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Review

Moving toward Net Zero Carbon Buildings to Face Global Warming: A Narrative Review

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Abstract: The increase in global surface temperatures will surpass the 2 °C target set by the Paris Agreement unless carbon emissions are lowered to zero by 2050. To date, the building sector is responsible for 38% of all carbon emissions, thus one of the main targets is represented by the development of building strategies that can facilitate the transition toward carbon-neutral buildings. The main strategies are today represented by nearly zero energy buildings (nZEBs), zero energy buildings (ZEBs)/net zero energy buildings (NZEBs) and net zero carbon buildings (NZCBs). Particularly, NZCBs completely target zero operational and embodied carbon during their life cycles, fulfilling the leadership role in the decarbonization of the construction sector. Moreover, adopting the European Standard EN 15978:2011, carbon emissions can be precisely classified to enhance strategies aimed at reducing them. Commercial viability remains a fundamental economic driver, but the higher initial capital costs hinder the NZCBs. In addition, legislative, socio-cultural, technological, professional and geographical barriers hold back its diffusion. NZCBs can be met by a four-steps program: embodied carbon reduction, operational carbon reduction, increase in renewable energy supply and offset and carbon storage. Circular economy principles are strictly connected to design for disassembly and for adaptability to reduce embodied carbon, while passive design and solar and geothermal energy production can satisfy the renewable energy demand of the building. The aim of this narrative review is to determine and describe which is the current state of the art for NZCB definition, the drivers and barriers toward its application in a broader context and which strategies are eligible to meet the ambitious goal of zero operational and zero embodied carbon emissions.

Keywords: net zero carbon buildings; carbon-neutral buildings; zero energy buildings; embodied carbon; climate change; global warming; Paris Agreement; LCA; nature-based solutions; drivers and barriers

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1. Introduction

The role of buildings has not changed during the millennia: their primitive purpose of shelter is still fundamental, although economical, technical and societal progress allowed an evolution that dramatically changed design principles, tectonics (architectural syntax study), comfort quality and environmental impact [1]. In fact, during the current century, global warming and climate changes are the most relevant threats to mankind. Due to the huge quantity of greenhouse gases in the atmosphere, the consequent increase in temperature is causing unusual meteorological phenomena, i.e., rising sea levels and a growing number of hot days without precedent in history [2]. Moreover, buildings have a crucial role in carbon emissions, accounting for 38% of global emissions [3]. Instead of taking care of and protecting people, it could thus appear that buildings could involuntarily become dangerous if a different path in construction technology is not followed. Designers, developers, governments, users and other stakeholders have started to ask for more energy-efficient buildings, leading to a series of efficiency targets and definitions, like nearly zero energy buildings (nZEBs) and zero energy buildings (ZEBs), and carbon-efficient buildings such as net zero carbon buildings (NZCBs), ready to satisfy the decarbonization process [4].

The aim of this narrative review is to determine and describe which is the current state of the art for NZCB definition, the drivers and barriers toward its application in a broader context and which strategies are eligible to meet the ambitious goal of zero operational and zero embodied carbon emissions. The paper highlights a significant uncertainty and a not universally shared strategy for building decarbonization. Thus, underlining which are the most promising research topics and where are the main problems to deal with will help in the development of new approaches in the construction sector.

2. Methods

The paper carries out a non-systematic, narrative literature review about building decarbonization, in particular about net zero carbon buildings, the design solutions and the drivers and barriers toward its diffusion. The most relevant articles were retrieved through the search engines Web of Science, Scopus and Connected Papers to select suitable original articles and reviews written in English, in addition to specific pamphlets and publications written by organizations such as the United Nations or the UK Green Building Council and books about the above-mentioned topics. The following keywords were combined to create ad hoc strings: net zero carbon buildings, nearly zero energy buildings, zero energy buildings, carbon-negative buildings, absolute zero carbon, carbon neutrality, climate change, global warming, drivers and barriers, bio-based materials, embodied carbon and operational carbon.

3. Increase in Carbon Emission and Reduction Pathways

3.1. The Era of Anthropocene

Worldwide temperatures were increasing in the last century more than ever, reaching new peaks every year so that each of the last 40 years turned out to be warmer than any one since before 1850. According to the Intergovernmental Panel on Climate Change (IPCC), the global surface temperature increase was about 1.07 °C in the decade 2010–2019 [2].

The main causes of global warming are greenhouse gases that lead to an increase in the global average temperature and in the growth in the number of hot days, unusual meteorological phenomena of strong intensity and in the rise of sea levels. Crutzen coined the term Anthropocene to figure out that a new geological era, human caused by the greenhouse gases emissions, started around 1784, when James Watt patented his steam machine that led to industrialization and the consequent rise in carbon emissions [5].

Several studies have proposed that an effective solution for controlling the rise in temperatures could be represented by the progressive reduction in carbon emissions, with the goal for them to become zero by 2050, pursuing a carbon-neutral strategy. Carbon emissions were at around 54 Gt CO_2e (carbon dioxide equivalent) in 2021, excluding land-use, land-use change and forestry (LULUCF) contributions, and will peak by 2024–2025. This means that complete decarbonization will be a huge task that will involve all production sectors [6,7].

A universal agreement about climate protection, the Paris Agreement, was signed in 2015 during the 21st Conference of Parties (COP21) by 197 countries. The deal established the pursuance of a carbon-neutral strategy to maintain the global average rise in temperature closer to 1.5 °C by 2050 and below 2 °C [8]. However, according to the IPCC publication, simulations indicate that this goal might not be respected since the increase in temperatures may vary between an additional 1.6 °C and 4.4 °C during the 21st century in the most severe simulation, leading to an increase in extreme events, including fires, floods, heat waves and monsoons [2].

The zero net emissions target set for 2050 by the Paris Agreement requires that all governments work together to increase renewable energy production (from eolic, hydroelectric, solar and nuclear plants) and the development of clean technologies [9]. At the same time, it is necessary to raise awareness and spread sustainable good practices among people for different choices and habits.

3.2. Carbon Emissions in the Construction Sector: Decarbonization Targets

The main contributor of carbon dioxide emissions is the construction sector, accounting for 38% in 2019, equal to 10 billion tons of CO_2e, of which 28% is related to buildings and 10% to the construction materials industry [3]. The building sector was also responsible for 33% of electricity consumed in 2020 in Europe, a percentage that will rise to 72% by 2050. However, in OECD countries in 2020, 53% of electricity production came from the combustion of fossil fuels, mainly natural gas and coal, which impact carbon emissions negatively, while 30% came from renewable sources and 17% from nuclear power plants [9–11].

To face climate change and environmental mitigation, the design of existing and future buildings is crucial to achieve building energy efficiency and neutrality [12]. The United Nations Framework Convention on Climate Change (UNFCCC) set two targets for carbon reduction in buildings. By 2030, the net-zero target in operations for all new or refurbished buildings and a reduction of at least 40% of the embodied carbon must be achieved, while by 2050 all buildings will have to meet the net-zero-carbon target over the entire life cycle [13]. In the faster transition scenario proposed by the International Energy Agency (IEA), near-zero-energy construction and deep-energy retrofitting will cut energy needs by 30% by 2050, even though the global floor area will double. Heating and cooling systems are expected to grow their energy efficiency, although nowadays heat pumps have already an efficiency factor of at least four, while heat produced with solar thermal provides carbon-free supply to nearly 3 billion people [14].

4. NZCB Compared to Other Energy and Carbon Target Classifications

4.1. Definition of Energy and Carbon Reduction Classification for Buildings

The construction sector accounts for about 38% of the total greenhouse gases emissions. Thus, it is the biggest contributor [3] but potentially the sector where it is more convenient to intervene to reduce the carbon footprint. This would necessarily require thinking beyond the actual regulatory schemes. Among the most relevant strategies to cut emissions it has to be considered a more efficient energy consumption, together with the wider adoption of clean and renewable energy sources [4].

Scientific literature offers many types of classification for low/zero-energy and low/zero-carbon buildings.

Each classification and rating focuses on specific values, for example, energy efficiency, carbon emissions (embodied or operational), renewable energy production and life-cycle behavior from a sustainability point of view. According to Berardi, the sustainability assessment rating schemes available worldwide number more than 600 and are still evolving but can be grouped into the cumulative energy demand (CED) systems (which focus on energy consumption), the life-cycle analysis (LCA) systems (more devoted to environmental aspects) and the total quality assessment (TQA) systems, which evaluate ecological, economic and social aspects [15,16]. In the following paragraphs, a complete overview of building classifications according to low/zero-energy and -carbon standards will be presented (Figure 1).

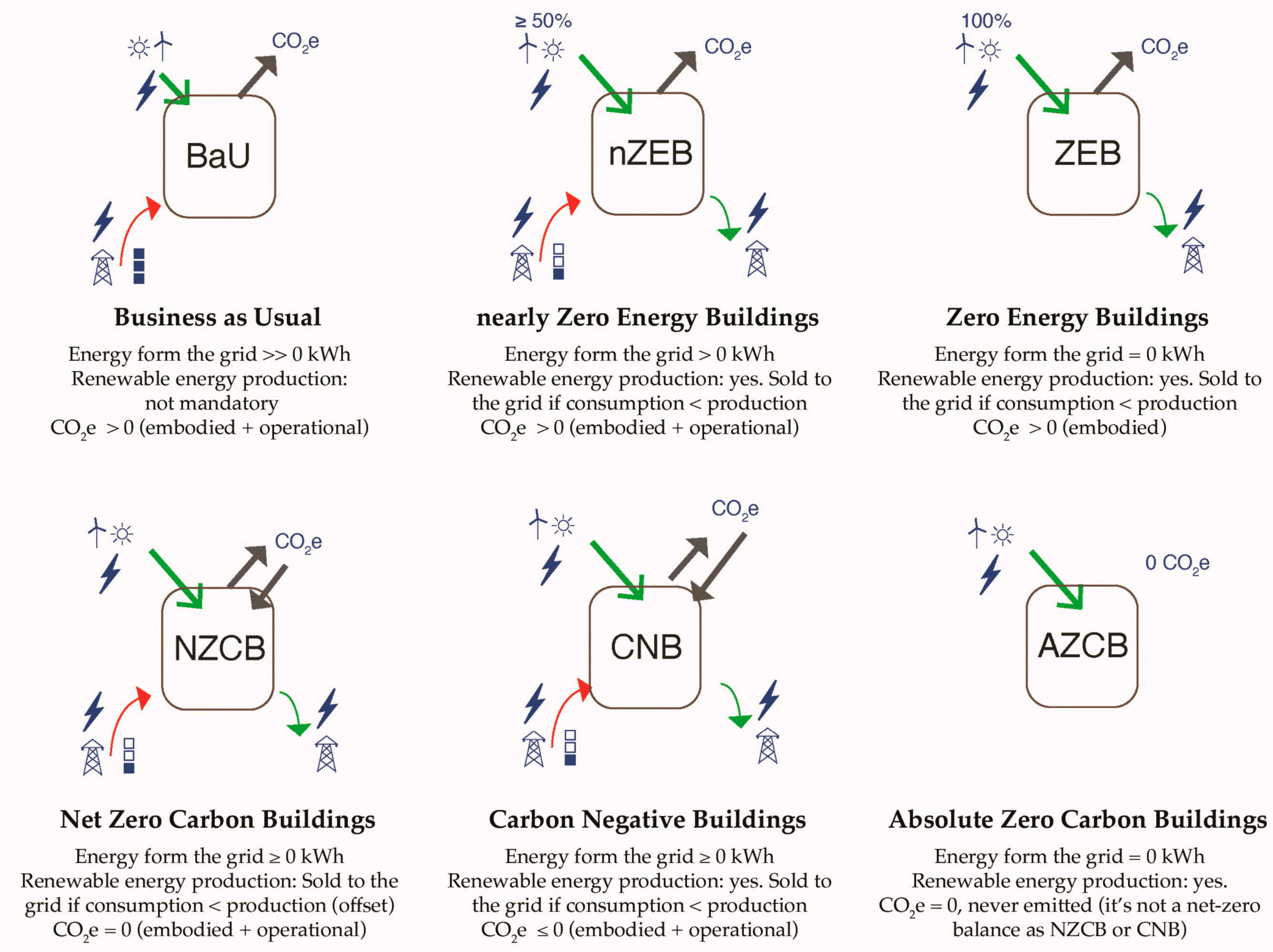

Figure 1. Different classifications for buildings based on energy consumption from the grid, renewable energy production, carbon emission production and offset.

4.2. Business as Usual (BaU)

The reference configuration of a building is commonly referred to as business as usual (BaU), i.e., a building that has been designed in compliance with energy performance standards but does not pay particular attention to the reduction in greenhouse gases (GHG) emissions, either operational or of those embodied [17]. The reference building consumes an average of about 220 kWh/m^2, has an amount of operational GHG emissions of about 70 kgCO_2e/m^2/year and embodied carbon emissions in the production and construction phases (upfront carbon) of about 1000 kgCO_2e/m^2 [18].

4.3. Nearly Zero Energy Building (nZEB)

One of the most relevant targets for energy efficiency is the nearly zero energy building (nZEB), which is now mandatory for new and renewed buildings in Europe, as prescribed by the Energy Performance of Buildings Directive (EPBD) 2010/31/EU in Art. 9: "Member States shall ensure that: (a) by 31 December 2020, all new buildings are nearly zero-energy buildings; and (b) after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings", meanwhile introducing a "numerical indicator of primary energy use expressed in kWh/m^2 per year" [19].

The notion of nZEB is included in Art. 2(2) of the EPBD: an nZEB "means a building that has a very high energy performance, as determined in accordance with Annex I. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby" [19].

EPBD Annex I states: "The energy performance of a building shall be determined on the basis of the calculated or actual annual energy that is consumed in order to meet the different needs associated with its typical use and shall reflect the heating energy needs and cooling energy needs (energy needed to avoid overheating) to maintain the envisaged temperature conditions of the building, and domestic hot water needs" [19].

Hence, the EU directive focuses on the envelope performance to meet low-energy needs [20] but fails in the definition of embodied energy and embodied carbon [18].

Introducing life-cycle cost (LCC) and life-cycle inventory (LCI) analyses adds further layers of assessment onto the application of nZEB in the construction sector. European Regulation 224/2012 [21], in Annex I, defines the comparative methodology framework to be applied by member states (MS) for the calculation of cost-optimal levels of minimum energy-performance requirements in the building sector. Nevertheless, many factors contribute to the economic uncertainty of the building LCC assessment, which are due to both macroeconomic, financial viewpoints and the energy price and performance of the building, so that it becomes a difficult task to find the cost-optimal level for nZEBs [22–24]. Overall, the strategies to reach the nZEB goal include optimal air tightness, insulation thickness and glass and windows performance (U-value), heating, ventilation and air conditioning (HVAC) systems with heat recovery and extensive installation of photovoltaic panels [25–33].

4.4. Zero Energy Building (ZEB)/Net Zero Energy Buildings (NZEB)

A further step into energy efficiency is provided by the concept of net zero energy buildings (NZEBs), which require a supply of energy from renewable sources to not use fossil fuels while increasing energy efficiency [34]. The "net" word specifies that this type of building has an overall balance of energy taken from and supplied back to the gird in a certain amount of time [35]. This classification is commonly referred to also as the zero energy building (ZEB), which is defined by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) as "a building that uses no more energy than is provided by the building on-site renewable energy sources on annual basis" [36,37]. The US Department of Energy definition includes the advantages of a ZEB: "ZEBs use all cost-effective measures to reduce energy usage through energy efficiency and include renewable energy systems that produce enough energy to meet remaining energy needs. There are a number of long-term advantages of moving toward ZEBs, including lower environmental impacts, lower operating and maintenance costs, better resiliency to power outages and natural disasters, and improved energy security" [38]. Still, the definitions of NZEB and ZEB lack the embodied energy or embodied carbon assessment, which can negatively affect the environment more than energy production, as later discussed [25].

Carbon metrics can be added to the ZEB definition, as well as exergy, energy cost defined by national policies, investor priorities and goals to balance costs and benefits [39–41].

4.5. Net Zero Carbon Building (NZCB)

To deal with climate changes indicators, the carbon footprint must be included to properly know the main causes of GHG emissions.

The UK Green Building Council's (UKGBC) proposed definition of NZCB is the clearest: a building is net zero carbon "when the quantities of greenhouse gas emissions associated with the operational and embodied footprint of the building throughout the life cycle, including its disposal, are zero or negative" [42]. This definition, which considers the entire life cycle, is considered particularly conservative and is still being studied. Therefore, a different formulation is also proposed by the institution divided into three successive steps: net zero carbon—construction (for embodied emissions), net zero carbon—operational energy (for the operational emissions) and net zero carbon—whole life (previous definition), as an end point to be reached in the future.

In particular, a building can be defined as net zero carbon—construction "when the amount of GHG emissions associated with the production and construction phases of a building up to completion is zero or less than zero, thanks to the offsetting of emissions or the net export of renewable energy produced on-site", and net zero carbon—operational energy "when the amount of GHG emissions associated with the building's energy in operation on an annual basis is zero or less than zero. A net zero carbon building is energy efficient and powered by on-site and off-site renewable energy sources, with any remaining emissions offsetting" [42].

A further explanation was formulated by the designers of the ARUP studio, for whom "Net zero carbon is defined as a reduction in the demand for energy and materials to a level that can be met solely by sources that do not emit greenhouse gases". To meet this definition, it is estimated that the intensity of energy use in buildings will have to be reduced by 60% by 2050 [4].

Despite the great number of studies about carbon emissions reduction, a shared definition and term for NZCBs is still lacking. This is why they are referred to also as zero carbon buildings (ZCB), especially in the US context [43], life-cycle zero energy buildings (LC-ZEB), passive houses, carbon neutral, net zero energy, zero net energy, zero energy, fossil fuel-free, energy plus, climate-neutral and 100% renewable [44–46], each one with specific adopted metrics. The NZCB concept appeared first in 2006 in the United Kingdom [47], but the boundaries of the energy balance, both geographically and in timing, must be set to establish a generally applied definition [39]. First, it is important to include both operational and embodied carbon deriving from construction, maintenance and the end of life of the building [48,49]. As shown in several studies, embodied carbon can exceed 50% of overall emissions and be greater than operational carbon [4] because of a strong reduction in energy consumption thanks to nZEB and ZEB principles. Specific materials added to satisfy energy demand reduction can considerably improve the embodied carbon of the building (such as mineral-based thermal insulation, mechanical equipment and new windows), eliminating the corresponding reduction in operational carbon during the life cycle [50–52].

Six materials or components (concrete, steel, aluminum profiles, glass and services such as lighting, heating and cooling) are responsible for about 70% of the embodied carbon contribution, while the maintenance phase can account for 20% of emissions over the life cycle [18]. The main metrics method for the zero-carbon assessment is provided by the EN15978:2011 standard, also called the whole-life carbon assessment (WLCA) [53,54]. Carbon emissions are divided into five phases: production (phases A1–A3), construction (A4–A5), use (B1–B7), end of life (C1–C4) and beyond life (D), to be assessed separately (production, construction, use, end of life and beyond life). The operational carbon is represented by modules B6 and B7, while all the other modules refer to the embodied carbon [55] (Table 1).

The WLCA evaluation is commonly conducted only for a few projects in the world because of insufficient carbon literacy and the lack of standard procedures and databases [56].

Table 1. Whole-life carbon assessment (WLCA) calculation methodology as defined by EN15978:2011. Emissions are unpacked into four modules to highlight where emissions come from.

<table>
<tr><th colspan="8">WLCA Methodology—EN 15978:2011</th></tr>
<tr><td>A1</td><td rowspan="3">Production</td><td>Raw material supply</td><td rowspan="3">Embodied</td><td rowspan="19">Cradle—to grave</td><td rowspan="5">Cradle to completion</td><td rowspan="4">Cradle to site</td><td rowspan="3">Cradle to gate</td></tr>
<tr><td>A2</td><td>Transport</td></tr>
<tr><td>A3</td><td>Manufacturing</td></tr>
<tr><td>A4</td><td rowspan="2">Construction</td><td>Transport</td><td rowspan="2">Embodied</td><td rowspan="16"></td></tr>
<tr><td>A5</td><td>Construction and installation process</td><td rowspan="15"></td></tr>
<tr><td>B1</td><td rowspan="7">In-use</td><td>Use</td><td rowspan="5">Embodied</td><td rowspan="14"></td></tr>
<tr><td>B2</td><td>Maintenance</td></tr>
<tr><td>B3</td><td>Repair</td></tr>
<tr><td>B4</td><td>Replacement</td></tr>
<tr><td>B5</td><td>Refurbishment</td></tr>
<tr><td>B6</td><td>Operational energy</td><td rowspan="2">Operational</td></tr>
<tr><td>B7</td><td>Operational water</td></tr>
<tr><td>C1</td><td rowspan="4">End of life</td><td>Deconstruction and demolition</td><td rowspan="4">Embodied</td></tr>
<tr><td>C2</td><td>Transport</td></tr>
<tr><td>C3</td><td>Waste processing</td></tr>
<tr><td>C4</td><td>Disposal</td></tr>
<tr><td rowspan="2">D</td><td rowspan="2">Beyond life</td><td>Benefits and loads</td><td rowspan="2">Embodied</td></tr>
<tr><td>Reuse, recovery, recycling</td></tr>
</table>

4.6. Beyond Carbon Neutrality

It is possible for a building to perform better than NZCBs, if the compensation for carbon emissions is bigger than their release into the atmosphere.

Carbon-negative buildings (CNBs) or beyond zero embrace eco-positive principles to reverse the negative impacts of construction and development, increasing the natural life support [57]. For a CNB, the embodied carbon is the main concern, since it produces more energy than it consumes in operation. Therefore, it is important to carefully select the materials used in the design to minimize the environmental impact [58].

A possible solution is the adoption of a carbon capture unit (CCU) at a building level, but the market feasibility, according to building managers, is scarce because of higher costs. Thus, the emissions reduction goal for the local governments is in conflict with the building sector stakeholders [59].

The last place within this classification can be occupied by the so-called absolute zero carbon buildings (AZCB), an asymptotic condition to strive for but currently conceivable only at a conceptual level. The absolute zero specification implies that emissions are actually avoided without the use of offsets, both in the operational phase, with the use of renewable energy (produced on site or not) that satisfies the energy needs of the building, and also in the construction phase through the use of materials from zero-emission supply chains, in the end-of-life (EoL) disposal phase and in the use of fuel and electricity for transport and construction [60,61].

5. Drivers and Barriers to NZCB Adoption

As seen in the previous paragraph, the NZCB is a tough target to reach in the construction sector but of vital importance to attempt to mitigate climate change and global warming by 2 °C and preferably by 1.5 °C [8]. Despite the legislative framework that set progressive targets to enable this pledge and the efforts in the research field, there are several barriers to overcome to promote and diffuse the adoption of the NZCB [62] (Figure 2).

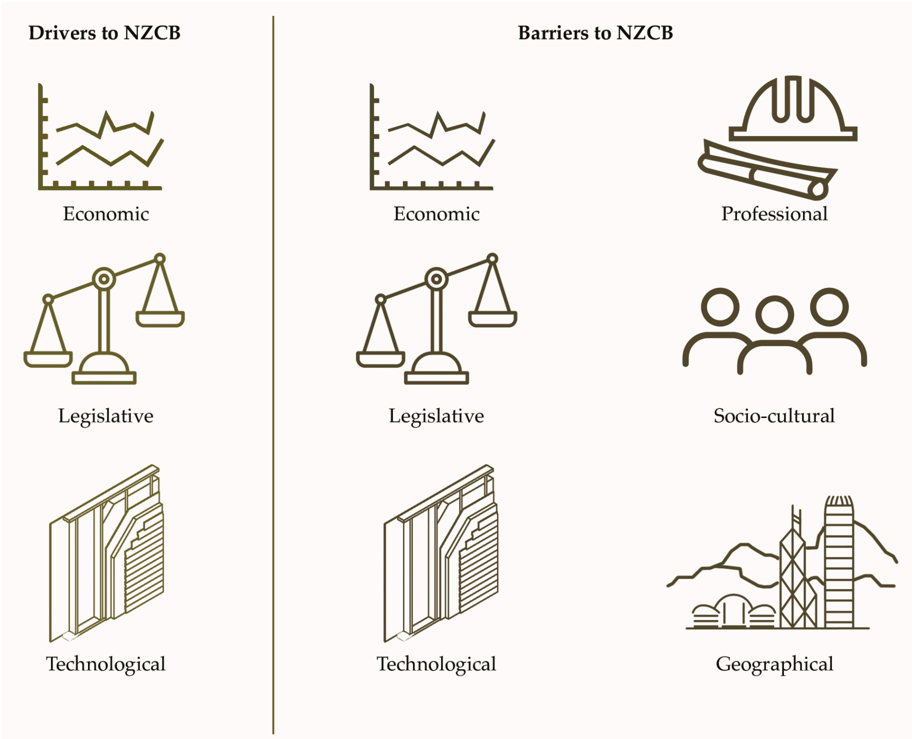

Figure 2. Drivers and barriers for net zero carbon buildings: it is possible to sum them up into six categories.

5.1. Main Drivers

As seen in the previous paragraph, the NZCB is hard to reach in the construction sector, but some drivers for delivering zero carbon buildings have been studied [63]. Osmani and O'Reilly analyzed cultural, legislative, financial and business drivers, as well as design, cultural, legislative and financial barriers in England to the realization of zero carbon homes from the housebuilder perspective [64]. Legislative and economic drivers are the most relevant, but also personal commitment to the climate change issue drives an important role, although this can represent a main barrier if absent [63,65–67]. As stated by the IEA, buildings have a clear role in carbon emission reduction through the adoption of existing technologies while improving comfort and services. Since the built-floor area is expected to double by 2050, construction of new buildings in association with the renovation of existing built assets is a crucial driver for delivering on the zero-carbon target by adopting specific design solutions and strategies that can become common practices in the next decades [14,68]. Moreover, market expectations about the carbon performance of assets and products are becoming higher, leading to the risk for carbon-intensive buildings to become stranded if they are not decarbonized. Stakeholders should be aware of this risk to progressively assess the stranding risk of their assets [4,69].

5.2. Main Barriers

There are still many barriers that limit the diffusion of NZCBs around the world; many studies provide evidence of this in some legislative frameworks [63,64,70–72].

Ohene et al. highlight that the NZCB delivery supply chain needs great collaboration between the stakeholders involved in the process (policymakers, developers, investors, urban planners, architects and construction companies) and classified the barriers to NZCBs into seven categories: economic, legislative, technological, professional/technical, market, social-cultural and geographic barriers [62].

5.2.1. Economic Barriers

The scientific literature broadly discussed the economic and market barriers to NZCB implementation, which are mainly related to the upfront investments (construction and design phase) necessary to adopt NZCB strategies [73]. Heffernan and Pan and Pan noticed that economic factors are the most significant barriers in the analyzed local contexts in Europe and Hong Kong, but commercial viability remains a fundamental economic driver to deliver the attractiveness of NZCBs. Therefore, the higher initial capital costs hinder the NZCBs. To understand the environmental and economic implications of buildings' construction, end users should know the carbon savings of their investments [63,65,74]. This is particularly relevant in developing and emerging economies or for lower- and middle-income earners, where it is more difficult to provide the initial investment [62].

According to some recent studies, global cost, life-cycle cost or investment cost are primarily considered, while energy consumption in the operational stage of the building is considered secondly [75].

In addition, a cost-optimal approach focused on the district level should be defined to establish the environmental and social impacts in terms of benefits at a local community level. This may help the development of decarbonization strategies to reduce impacts on a local scale [24,76,77].

5.2.2. Legislative Barriers

NZCB diffusion finds a big obstacle in legislative holes, since a common definition is still missing in policies and regulations all over the world, as extensively discussed in the literature [20,62,63,66,70,78–81]. Separating operational and embodied carbon calculations pushes industry practice toward the unintended consequence of demolishing and then replacing buildings with new ones, increasing the whole-life energy and carbon [82,83].

However, the legislative framework can stimulate the delivery of zero carbon practices among stakeholders and investors, compelling the construction industry to decrease the environmental impact, to supply energy-efficiency standards and to implement effective monitoring. Nationally determined contributions (NDCs) and climate policies should add building decarbonization strategies by the adoption of energy- and carbon-efficiency labels, and the shift of all markets toward more energy-efficient appliances, lighting and mechanical equipment can push forward to NZCB diffusion [62,78,84].

Moreover, the lack of specific governmental economic support through financial incentives, such as green bond financing and lease agreements for NZCBs, remains a substantial barrier given the great upfront investments by private customers, who are unsure that they will recover the bigger costs [62,63,85].

5.2.3. Technological Barriers

The NZCB target can be already reached by adopting existing technologies, but the availability of solutions to satisfy each performance requirement is limited and a really accurate evaluation must be done during the project, metaproject and WLCA phases [86].

Technologies for enhancing building energy efficiency focusing on building envelope, heating and cooling and energy generation are already diffused and are crucial to satisfy the NZCB requirements, especially for the operational carbon [87]. Cost implications are today much reduced for photovoltaic (PV) electricity (−75% since 2010) and for wind turbines (−32%) [88,89].

Market demand for NZCBs is still substantially lacking good marketing strategies [65,66,80], while the initial higher investment for energy efficiency [65] and the little knowledge of market potential [39,73] hinder its viability. Lastly, geographical characteristics, density and climate conditions can be obstacles for the adoption and integration of some carbon-zero technologies, such as energy and heat production [62,64].

5.2.4. Professional Barriers

NZCB design is still rarely diffused, since the lack of databases and standard procedures adopted by professionals, as much as inadequate carbon literacy, affect its feasibility [90,91]. Despite that environmental product declaration (EPD) databases had a significant increase in the number of products available, it is still difficult to source the necessary data to develop a carbon assessment, leading to the use of outdated or geographically misplaced data [92].

Professionals are commonly not trained to design an NZCB. Since professional and technical competencies are required to drive NZCB adoption, it is very difficult to diffuse them on a large scale. Designers need to spend more time on the design phase because of LCA evaluations, while knowledge of 3D modeling, building information modeling (BIM) and digital twins (DT) is compulsory [93]. Moreover, construction workers lack the appropriate knowledge, including dry construction methods that are not strictly connected with NZCBs, and stakeholder involvement and collaboration are still narrow [62,63,66,87,94,95].

Certification of net-zero buildings through recognized schemes is a big improvement both for commercial viability and for professionals' practices. However, experts perceive in these certifications an obstacle, given their complexity and the necessity for specific training to successfully obtain the results [62]. The certification of NZCBs does not require specific tools but commonly relies on schemes like Leadership in Energy and Environmental Design (LEED) in the US, the Building Research Establishment Environmental Assessment Methodology (BREEAM) in the UK, the Green Star system in Australia and the Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) system in Germany [62,96].

5.2.5. Socio-Cultural Barriers

Governments need to raise experience and knowledge about carbon reduction, highlighting the benefits for the building sector and other sources of GHG emissions relatable to people's choices. In fact, many customers and end users are not aware at all of the convenience of NZEB and NZCB homes, lessening their diffusion [63,65,81,95]. The perceived difficulty of avoiding fossil fuels and resistance to change are main causes of the slowness of the net-zero-carbon economy transition.

A fundamental driver to NZCBs is represented by favorable and easy financial support that allows the reduction in the higher upfront investment cost. It is therefore necessary that governments and loan companies provide adequate credit access for building owners and investors [62].

5.2.6. Geographical Barriers

Geographical location and climate conditions can be obstacles to NZCB distribution. Geography can affect in situ renewable energy production, in particular in high-rise, high-density cities, limiting the reliability and adequacy for some regions [97]. Elsewhere, it can be difficult to retrofit existing buildings because of climate conditions that restrict the economic and technical feasibility of the interventions [20,56,63,98].

6. Net Zero Carbon Building Strategies

The adoption of new construction standards with their own requirements needs to solve open questions on how to guarantee the willing performances set. The NZCB pushes the boundaries of carbon efficiency to very strict limits, since all emissions produced must be offset and compensated for, increasing the decarbonization strategy effort in the design phase. As explained by Hill et al. [4], to achieve the net-zero-carbon target, it is needed to reduce the demand for energy and materials and increase the sources of supply to meet the demand without carbon emissions.

According to ZEB guidelines, the energy consumption reduction in new building construction or renovation can benefit many strategies, all meant to reduce operational carbon, including integrated design, reduced plug loads and energy-efficiency retrofits [38].

This is only one step of a four-step program to meet the NZCB standards, which include a reduction in embodied carbon, a reduction in operational carbon, an increase in renewable energy supply and compensation for residual embodied emissions [4,42,86] (Figure 3).

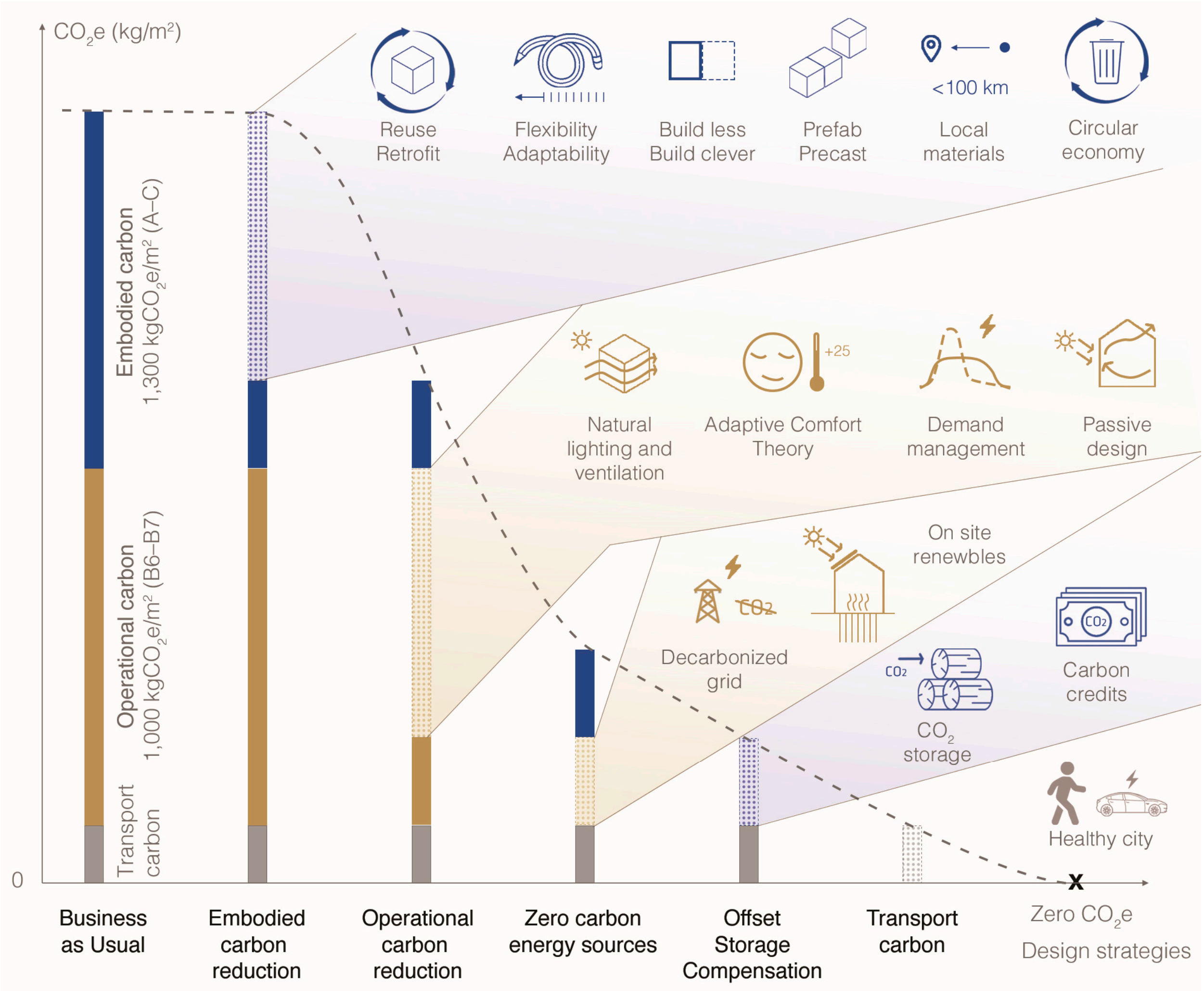

Figure 3. Embodied and operational carbon timeline to complete decarbonization in four phases. Starting from the business-as-usual (BaU) condition, it is possible to reduce embodied and operational carbon and then offset/compensate for the remaining part. Transport carbon can be considerably reduced by applying healthy-city principles.

Reducing emissions and energy consumption is crucial to meet the goal: the fewer emissions produced, the less offsetting and compensation have to be provided. According to UKGBC, the development of net-zero-carbon practices guarantees a competitive advantage in economic terms, following three guidelines: pay per pollute, encourage transparency and encourage immediate action. In fact, the cost of offsetting is lower if positive emission reduction practices are adopted; publishing data about carbon emissions drives trust and increases public awareness on this topic, while an early adoption of the zero-carbon approach for operational and construction emissions will help to meet the goal for the entire life cycle [42].

6.1. Embodied Carbon Reduction

As provided for EN 15978:2011, embodied carbon is present both during the transport and production of materials, as well as during construction, maintenance and the end of life of the buildings, making it really difficult to reduce its quantity. To reduce embodied carbon, one of the best strategies is to carefully evaluate the contractor's requirements, implementing the "Build Less, Build Clever" principle and, when possible, reusing existing buildings, which can save up to 50% in embodied carbon emissions [4]. In fact, demolition and new construction with energy-efficiency requirements impacts more than a well-designed retrofit and the reuse of existing assets [82,86], but it is possible that the best solution for the customer is not to build anything but to consider alternative solutions, assuring a complete reduction in carbon emissions [99].

To reduce embodied carbon, it is essential to make low-carbon choices during the design stage, including the designs for adaptability and flexibility. This allows the new construction to be more resilient to future changes and users' needs, extending the life cycle of the building without making major modifications [4,100]. This strategy includes, for example, designing new buildings with big story heights and very regular structural frames to allow free internal distribution [101]. Choosing local materials and material supplier is helpful to reduce transport carbon emissions, while enhancing the proximity economy. Another fundamental design strategy is to apply circular economy principles during construction and EoL, choosing recycled and recyclable materials [102].

The adoption of a design for disassembly principles, using mainly dry technologies and mechanical connections, allows the deconstruction of the building at the end of its life cycle, minimizing waste products and helping to reuse the materials. This will enable the application of circularity principles that will contribute toward sustainable development goals and climate change mitigation efforts [100,101,103].

Linked to circular economy principles, it is important to note the role of urban mining applied to deconstruction and waste generated by buildings' demolitions, providing precious resources to create new reusable components and materials [104,105]. Processing waste materials and components is likely to save more energy than the production of new elements, reducing embodied carbon in the A1–A3 stages. Analysis of the inventory of resources minable from the specific local context must be performed to determine the types of resources and the estimated quantities available [106].

Value engineering (VE) is a process of design optimization through design strategies that will deliver the value desired in the most effective way, substituting "building materials, systems or design strategies to reduce capital costs without negatively impacting functionality" [107,108]. The same approach can be extended to embodied carbon optimization, called carbon value engineering (CO_2VE), where an alternative design is considered to reduce embodied carbon and evaluate the feasibility of the new proposal. Langston et al. have analyzed several buildings in Melbourne, finding out that building cost reductions can also reduce embodied carbon through dematerialization, meaning that more expensive buildings and solutions also have higher embodied carbon [109]. A building's cost and embodied carbon are pointed out at three scales: the building scale, building components and building materials [108].

6.2. Operational Carbon Reduction

Reducing operational carbon can be achieved through the adoption of the solutions commonly provided for ZEBs and nZEBs, including integrated designs, reduced plug loads and energy-efficiency retrofits. Once energy consumption is downsized, less renewable energy production is required to meet the demand [38].

Reducing operational carbon emissions can be achieved by the adoption of solutions for passive design, which include natural lighting and ventilation, passive heating and cooling and adaptive comfort theories [86,110].

Users prefer to intervene directly in the internal climate, deciding to power on or off the heating and cooling system and lights, to open windows or change the air velocity controlled by fan –coil systems. To reduce operational carbon and satisfy users is therefore preferable, allowing people to freely intervene in uncomfortable conditions, avoiding unintuitive behavior such as the "blinds down, lights on syndrome" [103,111]. Moreover, users mainly tolerate situations in natural conditions where they do not meet the required standards (adaptive comfort theory) [112]. The use of an energy demands management shifts energy demand peaks, throttling it to use simpler energy-supply systems that are balanced to the common energy request occurring most of the time (in particular for electricity) [4].

The biggest operational carbon benefits can be achieved with architectural solutions, such as envelope thermal performance (both glazed surfaces and walls), where the transmittance level is the main key performance indicator, but also with the disposition of glazed surfaces, thermal masses and solar-reflective surfaces, both in case of new construction or retrofit [86,110,113,114]. The inclusion of green roofs is a good way to reflect between 20% and 30% of solar radiation, while absorbing light and carbon emissions through photosynthesis [115].

6.3. Zero Carbon Energy Sources

The compensation of operational carbon can be achieved through renewable energy production directly in situ. This requirement is satisfied also for nZEB and ZEB buildings, with the need to evaluate the embodied carbon associated with the energy production equipment. Energy production can occur with photovoltaic panels, eventually integrated in the facades and on the roofs, micro-eolic power units and geothermal pumps [4,28,86].

In association with heat pumps for heating, cooling and hot sanitary water production, it is possible to achieve the net-zero operational carbon target or surpass it; in fact, electricity production in excess can be sold to the grid, increasing its amount of green electricity, which is on a complex and long path toward decarbonization [116].

As for transport carbon, produced by the people reaching the building, following decarbonization in the transport sector, the amount of GHGs will be lower, but promoting healthy-city principles with a bigger share in the use of soft mobility and public transport must be preferred [103,117].

6.4. Offset, Carbon Storage and Compensation

To compensate for embodied carbon produced during modules A1–A5, B1–B5 and C, ascertaining that the AZCB target is beyond reach, it is possible to undertake two paths.

Carbon offsetting means to purchase carbon credits that will be used to develop investments in green energy and plant new forests. These credits can make a difference in funding global or local projects that would otherwise not start. This strategy is closely linked to weak sustainability and should be used only after applying every possible strategy to reduce operational and embodied carbon. However, in the future, it may become mandatory to reduce carbon emissions or compensate for them through the acquiring of certified carbon credits, which will increase their price enormously: it is estimated that in 2035, offsetting 1 ton of GHGs may cost GBP 43, a huge increase from the GBP 13 in the summer 2020, and the global trading market of carbon credits can rise to GBP 500 M worldwide [4].

Furthermore, the carbon credits market has a great potential to employ blockchain, helping the reduction in fossil fuel consumption, thanks to the interconnected data blocks [118].

To reduce carbon emissions and reach carbon neutrality, it is of great importance to avoid their release into the atmosphere during building operation and construction, so that compensation will need a minor effort. The adoption of nature-based solutions (NBS) and materials that assure carbon sequestration, thanks to biogenic carbon absorbed during its life span and growth before being manufactured, is a way to explore to reach the NZCB target [86]

Absorbing carbon dioxide, resulting in negative contributions for embodied carbon, is not a solution shared by the entire scientific community since the effective results can be dramatically different depending on the adopted method of calculation.

The most promising organic materials for applications in construction that can absorb and store CO_2 during their life cycles like “carbon sponges” are wood, hemp, mycelium, straw, bamboo, cork, cellulose and wool. These materials can be recycled, land-filled or reused at the EoL, enabling circular economy processes [101,119–122].

Storing carbon in buildings can benefit from the big number of new volumes built continuously to accommodate market requests for new and retrofitted buildings, changing the materials for structures, finishes and insulation from mineral-based to bio-based materials. The carbon storage in timber, for example, can offset the temporary reduction in the forest carbon stocks, which can regrow, restarting carbon absorption. Thus, buildings can act as a forest inside the city, with a carbon density that grows when building density intensifies, as long as wood is sourced from controlled producers [123,124]. Several studies have shown that bio-based materials offer not only stored biogenic carbon but also lower embodied carbon [123,125,126]. However, there is not an unambiguous consensus on the calculation for negative contributions in the literature, given that it is not always specified in which module they occur [86].

Bio-based materials store carbon deriving from their organic origin, though it is not locked in forever: during the decomposition process, this carbon will be free in the air. Thus, following the "0/0 approach", no negative contributions are accounted along the materials' life cycles; otherwise, the "−1/+1 approach" tracks all the biogenic carbon exchanges in and out during the life cycle in a more detailed way [86,127].

As analyzed by Cordier et al., cogeneration at the end of wood's life cycle can be a low-carbon energy source, but this can lead to positive carbon emissions nullifying all the negative contributions during the building's whole life [128]. Carbon stored in timber buildings must be preserved on land as long as possible, so that their components can be not only reused or recycled, but also sold in the market as used wood. Smaller components can be recycled in structural and nonstructural components such as flake for panel boards, cellulose insulation or interior finish products [123].

For these reasons, the adoption of biogenic materials in construction should be preferred, but stored carbon and the negative contribution in the WLCA assessment are uncertain and unpredictable.

6.5. NZCB Case Studies

The diffusion of the NZCB standard, as mentioned in the paragraphs above, is still limited. However, there are a few examples described in the literature that belong to the NZCB definition, or they at least try to reduce embodied and operational carbon following the application of some of the strategies described above.

In 2012, the Construction Industry Council (CIC) built the first zero carbon building (ZCB) in Hong Kong, a three-story building with a footprint of approximately 1400 sqm. Specific design strategies helped to reduce the embodied carbon and to offset the remaining through renewable energy production and transfer to the grid, reaching a carbon balance in 50 years [129].

A good example of integrated operational and embodied carbon reduction is provided by the GSK Centre for Sustainable Chemistry in Nottingham, UK (2017), a laboratory of 4500 sqm designed by AECOM. Wooden structures, big internal spaces and specific strategies to reduce the energy consumption of chemical laboratories in combination with winter gardens, green roofs, natural ventilation and PV energy production allowed the building to be awarded BREEAM Gold and LEED Gold. The building reduces its energy consumption by 60% and can offset its embodied carbon in a 25-year life span [130,131].

The application of NZCB strategies in one-off projects to experiment with new technologies can deliver breakthrough solutions that can be later applied in a broader context. For instance, adopting circular economy principles can lead to the reuse of many waste materials that were never associated with architecture. This is the case of the Brighton Waste House by Baker-Brown (2014), in which 85% of the materials originates from the building site and household waste, including toothbrushes, denim cuts and VHS tapes for insulation [132]. Moreover, some papers deepened the application of NZCB strategies at a model scale, understanding when emissions occur during the building life cycle [86,133].

7. Discussion and Conclusions

Net zero carbon buildings may constitute a real change to slow down climate changes, since the construction sector accounts for 38% of total GHG emissions in the world [3]. Currently, the best definition is offered by UKGBC: an NZCB has an overall balance of operational carbon and embodied carbon emissions during its life cycle equal to or less than zero [42]. As discussed in the paper, for each strategy for energy efficiency and carbon reduction targets, it appears that multiple definitions are possible. Anyway, in many cases substantial differences refer to the same word: for example, the ZEB definition can also include embodied energy, becoming very similar to the NZCB definition [25].

The NZCB target is still very difficult to achieve in real life, as shown by the lack of published case studies in the literature, although existing technologies allow the reaching of the goal [86]. Nevertheless, major barriers to NZCB adoption have also to be considered [62]. Particularly, they can be summed up in six categories: economical, legislative, technological, professional, socio-cultural and geographical. Simultaneously, driver classifications include economical, legislative and technological, showing that, in the near future, it desirable for further exploration and application of this standard to be made.

Materials and components with EPD certificates are still hard to find, especially in countries that do not have national databases like Italy, weakening the diffusion of WLCA evaluation and NZCB diffusion. To satisfy the strict requisites of NZCB, comprehensive knowledge and professional quality along the entire supply chain, from design stage to material supply, construction, maintenance and EoL of the building, are in fact necessary. Moreover, the application of carbon-value engineering can reduce both costs and embodied carbon emissions [108].

To conclude, NZCBs are a viable and internationally renowned path to follow to reduce environmental footprints in architecture, but there are still many obstacles toward its diffusion. Future research directions may concentrate on the relationship between buildings and carbon-neutral materials and components and on new simplified ways to assess embodied carbon and its reduction path. Legislative frameworks must globally include carbon assessments for buildings and construction products as among the requirements prior to mass production.

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Abbreviations

ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
AZCB	Absolute Zero Carbon Buildings
BaU	Business as Usual
BIM	Building Information Modeling
BREEAM	Building Research Establishment Environmental Assessment Methodology
CCU	Carbon Capture Unit
CED	Cumulative Energy Demand
CNB	Carbon Negative Building
CO_2e	Carbon Dioxide Equivalent
CO_2VE	Carbon Value Engineering
COP	Conference of Parties
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen

DT	Digital Twins
EoL	End of Life
EPBD	Energy Performance of Buildings Directive
EPD	Environmental Product Declaration
GHG	Greenhouse gases
HVAC	Heating, Ventilation and Air Conditioning
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	Life-Cycle Analysis
LCC	Life-Cycle Cost
LCI	Life-Cycle Inventory
LC-ZEB	Life-Cycle Zero Energy Buildings
LEED	Leadership in Energy and Environmental Design
LULUCF	Land Use, Land-Use Change and Forestry
NBS	Nature-Based Solutions
NDCs	Nationally Determined Contributions
nZEB	Nearly Zero Energy Building
NZCB	Net Zero Carbon Building
NZEB	Net Zero Energy Building
OECD	Organisation for Economic Co-operation and Development
PV	Photovoltaics
TQA	Total Quality Assessment
UKGBC	UK Green Building Council
UNFCCC	United Nations Framework Convention on Climate Change
VE	Value Engineering
WLCA	Whole-Life Carbon Assessment
ZCB	Zero Carbon Buildings
ZEB	Zero Energy Building

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