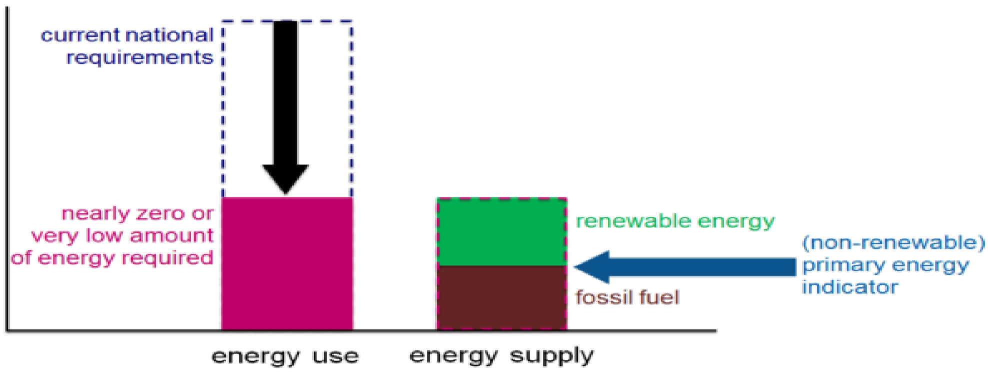

Figure 2. Graphic interpretation of the NZEB definition according to sections 2 and 9 of the EPBD (Magrini et al., 2020).

EPBD 2010/31/EU is an update of EPBD 2002/91/EC. Member States have attempted to address this global challenge by focusing on all components that affect building performance and establishing their minimum requirements for improving energy performance, setting the NZEB as a policy goal. Indeed, to avoid a further increase in greenhouse gas (GHG) emission levels, Member States decided to issue several directives to encourage the reduction of energy consumption and promote the use of RES. A framework was initially defined for all MS to:

- reduce GHG at least 20% below 1990 levels by 2020.
- increase the share of RE in the overall energy mix to 20% in the Member States (and a 10% share of biofuels in transport fuels).

- Achieve the 20% energy efficiency target by 2020 by reducing primary energy consumption through the implementation of energy efficiency instruments and technologies.

This was called 20/20/20. The European policy statement issued with its a cross-cutting guideline of ambitious targets for achieving high energy efficiency in buildings. Later, the new guidelines continued to follow the same working policy and set even more ambitious targets as planned on energy performance in 2012, which highlights key issues such as "smart" grids. Another key factor was highlighted in January 2014, where targets were set on energy and climate by 2030. This new guideline aims to reduce GHGs by 40% from 1990 levels, as well as improve energy performance by 30% to achieve a binding target of at least 27% RES along the MS (Santos-Herrero et al., 2021).

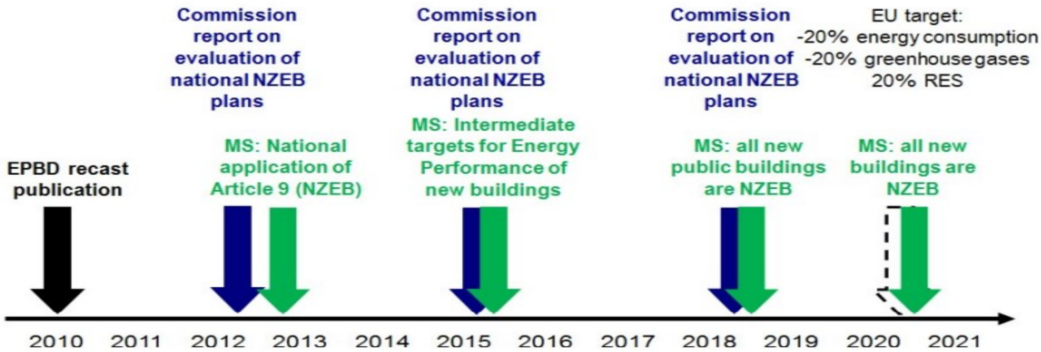

Figure 3. Timeline of NZEB-related actions according to the EPBD

Another important provision of the EPBD recast concerns the introduction of cost optimality. A comparative methodological framework for deriving cost-optimal levels of minimum energy performance requirements for buildings and building elements is provided in Delegated Regulation 244/2012 completing the EPBD recast. The cost-optimal level is defined as "the level of energy performance that leads to the lowest cost over the estimated economic life cycle" (D'Agostino & Mazzarella, 2019).

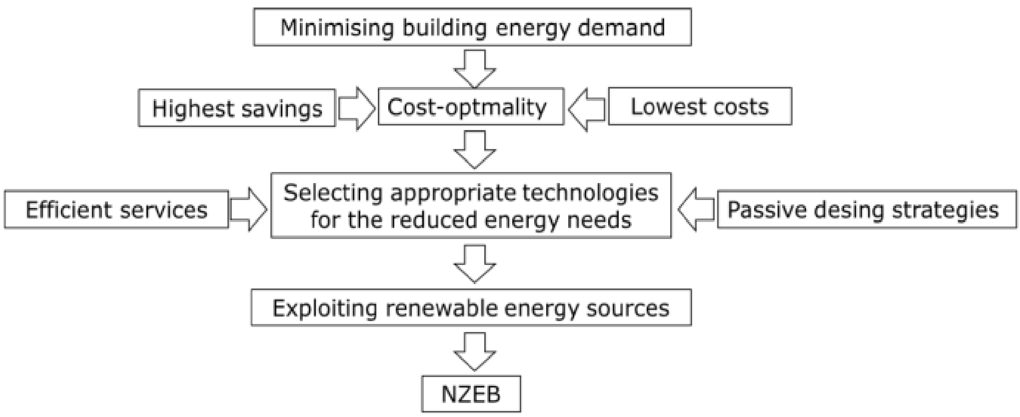

Figure 4. Concept of NZEBs (D'Agostino & Mazzarella, 2019).

1.2. NZEB and Net Zero energy building, not to be confused!

The basic elements of the definition of Net ZEB and their relationship are presented in Figure 5:

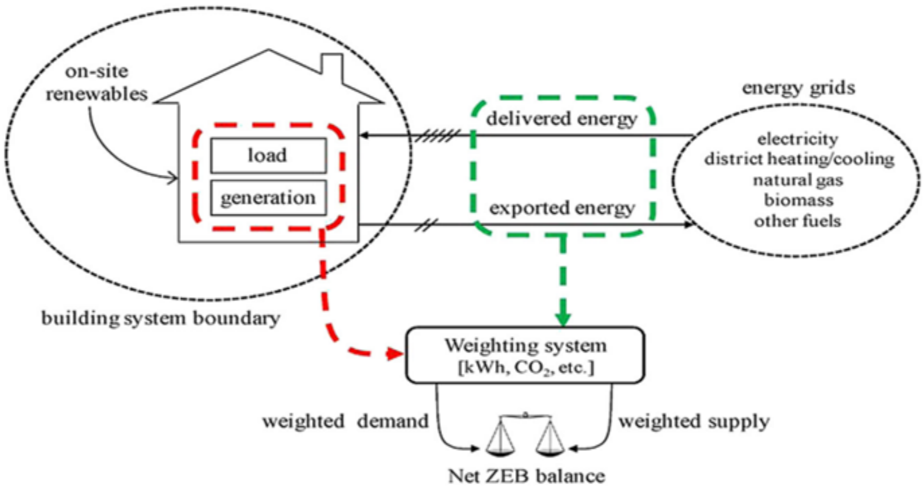

Figure 5. Sketch of connection between buildings and energy grids showing relevant terminology (Sartori et al., 2012)

The basic elements are the building system, the energy network, and the weighting system. In order to make a clear balance calculation for the net zero targets, a limit must be clarified for the building system with on-site renewable energy. Within this limit, the building system consumes the supplied energy, such as electricity, natural gas, from the renewable energy and on-site energy grids, and returns the energy to the grid when the REP (renewable energy) system generates excess electricity. Because of the different design goals, different weighting systems are chosen to calculate the net energy achieved by the entire building system. For example, building owners are usually concerned about energy costs, so they prefer to choose a weighting system in the cost balance, rather than the energy balance. Finally, the weighted demand and supply are compared to see if the net zero balance can be achieved based on the specific technology solution (Deng et al., 2014).

The Net ZEB balance is calculated as in Eq (1):

Net ZEB balance: |weighted supply| − |weighted demand| = 0 (Deng et al., 2014)

Since the basic principle of the NZEB definition is a balance between weighted demand and supply, different types of balance can directly lead to different evaluation conclusions. In most cases, only two parameters: building consumption and RES (renewable energy source) production, are taken into account in the calculation and evaluation of the net energy (Deng et al., 2014). In contrast to these two approaches, in Near Zero Energy, the primary energy requirements on the grid are neither zero nor necessarily fully offset by strong on-site or nearby renewable energy production (Net Zero Energy). Here, the primary energy requirements for normal building operation are greatly reduced and, in some cases, partially offset by energy generated from renewable sources to meet varying requirements (*REHVA Journal 03/2013 - Technical Definition for Nearly Zero Energy Buildings*, n.d.)

2. Research method

The methodology followed in this work has been to review different articles published in recent years dealing with the NZEB building, in order to clarify this concept, the reasons for its definition and its importance, as well as the tools and main factors necessary to achieve it. For this purpose, it was searched, using the keyword "NZEB" and "Renewable Energy", in articles published in prestigious scientific journals in recent years.

Solar energy supply has always been an important design factor in architectural and urban planning, as evidenced by the design of Buildings and cities in various ancient civilizations. However, the issue of solar urbanism is relatively modern and stems from the current need of increasing solar potential to meet energy needs that can lead to smart cities, integrated with NZEB (Savvides et al., 2019). The design and construction of a NZEB (Nearly Zero Energy Building) start with sustainable passive solar planning considerations (Aelenei et al., 2011; Sartori et al., 2010), and relies on two fundamental pillars, the reduction of its energy needs, and its energy production potential (e.g. electricity), in order to achieve the desired energy balance between consumption and production. All of the above can be achieved through the implementation of two main design strategies. The first is the inclusion of passive solar design considerations for a building, which takes into account its location and climatic conditions affecting the geometry of the building mass relative to the sun (Hachem et al., 2010), to minimize energy consumption and maximize the energy production potential of the building. The second factor is the location of the building in the urban fabric, where careful consideration of site orientation in relation to a building's passive strategies can result in 20 to 50% energy savings (Savvides et al., 2019).

Figure 6. an example of sustainable solar urban planning, with integrated solar systems on the urban scale (Savvides et al., 2019)

In the same context, recent research is aimed at determining the optimal geometry of building blocks to ensure the viability of certain building integrated solar systems (BISTS, BIPV). A more extensive literature review includes a series of studies that examine the topic. Kanters & Horvat (Kanters & Horvat, 2012) explored the geometric shapes of urban buildings and the potential of solar energy for local power generation and found that the impact of geometric shape on solar energy potential is significant (up to 50%). while other researchers also address the calculation of the effect of geometry and spatial arrangement of buildings, on solar potential and energy demand.

Each building is unique, not only because of its location, orientation, or surrounding conditions but also because of its size, geometry, construction materials used in its envelope, the distribution of each area, the use of each space, and its identification (Habash et al., 2014). According to its type of construction. The envelope of a building is one of the most important factors (Horn et al., 2020). As represented in Figure 7, NZEB mainly involves three types of energy efficiency measures: passive design, service system, and electricity generation from RES. Good passive building design, which can include optimized orientation, a high-performance thermal insulation envelope, good airtightness, and well-designed window shading, generally decreases the thermal and electrical load of buildings. In order to meet the reduced loads, different HVAC (heating, ventilation, air conditioning) systems, DHW (domestic hot water) systems, lighting systems, etc., are proposed(Deng et al., 2014).

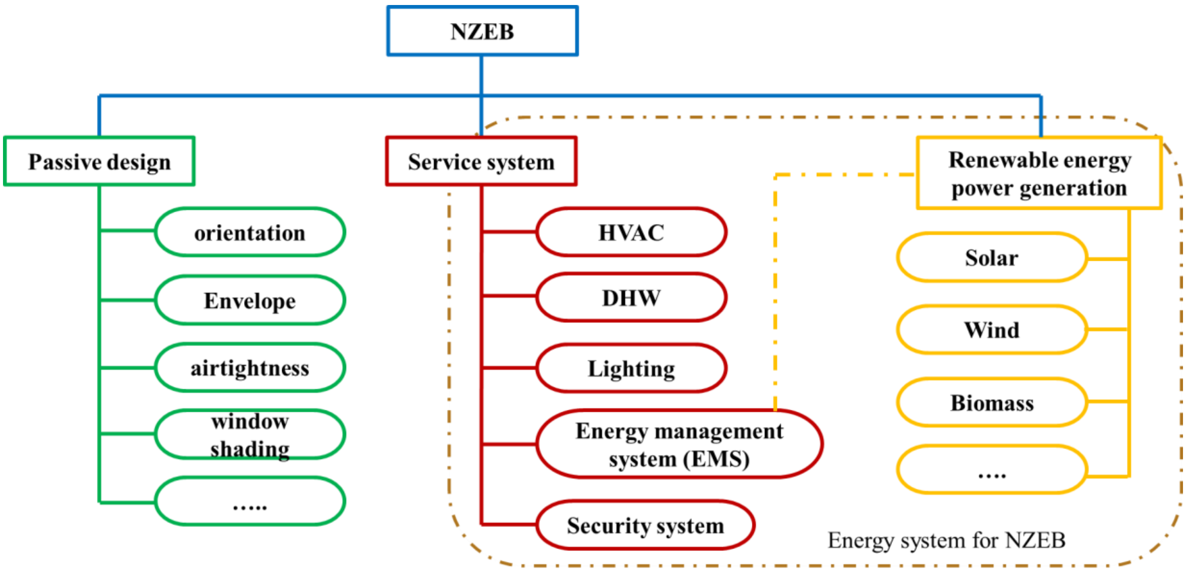

Figure 7. Design elements for NZEB (Deng et al., 2014).

With the implementation of the appropriate passive strategies in the design phase, the following steps, such as the definition of the appropriate HVAC system and its possible control alternatives, will be much more effective. To determine the active strategies, it is fundamental to consider an economic analysis: for example, the selection of the type of HVAC system and the most appropriate renewable energy source (RES) to ensure the required comfort levels, as well as to reduce the impact of the climate inside the building (Santos-Herrero et al., 2021).

Recently, on-site renewable energy generation has attracted the attention of researchers, and several research works have been conducted to design and optimize energy demand and supply for building-scale infrastructure, For example, ground source heat pumps (Jeong et al., 2018; Trillat-Berdal et al., 2007), solar heat pumps (Pinamonti & Baggio, 2020), rooftop PV(Al-Quraan et al., 2022; Hong et al., 2017).

Building-integrated photovoltaics (BIPV) is an innovative approach to incorporating solar energy systems directly into building materials. According to the review of (Skandalos et al., 2022) it can be divided into four main categories: PV shadings, roofs, façades, and balconies integration (Fig. 8). PV shadings can be installed as overhangs or louvres, as well as lamellas. Roof integration options include applied PVs, (dis)continuous PVs, PV tiles, and skylights. When it comes to façades, transparent or semi-transparent windows and wall applications are considered. For wall integration, we can identify four categories: rain screen, curtain wall, opaque PV component (structural), and double skin (non-structural). The latter can be further classified into two types: close to wall ventilated façades, which extend the thermal envelope of the building by up to 30 cm from the existing wall, and wider integrations up to 1.0 m, focused on utilizing heat convection, improving daylighting, and providing sufficient space for wall maintenance. In PV Curtain Walls, PV glass replaces traditional glass facades, ensuring appropriate transmittance for indoor lighting, shading, and electricity generation.

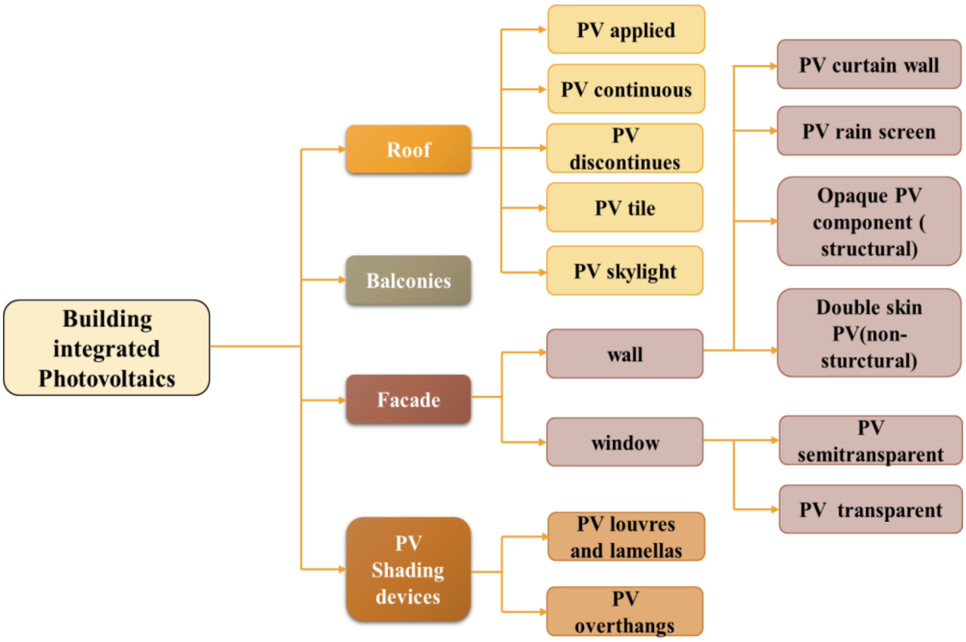

Figure 8. BIPV categories based on the building design integration and application type (Skandalos et al., 2022).

Over the past ten years, there has been a significant number of articles discussing experimental and simulated research on various aspects of Building-Integrated Photovoltaics (BIPV). These articles cover topics such as:

- PV materials and systems (Petter Jelle et al., 2012)
- integration shapes and design (Kuhn et al., 2021)
- energy performance and functionality (Martín-Chivelet et al., 2022)
- architectural forms and aesthetics (Awuku et al., 2021)
- electrical and safety concerns (Awuku et al., 2021), as well as benchmarking and regulations (Osseweijer et al., 2018).

Given the increasing number of publications and the presence of numerous demonstration projects globally, one would anticipate a corresponding growth in the implementation and wider acceptance of BIPV applications. However, there are notable challenges that can be categorized as follows, indicating a shortfall in achieving these expectations (Skandalos et al., 2022):

a) Complexity of energy-related properties of BIPV modules and systems
b) Difficulty in assessing the quality of architectural integration
c) Outdoor performance and predictive maintenance
d) Integration dependence on regional climate conditions

Many of the journal articles have largely covered the first three challenges. In contrast, the fourth challenge has been very weakly addressed in the literature. In order to meet the energy demand of the building and assess the emission of greenhouse gases, researchers have analyzed from a life cycle perspective (Marszal et al., 2012), using a research method used (LCA) that cannot only provide a more comprehensive and reasonable analysis of the energy and environmental impact of the product for the entire life cycle but also be used to determine the main design priorities and quantitatively inform the sustainable design decision (Oldewurtel et al., 2010).

simulation tools

More than a decade after the establishment of the NZEB terminology in the EU, it is necessary to assess the progress made in the field by examining the existing techniques, with particular attention to the tools at hand for scientists and practitioners. These are typically computer programs dedicated to modeling, simulation, and control to achieve NZEB goals. According to (Santos-Herrero et al., 2021), There are different Building Energy Performance Simulation (BEPS) tools that can be used to model and perform building energy simulations, such as IDA-ICE, Energy Plus, CPLEX, or TRNSYS, as shown in Table 1. By showing how the use of BEPS tools has been successfully applied to optimize air conditioning in buildings, they can also be applied to NZEB. BEPS tools can be used during the design phase, but are also useful in other phases of the building life cycle, as they allow for the optimization of energy consumption, especially during building renovation.

Table 1. List of the reviewed papers about BEPS (Santos-Herrero et al., 2021)

BEPS Tool	The focus of the article	Authors
TRNSYS	"Multiobjective optimization of building design using TRNSYS simulations, genetic algorithm, and Artificial Neural Network"	Magnier et al. (2010)
	"A review on modeling and simulation of building energy systems"	(Harish & Kumar, 2016a)
	"Reduced order modeling of a building energy system model through an optimization routine"	(Harish & Kumar, 2016b)
	"Multi-functional integrated system for energy retrofit of existing buildings: a solution towards nZEB standards"	(Aste et al., 2017)
	"Optimal renovation of buildings towards the nZEB standard"	(Iturriaga et al., 2018)
Energy Plus	"nZEBs: Expense or Investment?"	(Adhikari et al., 2012)
	"Cost optimality assessment of a single-family house for the nZEB target"	(Becchio et al., 2015)
	"Development of an nZEB life cycle cost assessment tool for fast decision-making in the early design phase"	(Kang, 2017)
IDA-ICE	"Energy saving assessment of STPV modules Integrated into nZEB"	(Cornaro et al., 2017)
CPLEX	"Optimization model for evaluating onsite renewable technologies with storage in nZEBs"	(González-Mahecha et al., 2018)

3. Results and discussion

The use of solar energy is a key factor in the production of renewable energy that can meet all or part of a building's energy needs. This means that the integration of active solar systems (photovoltaic, solar thermal, and hybrid systems) play a key role in the future design and operation of buildings (Savvides et al., 2019).
Extensive research has been conducted on case studies related to the application of photovoltaics (Ghosh, 2020) and the integration of this system into (BIPV) in NZEBs (Knera & Heim, 2016), by significantly reducing the use of fossil fuels that contribute to global warming, these systems can provide sustainable micro power generation that can be integrated into a variety of building designs. Several studies have been conducted and report that the application of BIPV can result in significant energy savings and reductions in energy consumption and pollution sources. BIPV can act as both a building envelope component and as an energy source material for modern infrastructure, based on cost-effectiveness and availability to architects. They can be more cost-effective simply because their composition and placement replace many traditional components, resulting in a variety of benefits, such as material and electricity savings, reduced fossil fuel use, reduced carbon, and greenhouse gas emissions, and improved architectural appearance of the building (Basher et al., 2022).

4. Conclusion

Over the past decade, the European Union has implemented energy efficiency policies that promote the energy transition from fossil fuels to renewable energy sources that have less impact on the environment. Therefore, the construction sector must also meet the targets set by the EU. This paper has addressed NZEB buildings, clarifying the concept, the reasons for its definition and importance, as well as the tools and main factors needed to achieve it. The main objectives of the NZEB model are to reduce energy needs and improve energy efficiency. An important role is played by the heating and cooling systems that must be used to cover the extremely low energy needs and must be powered mainly by renewable energy, such as the use of solar energy which is a key factor that can meet all or part of the energy needs of a building.

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