

Article

From Nearly Zero Energy to Carbon-Neutral: Case Study of a Hospitality Building

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Abstract: In recent years, many cities around the world have pledged to upgrade their building stocks to carbon-neutral. However, the literature does not yet provide a shared definition of carbon-neutral building (CNB), and the assessment objectives and methodological approaches are vague and fragmented. Starting from the available standards and scientific literature on life cycle assessment (LCA), this paper advances an operational definition for CNB on the basis of an explicit calculation approach. It then applies the definition to an urban case study, comparing it against a state-of-the-art nearly Zero Energy Building (nZEB) scenario, with the intent of highlighting the major practical limitations connected to the application of a methodologically sound carbon neutrality calculation. The case study shows that carbon neutral objectives can hardly be achieved by single urban buildings because of the lack of spaces that can provide onsite carbon offsetting actions. Carbon neutrality may be better approached at the city, regional, or national scales, where overarching policies may be defined.



Citation: Causone, F.; Tatti, A.; Alongi, A. From Nearly Zero Energy to Carbon-Neutral: Case Study of a Hospitality Building. *Appl. Sci.* **2021**, *11*, 10148. <https://doi.org/10.3390/app112110148>

Academic Editors:
Francesco Salamone, Lorenzo Belussi, Ludovico Danza, Francesco Guarino and Sonia Longo

Received: 27 August 2021
Accepted: 26 October 2021
Published: 29 October 2021

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Keywords: carbon neutrality; carbon-neutral building; zero-carbon building; building carbon footprint; nZEB

1. Introduction

In recent years, efforts to reduce the environmental impacts of the construction sector have led to continuous refinements and upgrades of nearly Zero Energy Building (nZEB) policies towards an even more sustainable building approach: the carbon-neutral building (CNB) or the zero-carbon building (ZCB). Decreasing the carbon footprints of buildings, and increasing the green infrastructures of cities, can be key actions to combat global warming and to meet the Paris Agreement Goal. However, less than 1% of the buildings in the world may currently be labelled as “carbon-neutral” [1,2]. The massive use of resources, and the related environmental impacts, are evident in the construction sector that, in 2018, globally accounted for 36% of final energy use, and 39% of energy and process-related carbon dioxide (CO₂) emissions. In particular, 11% of the emissions resulted from manufacturing building materials and products, such as steel, cement, and glass, and 28% resulted from building operations [3,4]. For this reason, a carbon-neutral approach has been adopted in several countries and regions as a governmental climate change strategy [5]. A roadmap for moving to a competitive low-carbon economy by 2050 has been set by the European Commission since 2011 [6], while, in November 2018, the European Commission presented a long-term strategy for the EU to achieve a climate-neutral economy by 2050. In June 2019, EU leaders called on EU countries and the Commission to work to ensure a transition toward a climate-neutral EU, in line with the Paris Agreement [7–9]. As part of this broad scenario, many cities in the world (not only in the EU) pledged to become carbon-neutral by 2050, and are developing projects to achieve this objective, as summarized by the document “Paris, an air of change” [10]. Moreover, in 2018, 19 cities all over the world committed to put in place regulations requiring all new buildings to be carbon-neutral by 2030, and existing ones to reach the same goal by 2050 [11]. This pledge from cities is part of the World

Green Building Council's Net Zero Carbon Building Commitment, officially launched at the Global Climate Action Summit in September 2018, that challenges companies, cities, states, and regions to reach net-zero operating emissions in their portfolios by 2030, and to advocate for all buildings to be net-zero in operation by 2050 [12]. As part of this community, 48 businesses and organizations, 28 cities all over the world, and 6 states and regions are showing and sharing their lessons learnt, as well as the knowledge and frameworks to develop globally ambitious, yet locally relevant, flexible, and universally viable solutions for their portfolios in order to both reduce energy demand and achieve net-zero carbon emissions [12].

Nevertheless, the uptake of the CNB approach is low, far from the mainstream practice of building [13]. The first CNB in Hong Kong was commissioned by the Construction Industry Council (CIC) and constructed in 2012 [5,14,15], and the construction of the first carbon-neutral office building in Melbourne started in mid-2009 [16], while, in 2019, Mohawk College's Joyce Centre for Partnership and Innovation was selected by the Canada Green Building Council (CaGBC) as a national pilot project to demonstrate its new net-zero energy carbon standard and validation process [17].

Other examples of the applied CNB/ZCB approach include guidelines and directives promoted by different countries all over the world, as well as global competitions for innovative carbon-free and resilient urban projects, such as those initiated by the C40 Cities Climate Leadership Group [18]. In 2013, the Australian Government promoted the "Your Home" guidelines that contain environmentally sustainable solutions for designing and building carbon-zero or carbon-positive homes [19]. The Society of Building Science Educators (SBSE), in the framework of the Carbon Neutral Design (CND) Project, provided a guidebook in 2012 to create and disseminate the resources and tools needed to integrate carbon-neutral and zero-energy design into professional architecture programs and practices [20,21]. In 2006, the UK's Department for Communities and Local Government (DCLG) set a timetable to achieve zero-carbon new homes by 2016 [22,23], and, in 2009, the UK's Department of Energy and Climate Change (DECC) provided the "Guidance on Carbon Neutrality" to give an overview of the process that should be followed in order to achieve carbon neutrality, as well as pointers to existing recognized standards and guidance [24]. The city of Vancouver, as part of the Greenest City 2020 initiative, established targets involving the achievement of carbon neutrality for all new buildings by 2030, and the same applies to the Canada Green Building Council that, with the 2012 Strategic Plan, set a goal for carbon-neutral buildings and communities by 2030 [25].

Although CNB/ZCB is emerging as an innovative and sustainable building approach [5,22], its understanding is fragmented, and gaps can be identified in the definitions and in policy frameworks. Different aspects of this approach are not globally shared, and the key points of the debate concern: (i) The need for a shared definition for CNB/ZCB (different terms sharing similar, or the same, meanings can be found in the literature, such as carbon-zero building, net-zero carbon building, zero-carbon home, net-zero emissions building, etc.); (ii) The energy use (for specific building services); (iii) The life cycle phases to which carbon emissions are associated; (iv) Whether or not to focus on user-related embodied carbon (e.g., user-transportation-related emissions); (v) The need for recognized solutions to compensate for residual emissions; (vi) How to account for biogenic carbon in bio-based building materials and; (vii) The vagueness about the national and international commitments for moving to a carbon neutral economy by 2050.

This paper tries to bridge some of these gaps: (i) By reporting the available definitions from the literature (Section 2), with the intent to highlight and overcome current misunderstandings; (ii) By proposing a new clear definition for CNB, on the basis of an explicit calculation approach (Section 3); and (iii) By applying it to a representative urban case study with the intent of comparing the CNB performance to the nZEB certification, and of highlighting the major practical limitations connected to the real-world application of a methodologically correct carbon neutrality calculation (Sections 3–5). Finally, Section 6 investigates the possible implications of the pledges made by cities to achieve carbon

neutrality without a clear and shared definition of carbon neutrality and a corresponding assessment procedure.

2. Zero-Carbon and Carbon-Neutral Building Definitions

Since no official definition for CNB/ZCB is already internationally agreed upon, and since there are no clear requirements to be fulfilled to reach carbon neutrality in buildings, countries and companies are referring to quite different definitions, criteria, and guidelines. Therefore, a series of terms sharing similar meanings can be found in the literature [13,26,27]. As an attempt to review the CNB/ZCB definitions, Table 1 reports those containing the terms “carbon” or “emission”, such as “Zero emissions building”, “Zero carbon home”, etc. The last column on the right indicates which impacts, with respect to the whole-building lifecycle, the definition/approach takes into account in the calculations.

Table 1. Summary of CNB/ZCB definitions, core requirements of the definition, and accounted emissions. Please note that the abbreviation “RES” stands for renewable energy sources.

Reference/s	Terminology	Core Requirements of the Definition	Lifecycle Stage Impacts Accounted
Torcellini et al., 2006 [28], Crawley et al., 2009 [28]	Net-zero emissions building	Net-zero energy building, production/purchase of emissions-free renewable energy to offset emissions from all energy used in the building annually	Use stage—operation (yearly)
UK DCLG, 2007 [23], UK DCLG, 2008 [29], Zero Carbon Hub, 2014 [30]	Zero-Carbon Home (or Non-Domestic Building)	High level of energy efficiency, onsite RES exploitation, offset solutions for tackling the remaining emissions. Energy use for space heating, ventilation, hot water, fixed lighting, and appliances taken into account.	Use stage—operation (yearly)
Riedy et al., 2011 [31]	Carbon-zero building	Energy efficiency strategies, onsite energy generation, no net annual emissions from the operation of building incorporated services (heating, cooling, water heater, built-in cooking appliances, fixed lighting, renewable energy generation)	Use stage—operation
SBSE, 2012 [20], SBSE et AIA, 2012 [21]	Carbon-Neutral—Operating Energy (OE)	Sustainable design strategies, onsite RES exploitation, purchase (20% maximum) renewable energy and/or certified renewable energy credits. No fossil fuel greenhouse gas emitting energy to heat and cool the building, and for lighting	Use stage—operation
	Carbon-Neutral—OE + Embodied Energy	Previous definition + offset of the embodied energy associated with the materials used to construct the building	Materials and use stages
	Carbon-Neutral—OE + Site Energy + Occupant Travel	OE definition + offset of the personal carbon emissions associated with the means and distance of travel of all employees and visitors of the building	Use stage + users transportation-related emissions
Light House Sustainable Building Centre Society, 2012 [32]	Carbon-neutral building	Significantly reduced energy consumption, RES exploitation, and use of low-carbon energy sources to meet the remaining demand, carbon offsets	Use stage—operation

Table 1. Cont.

Reference/s	Terminology	Core Requirements of the Definition	Lifecycle Stage Impacts Accounted
Reardon et al., 2013 [33], Pipkorn and Reardon, 2013 [34]	Carbon-zero/carbon-neutral/zero-energy/zero-emission building	Energy efficiency strategies, onsite RES exploitation, net amount of energy generated on site equal to the net amount of energy required by the building over a year	Use stage—operation (yearly)
Architecture 2030, 2014 [35]	Carbon-neutral building	Energy efficiency strategies, satisfaction of energy needs from sources that do not produce CO ₂ emissions resulting in zero-net CO ₂ emissions	Use stage—operation
Selamawit, F. et al., 2016 [36]	ZEB-O÷EQ	CO ₂ or carbon dioxide equivalent (CO ₂ -eq) emissions related to all energy use for operation “O”, except that for equipment and appliances (EQ), compensated through RES generation	Use stage—operation except EQ
	ZEB-O	CO ₂ -eq emissions related to all energy use for operation compensated through RES generation	Use stage—operation
	ZEB-OM	ZEB-O definition considering embodied emissions from materials, “M”, phase	Materials and use stages
	ZEB-COM	ZEB-OM definition considering emissions related to the construction, “C”, phase	Materials, construction, and use stages
	ZEB-COME	ZEB-COM definition considering emissions related to part of the end-of-life, “E”, phase	Materials, construction, use, deconstruction stages
	ZEB-COMPLETE	CO ₂ -eq emissions related to the whole-building lifecycle	Materials, construction, use, deconstruction, disposal stages
EllisDon Corporation, 2018 [17]	Carbon-neutral building	CO ₂ -eq emissions from the construction and operation equal to zero, or balanced by the actions taken to reduce and offset these emissions	Construction and use stages
GBCSA, 2019 [37]	Net Zero/Net Positive Carbon building	Highly energy-efficient building, onsite production and, if necessary, offsite renewables to offset the remaining emissions associated with annual energy use	Use stage—operation (yearly)
Architecture 2030, 2018 [38], Becqué et al., 2019 [1]	(Net)-zero carbon building	High energy efficient building, onsite production or provision of enough carbon-free energy (onsite, offsite renewables, and/or credible offsets) to meet yearly building energy consumption in operation. Balance achieved at building or at the district level	Use stage—operation (yearly)
Becqué et al., 2019 [1]	(Net)-zero carbon building + embodied carbon	definition [17] + offset of the carbon embodied in the building’s construction	Materials and use (yearly operation) stages

Table 1. Cont.

Reference/s	Terminology	Core Requirements of the Definition	Lifecycle Stage Impacts Accounted
UKGBC, 2019 [39]	Net-zero carbon—construction	Zero or negative carbon emissions associated with building’s product and construction through emissions offset or export of onsite renewable energy	Materials production and construction stages
	Net-zero carbon—operational energy	High energy efficient building powered from onsite and/or offsite RES, zero or negative carbon emissions associated with building’s operational energy on an annual basis, offset of remaining carbon emissions	Use stage—operation (yearly)
	Net-zero carbon—whole life	Zero or negative carbon emissions associated with building’s embodied and operational impacts over the life of the building (including its disposal) through energy efficient measures, onsite RES exploitation, emissions offset	Materials production, construction, use, and end-of-life stages
Climate Active, 2020 [40]	Carbon-neutral base building operations	Emissions from the building’s core services (air conditioning, common area, and external lighting, hot water, lifts, car parking, or similar) to be measured and offset	Use stage—operation
	Carbon-neutral—whole building operations	Building’s total emissions (from base building services operation and from equipment and appliances) to be measured and offset	Use stage—operation
USGBC, 2020 [41]	(LEED) Zero-Carbon building	Emissions from delivered energy and occupant transportation to be measured and offset. Carbon offset includes onsite RES generated and exported to the grid, offsite RES procurement, and the purchase of carbon offsets	Use stage—operation and occupants transportation
CaGBC, 2021 [42]	Zero-Carbon Building	Highly energy-efficient building, production/procurement of carbon-free renewable energy, or high-quality carbon offsets, to compensate for the annual emissions from building materials and operations.	Materials and use (yearly operation) stages

According to the CNB/ZCB definitions reported in Table 1, only two (UKGBC [39] and Selamawit, F. et al. [36]) consider the deconstruction/disposal phase, i.e., the end-of-life (EoL) scenarios, while most of them consider only the operational phase of the whole building’s lifecycle. Therefore, the environmental impacts related to the building’s materials production, their assembly procedures and transportation to the construction site, as well as their replacement and their disposal at the end of their service life, are not accounted in the analysis. Moreover, the definitions do not typically include an explicit calculation reference to be used to verify compliance with the goals, but just overall lists of the possible actions of intervention.

A clearer definition related to an explicit calculation and assessment procedure is, thus, urgently needed to define which impacts should be taken into consideration, and to allow comparisons between buildings, districts, and cities.

3. Methodology

In order to overcome the issue highlighted in Section 2, a new operational definition for CNB is proposed as follows: “A carbon-neutral building is defined as a building

able to achieve a net amount of carbon-dioxide-equivalent emissions (CO₂-eq) related to the whole-building lifecycle, equal to zero. Its performance should be assessed through the life cycle assessment (LCA) common framework, provided by ISO 14040:2006 and ISO 14044:2006 [43,44]. In particular, the calculation of the building carbon emissions, in terms of the tons or kilograms of carbon dioxide equivalent (tonCO₂-eq, kgCO₂-eq) emitted into the atmosphere, is based on the EN 15804+A1:2019 and EN 15978:2011, specifically developed for construction products and services [45,46], or on any equivalent or more stringent standard, compliant to EN standards and provided by authorized bodies. The calculation must consider the whole-building lifecycle, from materials production to their disposal and deconstruction, as shown in Figure 1 (the production phase of the construction material (stages A1–A3), the transportation of material to the construction site (stage A4), the installation of the construction materials (stage A5), the replacement and maintenance of materials (stages B4–B5), the energy usage (stage B6), and the disposal and deconstruction of materials (stages C1–C4). No embodied carbon due to user-related activities is (yet) considered in the calculations since they are heavily dependent on the users and their aleatory lifestyle choices, and neither have carbon emissions related to the B1–3 stages that cover the release of greenhouse gases from products and materials (e.g., paints, carpets, etc.) during the normal operation of the building, the carbon emissions of all ordinary maintenance activities (e.g., cleaning), and of the repair of the relevant building components before the end of their service life. Biogenic carbon should not be included in the calculation until scientific literature and standards can provide a shared methodology to assess it. Any residual carbon emissions at the end of the building's service life should be offset. Offsetting criteria can include the financing of local or delocalized vegetation and renewable energy projects, the purchase of certified green energy and carbon credits, and the local contribution of renewable energy on site. The standard service life for a residential building may be assumed as 50 years, unless properly argued (e.g., offices and retails may report a shorter service life), whereas the service lives of the building components and materials should be as declared by the producer. Operational energy-related emissions must derive from dynamic energy simulations, including all the main building services (heating, cooling, ventilation, hot water, lighting, and appliances), and the nomenclature must be compliant with the ISO 52000-1 standard [47].

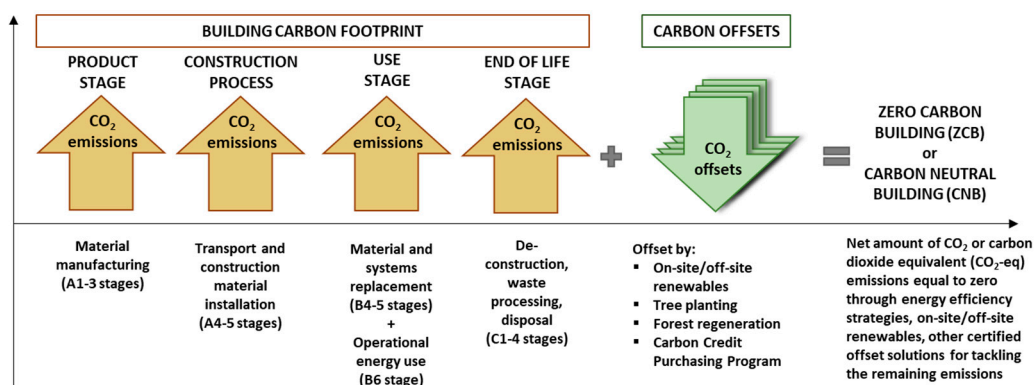


Figure 1. The overall approach to carbon neutrality considered in the study.

In the paper, the new definition of CNB is tested via a case study. In order to assess the practical consequences of the definition on the design, a real lot in an urban environment has been selected, choosing a final use that might provide actual, though challenging, conditions to the carbon neutrality objective. If a countryside single family house, with large envelope surfaces and a relatively small volume, may easily offset its emissions through large active surfaces producing renewable energy, and via the planting of a few trees, an urban building, because of urban laws, including front alignment and limitations in the use of active renewable technologies because of low irradiance values, may experience more

challenging conditions. The selected case study is, thus, a hostel located on an urban lot in Milan, Italy. The calculations are developed both for the CNB objective and for a reference, or state-of-the-art, scenario, which, according to national and regional legislations [48–50], requires reaching the nZEB standard. This will allow for understanding if an nZEB building may also reach carbon neutrality, or how far it might be from it.

According to the new CNB definition, the evaluation of the carbon emissions related to the use stage (B6), the operational energy use in both the nZEB and CNB scenarios, is performed by means of numerical simulations under dynamic conditions, using the calculation suite TRNsys 17 [51], in order to achieve the yearly energy need. The energy use for all of the main building services (heating, cooling, ventilation, hot water, lighting, and appliances) was considered in the calculations. The carbon emissions were assessed via LCA according to ISO 14040:2006, ISO 14044:2006, and to EN 15804+A1:2019 and EN 15978:2011.

A comparison of the results between the CNB and nZEB leads to general considerations about the feasibility of the carbon neutrality objective for urban buildings, either new constructions or renovations, posing important questions to the pledges of cities and businesses.

4. Case Study

The case study is an eight-story hostel building, located in Milan, Italy, with a net average surface per floor above ground equal to about 260 m², while the whole footprint area of the lot is around 600 m² (Figure 2). The building comprises 280 beds distributed in different single and multiple bedrooms between the basement and the seventh floor. The basement is also partially occupied by service systems, while the ground floor is partially occupied by the reception and the common areas of the hostel. The eighth floor is occupied by a private penthouse of about 140 m². Overall, the gross surface is around 2800 m². The windows and transparent elements constitute around 30% of the whole vertical envelope.

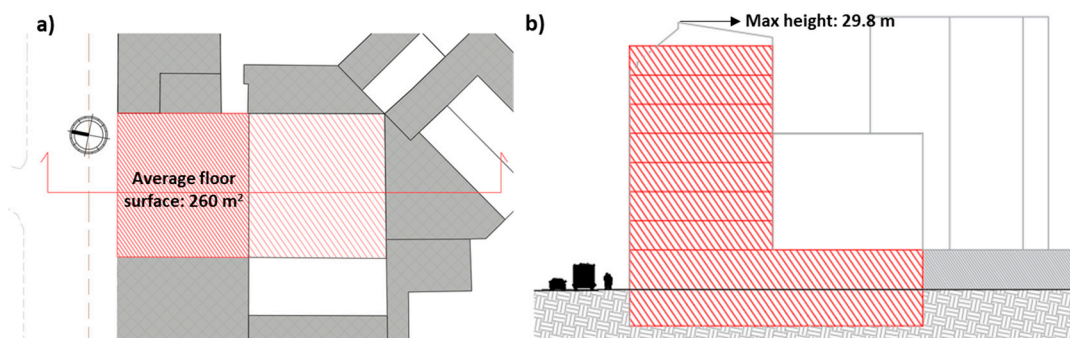


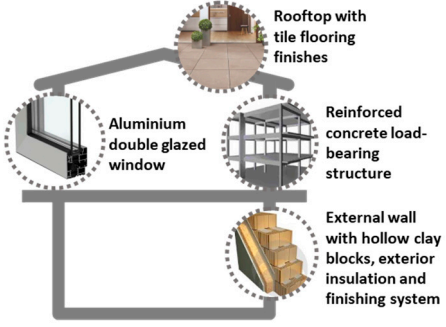
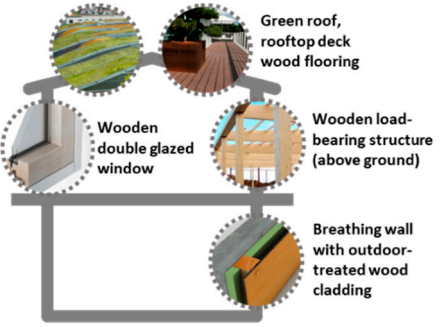
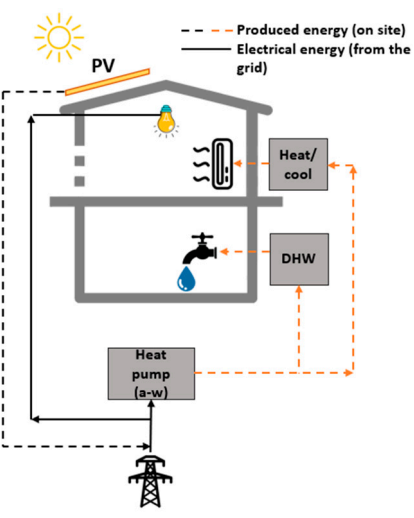
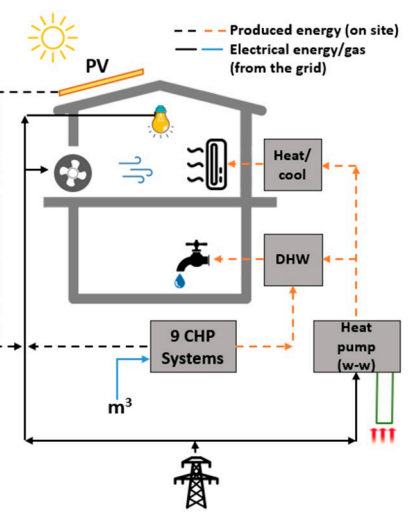
Figure 2. Plan (a) and section (b) views of the building area.

Because of the lack of space for photovoltaic (PV) panels, and the negligible contribution that micro-wind systems may provide in the climate of Milan, the reduction of the overall carbon footprint has to be achieved mainly through a careful choice of materials and construction technologies. Table 2 summarizes the construction technologies and the service systems considered at the end of the design process to achieve, respectively, the nZEB and carbon-neutral targets. It is important to notice that, while for the nZEB, the envelope insulation performance is defined by the Italian legislation, for the CNB, the values reported are the final results of a long design process that took into account not only thermal efficiency, but also architectural and economic constraints. Finally, the geometry of the building was the same for both the nZEB and CNB scenarios.

Since the purpose of the work is to analyze the possibilities and limitations of adopting carbon-neutral buildings at the urban scale, as pledged by many cities and international bodies, in this paper, we do not report the details of the design optimization process or any of the assessments required by the local standards (e.g., structural and fire resistance,

etc.) that have been performed to guarantee the feasibility of the building. The building is, therefore, here presented just as a representative case study. In this section, we only report the outcomes of the design process that led to the fulfillment of the nZEB target (according to Italian legislation), and to carbon neutrality, according to EN 15804+A1:2019 and EN 15978:2011, and the newly provided definition of CNB. In the following sections, we will present the energy and carbon emission outcomes of the analysis that informed the design process, and we will discuss the practical consequences of adopting a carbon-neutral approach for all the buildings in a city.

Table 2. Material and service system technologies considered in the nZEB and CNB scenarios.

nZEB Scenario	CNB Scenario
 <p>Roof with tile flooring finishes</p> <p>Reinforced concrete load-bearing structure</p> <p>External wall with hollow clay blocks, exterior insulation and finishing system</p> <p>Aluminium double glazed window</p>	 <p>Green roof, rooftop deck wood flooring</p> <p>Wooden load-bearing structure (above ground)</p> <p>Breathing wall with outdoor-treated wood cladding</p> <p>Wooden double glazed window</p>
 <p>Legend: - - - Produced energy (on site) — Electrical energy (from the grid)</p> <p>Components: PV, Heat/cool, DHW, Heat pump (a-w)</p>	 <p>Legend: - - - Produced energy (on site) — Electrical energy/gas (from the grid)</p> <p>Components: PV, Heat/cool, DHW, 9 CHP Systems, Heat pump (w-w)</p>
<p>Reinforced concrete structures for the whole building</p>	<p>Wooden structures (above ground) and reinforced concrete structures for the basement</p>
<p>Envelope with hollow clay blocks and mineral wool insulating layer, $U = 0.208 \text{ W/m}^2\text{K}$</p>	<p>Breathing wall with outdoor-treated wood cladding, $U_{BW} = 0.137 \text{ W/m}^2\text{K}$</p>
<p>Double-glazed façade and windows with aluminum frames ($U_{\text{glass}} = 1.4 \text{ W/m}^2\text{K}$, $U_{\text{frame}} = 1.84 \text{ W/m}^2\text{K}$)</p>	<p>Double-glazed façade and windows with low-E glass and wooden frames ($U_{\text{glass}} = 1.0 \text{ W/m}^2\text{K}$, $U_{\text{frame}} = 1.51 \text{ W/m}^2\text{K}$)</p>
<p>Internal horizontal floor slab with cement-based screeds and tile finishes</p>	<p>Internal horizontal floor slab with dry screed and wood finishes</p>
<p>External horizontal envelope with gravel ($U = 0.219 \text{ W/m}^2\text{K}$) or tile flooring finishes ($U = 0.209 \text{ W/m}^2\text{K}$)</p>	<p>External horizontal envelope with green roof ($U = 0.146 \text{ W/m}^2\text{K}$), gravel ($U = 0.150 \text{ W/m}^2\text{K}$) or wood flooring ($U = 0.145 \text{ W/m}^2\text{K}$)</p>
<p>PV (minimum standard requirements) coupled with an air-to-water heat pump</p>	<p>PV and combined heat and power (CHP) systems coupled with a geothermal water-to-water heat pump (GWHP)</p>

4.1. nZEB Scenario

The nZEB scenario is characterized by typical construction technologies: the whole structure is made of reinforced concrete and the vertical envelope is composed of hollow clay blocks (25 cm) and an external mineral wool insulating layer (12 cm). The external horizontal envelope surfaces are characterized by concrete slabs with cement-based screeds, EPS insulating panels (14 cm), and tile flooring or a gravel drainage layer. Double-glazed windows with aluminum frames (and thermal break) were considered in this scenario.

A PV system with a total peak power of 17.8 kW_p was installed on the roof surface to comply with the minimum energy performance requirements defined in the regional legislation, and the heating/cooling and domestic hot water (DHW) demands are covered by an air-to-water heat pump. Finally, fan coils are used as terminal devices in bedrooms, coupled with a dedicated air handling unit (AHU) for mechanical ventilation, whereas the ground floor common areas are conditioned just through an AHU.

4.2. CNB Scenario

Because of the characteristics of the urban lot and regulations, with a bonded orientation and shape, and limited access to solar energy (see Figure 2), the building envelope and systems cannot be conventional ones to achieve the CNB objective, but they must outperform the nZEB approach. Therefore, the CNB scenario is characterized by wooden structures for the floors above ground, and by reinforced concrete structures with a high level of recycled materials for the basement, whereas the limitation of the building's thermal energy need for space heating and cooling was based on a careful design of the building envelope components, and their integration within the system infrastructure. As far as the opaque vertical envelope is concerned, the breathing wall (BW) technology was adopted [52–56]; the overall layer sequence of this technology consists of an external cladding, a ventilated air gap, a multilayer porous core based on air-permeable materials, a second air gap, and an internal cladding. Through a small indoor–outdoor pressure difference, it is possible to generate a low velocity airflow (around 0.001 m/s) driven across the wall, which is integrated into the mechanical ventilation system [57,58] as a heat recovery component and a filter.

The BW technology operates in two modes, according to the direction of the heat flux and the airflow [58]: pro-flux and contra-flux. In the first configuration, the heat flux and the airflow go in the same direction, while they are opposite in the second one. Through the selection of the working regime and airflow velocity, it is possible to: (i) Affect the temperature distribution across the wall [55,56,58]; (ii) Preheat the ventilation air [53], which reaches the same temperature as the interior ventilated air cavity; (iii) Drop the effective thermal transmittance, as shown in the literature [59], and mitigate heat losses due to transmission in winter; (iv) Maximize the heat dissipation through the envelope in summer and exploit night-free cooling (pro-flux); (v) Modulate the effective wall heat capacity [52] and the indoor–outdoor thermal coupling; (vi) Filtrate the incoming ventilation air. BW technology is considered, in the CNB scenario, as a tool to further reduce the energy need with respect to the nZEB scenario, consequently mitigating the CO₂-eq emissions related to the B6 stage of the LCA analysis.

The horizontal structures (roof and terrace) are made, in the CNB scenario, of CLT (cross-laminated timber) slabs, wood-based insulation panels (16 cm), waterproofing and breathable membranes and a gravel drainage layer, and outdoor wood flooring, or a green roof, according to the zone of the building. Table 2 reports the thermal transmittance values (U-values) of the chosen external horizontal and vertical envelope structures. All of the insulating materials of the internal partitions and the external envelope are wood-based, except for the external layer of the BW that, to comply with fire regulations, is made of mineral wool. High-performance low-emissivity double-glazed windows with wooden frames were considered for the transparent envelope.

The high envelope performance is complemented by the local production of renewable electric energy by means of 72 PV panels, of 300 W_p each, installed on the roof, for a total

peak power of 21.6 kW_p, overcoming the minimum nZEB requirements. The size of the PV plant, as declared previously, is, nevertheless, limited by the small roof area available and by the urban context (i.e., shadows projected by adjacent buildings). To further increase the local production, electric energy, as well as thermal energy, are also generated by 9 micro-combined heat and power (CHP) systems, based on fuel-cell technology, able to produce 0.9 kW_{TH}, used for DHW, and 1.5 kW_{EL} each, with an hourly natural gas consumption of 0.25 m³/h. The micro-CHP systems are coupled with a geothermal water-to-water heat pump (GWHP) of 300 kW_{TH} to cover the heating/cooling loads. The DHW is managed by two thermal storage boilers of 5000 L each, supplied by the CHP systems. Fan coils are used as terminal devices in the bedrooms, while the ground floor common areas are conditioned through an AHU. In each bedroom, to effectively exploit the BW function of filter and air pretreatment, a localized mechanical ventilation system was designed to be installed over the windows in order to modulate the airflow according to the number of people inside the rooms, and to reduce the thermal loads.

4.3. Energy Model

The energy use is calculated in both scenarios through dynamic simulations over one year, performed using the calculation suite TRNsys 17 [51], and considering Milan's typical meteorological year (i.e., MI_Linate_1951-1970 weather file [60,61]).

4.3.1. Thermal Zones and Occupancy Profiles

Thermal zones have been set as clusters of rooms located at the same story and provided with the same features (e.g., type of facilities, activity, orientation, etc.): in the basement, there is a thermal zone for the bar and another for the bedrooms; at the ground floor, there is a zone for the reception and another zone for the bedrooms; from floors 1 to 7, a total of 14 thermal zones are defined for bedrooms; and finally, the penthouse is divided into two zones (one for the kitchen and another for the rest of the flat). Every floor is also provided with a thermal zone dedicated to stairs and corridors. Table A1 lists all the thermal zones, along with their gross dimensions, the internal load sources, the ventilation systems, and the heating/cooling supply devices.

Taking into consideration the receptive function of the building (Figure 3), a yearly occupation profile was established, then a daily occupancy profile (Figure 4), and a heating/cooling plant schedule (Figure 5) was defined for each zone, according to the suggestions provided by the hostel manager who took part in the design process. As far as the heating and cooling plant activation was concerned, it is important to notice that the temperature control switches from a full set-point (20 °C in winter and 26 °C in summer) to a reduced one (18 °C in winter and 28 °C in summer). The effective occupation percentage of each zone at any given timestamp is obtained by multiplying the overall yearly occupation factor from Figure 3 by the thermal zone daily occupation factor from Figure 4.

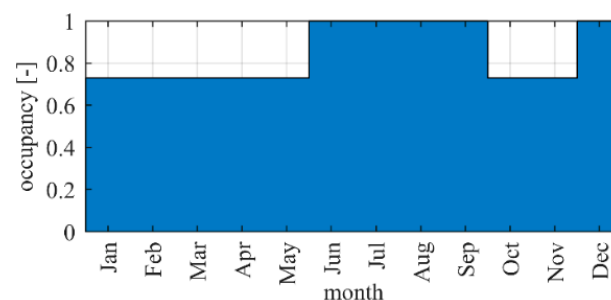


Figure 3. Annual occupancy profile of the overall building.

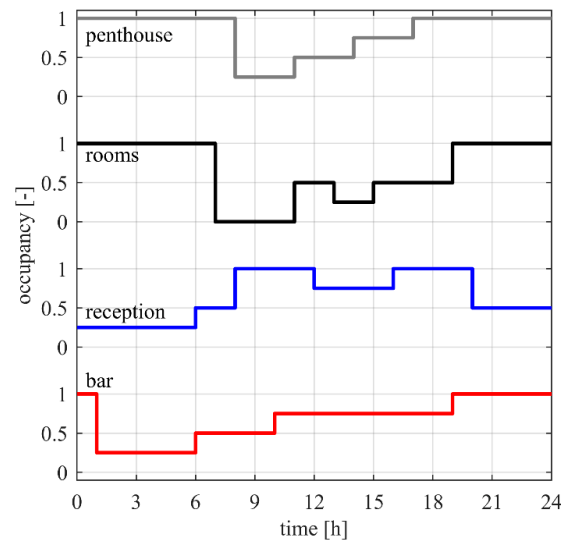


Figure 4. Daily occupancy profile of the thermal zone in the building.

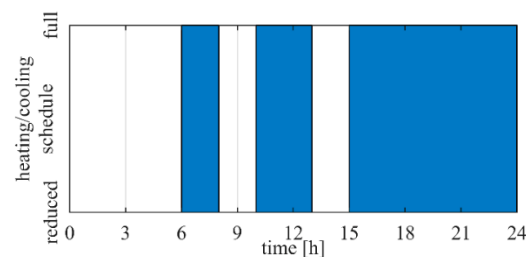


Figure 5. Heating and cooling plant daily schedule.

4.3.2. Heat Transfer Calculation

TRNsys 17 uses the transfer function approach to manage the heat transfer problem across capacitive opaque structures. The inner and outer surface heat flux densities at any given time are related to their values in the past timestamps, along with the corresponding past and present surface temperature values. Every structure is treated as a black box, i.e., the model is able to provide a reliable depiction of the superficial temperature and heat flux density conditions for a given set of boundary conditions, but it is not able to calculate the temperature distribution across the considered structure. Moreover, the coefficients for the heat transfer function of each structure are calculated in a preprocessing phase, according to the geometry and the thermophysical properties of the layers. Even though this approach is adequate to simulate the standard envelope foreseen by the nZEB scenario, it is not able to manage the dynamic changes in thermal behavior typical of the BW technology chosen for the CNB scenario. In this scenario, the functions of TRNsys 17 are integrated through the development of a dedicated finite difference algorithm [54,62]. This numerical method, although more computationally expensive, allows for the simulation of the evolution over time of the temperature distribution within a multilayer structure, taking into account unsteady boundary conditions (indoor and outdoor air temperatures, solar radiation), and airflows crossing the layers with variable velocity.

At the same time, airflow velocity is treated as an input, calculated according to a dedicated control strategy. The algorithm is then coupled with the building module inside TRNsys 17 (namely TRNbuild), which is able to simulate the overall BW component performance, both in terms of conduction heat transfer, and heat recovery on the ventilation component.

4.3.3. Ventilation

Ventilation air-change rates are set according to the technology implemented, as shown in Table A1. For each thermal zone provided by a daily occupancy profile, its hourly value was used to modulate the air-change rate between a null value (the system is shut down if there are no occupants), and a maximum value corresponding to the maximum occupation defined (Table A1). This approach simulates the feedback of a presence or CO₂ sensor. Moreover, traditional heat recovery units were used in the models of both buildings, with an average recovery efficiency of 0.7.

The ventilation provided by the BW was defined proportionally to the number of people in the thermal zone at any given time, as for the AHU. Moreover, the ability of this technology to recover heat was considered. If the air was supplied into the thermal zone after crossing the wall, the fluid temperature was calculated by the finite difference algorithm, while it was set equal to the outdoor temperature if the wall worked as exhaust and the air was supplied by a dedicated vent. At this stage, a simple control algorithm was implemented: under heating conditions, air intake happens through the BW when the outdoor air temperature is below the indoor set-point, and it is exhausted through the wall the rest of the time, while the opposite logic is active in the cooling season.

4.3.4. Internal Gains

The occupancy profile for each thermal zone was defined in agreement with the intended use, also taking into account the corresponding level of activity, along with the number of occupants. The resulting maximum value was modulated during every timestamp according to the yearly and daily occupancy profiles.

A similar approach was used in dealing with the loads because of artificial lighting to simulate the action of presence sensors. Additional profiles were also introduced to simulate the loads coming from other appliances. More details about all the internal gains are reported in Appendix A.

Because of the high level of innovation introduced in the envelope, and the lack of previous experience in the application of the BW technology to full-scale buildings, internal gains have been augmented during the cooling season and reduced during the heating season, as a safety factor.

4.3.5. Heating and Cooling Plants

Once the energy need profiles for the CNB and the nZEB scenarios were obtained, as ideal thermal loads through the numerical simulations performed in TRNsys 17, all the subsystems of the heating and cooling plants were taken into consideration, i.e., emission, regulation, distribution, and generation. For the first three subsystems, suitable efficiencies were applied in compliance with the national technical standards [63,64] (Table A2), since the design process at the stage considered in this work is not advanced enough to allow the detailed simulation of every component of the plant. The result is the energy delivered by the generation system, further adapted to obtain the corresponding absorbed electrical energy profile by dividing all the hourly values, by either the heat pump seasonal coefficient of performance (SCOP—heating season), or the chiller seasonal energy efficiency ratio (SEER—cooling season), which are defined according to the technology implemented in each building scenario. For the nZEB scenario, a SCOP of 2.8 and a SEER of 2.8 were adopted, whereas for the CNB scenario, a SCOP of 4.3 and a SEER of 4.7 were assumed. At the same time, the profiles of energy delivered by the generation system were used to estimate the hourly electrical energy use due to the heating and cooling plant auxiliaries (pumps, motorized valves, fan-coils, etc.). It was assumed that the energy consumption due to auxiliaries is, at any given timestamp, proportional to the ratio between the instantaneous value of the energy delivered by the generation system and its maximum annual value.

4.3.6. DHW Consumption and Electric Appliances

The energy consumption related to DHW production was based on the definition of a daily requirement profile for the overall building: a load curve that provides the percentage of the overall water daily need was defined (Figure 6). The corresponding hourly energy consumption was calculated according to the generation system implemented (electrical heat pump in the nZEB scenario, micro-CHP and GWHP in the CNB scenario).

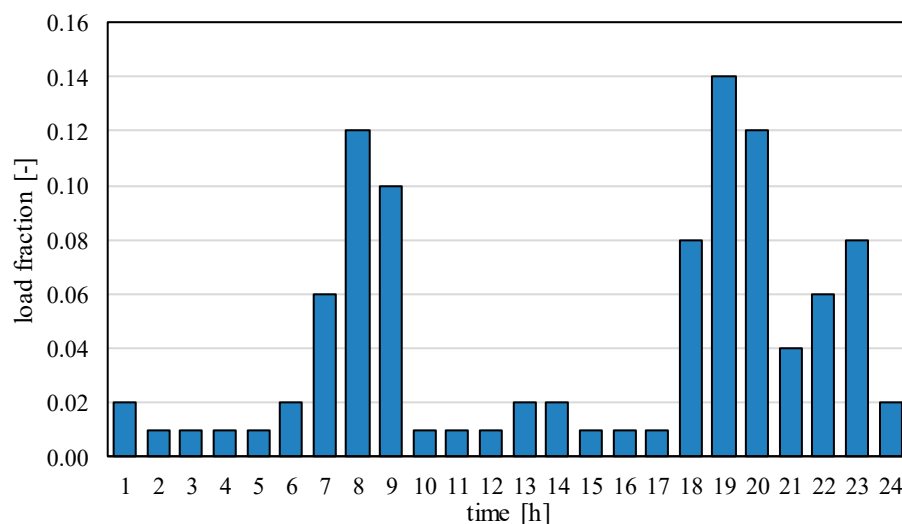


Figure 6. Daily load curves for the hot water need.

In this work, lights and appliances were considered too, taking into account small devices (e.g., smartphones, laptops) for rooms, vacuum cleaners for all spaces, and electric equipment related to the bar and the penthouse for both scenarios (Table A3). For each component, an annual time schedule was defined to achieve a total electricity consumption, used in both scenarios. These energy uses were included in the analyses since they prove to be relevant in the overall energy balance of a carbon-neutral building in an urban context.

4.3.7. Electric Production

The overall energy production for both scenarios was computed. For the nZEB only, PVs were considered, while for the CNB, energy came from both the micro-CHP and PV panels. The overall energy production profile was, in both cases, subtracted from the corresponding energy use profile to finally get the total CO₂-eq annual emissions.

4.4. Assessment of the Whole-Building Life Cycle Carbon Emissions

The building carbon emission assessment was based on the EN 15804+A1:2019 and EN 15978:2011. The EN 15978 provides a framework for calculating and assessing environmental performance at the building level, for both new and existing buildings, whereas the EN 15804 provides the structure to develop the environmental product declarations (EPDs) for all construction products and construction services. As mentioned in Section 3, and as shown in Figure 1, the approach adopted in this study considers the whole-building life cycle, from material production to the disposal and deconstruction, and it is based on data gathered from EPDs and the ecoinvent database [65].

The calculation of the CO₂-eq emissions under the two scenarios was carried out considering a building service life of 50 years, since the final use may be assimilated to the residential one, and was performed using a combination of commercial software, trying to exploit their best characteristics. In particular, for phases A1–A5, B4–B5, and C1–C4, One Click LCA software [66], specifically developed for the LCA analysis of buildings, was used, while the B6 stage's CO₂-eq emissions were assessed through SimaPro 8.5.2.0 software [67] in order to better model the micro-CHP systems. The boundaries of the

system were expanded to consider the CO₂-eq emissions of specific energy end-uses of the building (e.g., HVAC, DHW, appliances, and lighting energy uses) and specific EoL scenarios (e.g., demolition/deconstruction, waste processing, and disposal).

4.4.1. Product Stage A1–3 (Construction Materials Production)

The product stage includes carbon emissions derived from the production of building materials, including the extraction of their raw components (A1), the transportation of raw materials to the production site (A2), and the manufacturing process (A3). In this study, the CNB scenario is characterized by more sustainable wood-based materials for the main technological unit classes (load-bearing structure, vertical and horizontal envelope, and internal partitions), while the nZEB scenario has more traditional construction technologies, typically used in the Italian construction sector. Tables A4 and A5, in the Annex, report the environmental impacts of each technological unit and the material considered in the analysis for the nZEB and CNB scenarios. The quantity of construction materials was estimated through project analysis and investigations.

4.4.2. Construction Stage A4–5 (Construction Materials Transportation and Installation)

The construction stage refers to the emissions related to the transportation of materials from the manufacturer to the construction site (A4), and those related to the installation of construction materials (A5). Factors that affect the emissions of this stage are the location of the construction site, the building size, and the type of energy used in the construction site [68].

Materials produced as close as possible to the construction site were selected for the A4 phases of both scenarios, and the distances from the manufacturer construction site to the building site were inserted in One Click LCA software. The CO₂-eq emissions of stage A5 (construction materials installation) were, instead, calculated using the hypothesis included in One Click LCA software that considers a waste production of 5 kg/m², an energy use equal to 25 kWh/m², and a total use of diesel fuel equal to 3.5 L/m², corresponding to 22.07 kgCO₂-eq/m² of the gross surface area of the building. Therefore, considering the same building with the same surfaces and footprint areas, the same environmental impacts were estimated between the two analyzed scenarios.

4.4.3. Use Stage B4–6 (Construction Materials Replacement and Energy Use)

The use phase accounts for most of the CO₂-eq emissions in the lifecycle of buildings and generally reflects the building energy performance. The building location, occupation type, and energy source directly affect the energy consumption [68]. Associated to this stage, the replacement and the refurbishment works (B4–5) were considered in both the scenarios, according to the service life of each construction material, as declared in each EPD, and the impacts were calculated through One Click LCA software.

As far as the energy-use stage of the building (B6) is concerned, as already mentioned, the calculation of the environmental impacts was carried out through SimaPro 8.5.2.0 to better define the CO₂-eq emissions due to the 9 micro-CHP fuel-cell systems (considered in the CNB scenario), able to produce 0.9 kW_{TH} and 1.5 kW_{EL} (thermal and electric) each, with an hourly natural gas consumption of 0.25 m³/h. To assess the environmental impacts due to the thermal and electric energy production by the CHP systems, a 2 kW CHP system process present within the SimaPro 8.5.2.0 software was considered and adapted to the case study. The process was modeled according to two different scenarios for the allocation of environmental impacts, based on the products and coproducts generated by the CHP system. The scenarios considered were based, in one case, on the exergetic allocation of impacts, which considers the two CHP products (electricity and thermal energy), and, in the other, on the allocation of impacts considering only the electricity as a product of the CHP [65].

The exergetic allocation produces 0.354 kgCO₂-eq per each generated electric kWh_{EL}, and 0.275 kgCO₂-eq per each generated thermal kWh_{TH}, while the second scenario (electricity allocation) produces 0.47 kgCO₂-eq per each generated electric kWh_{EL}, and null emissions to produce thermal energy. To assess the environmental impacts related to the

electric energy supplied by the national grid and used on site, an emission factor equal to 0.414 kgCO₂-eq/kWh_{EL} [67,69] was used. Therefore, the CO₂-eq emissions assessment of the B6 stage for the CNB scenario considered the emissions related to the natural gas consumption, i.e., the emissions related to the production of electric and thermal energy by CHP systems, and the emissions related to the remaining electric energy demand supplied by the national grid, used on site, and not compensated for through onsite RES. The nZEB scenario considers only the electric energy supplied by the national grid and not compensated through onsite RES.

4.4.4. End-of-Life Stage C1–C4 (Materials Disposal/Deconstruction)

The environmental impacts of stages C1–C4 (the disposal and deconstruction of the construction materials used in the building), were considered in both scenarios, as defined in the One Click LCA software, and as reported in Table 3.

Table 3. Phase C1–C4: waste treatment processes considered in the calculation.

Material	Waste Treatment and Landfill
Mineral materials (cement, stone, ceramic, etc.)	Preparation for recycling
Metals	Preparation for recycling
Natural matrix materials	Incineration of construction waste for energy recovery
Other materials (synthetic materials, glass, etc.)	Disposal of inert construction waste in landfills

4.4.5. Evaluation of Benefits and Loads beyond the System Boundary (Stage D)

Consistently, with a cradle-to-cradle approach, in the construction sector, the benefits and burdens of disposal after demolition can be considered with stage D, which is aimed at exploring the potential of reusing, recovering, and recycling the building and its components. The EN 15804+A1:2019 and EN 15978:2011 standards contain minimum indications on how to consider the stage D, related to construction materials after their disposal. This stage is to be considered optional [70] and, therefore, we decided not to include it in the calculation, waiting for advancement and agreement in the research.

4.4.6. Biogenic CO₂

Products with a natural origin, such as wood, contain within them the so-called biogenic CO₂, which is the quantity of CO₂ transformed into biomass by the trees, up to the moment of their cutting and transformation into building products. This CO₂ remains incorporated within the construction elements until their EoL, when it is finally partly, or totally, emitted into the atmosphere, according to the expected scenario (e.g., incineration with or without heat recovery, landfill disposal, reuse or recycling). There is, therefore, a considerable time difference between the biogenic CO₂ sequestration and its release into the atmosphere. Whether, and how, to evaluate this emission lag is a topic strongly debated in the scientific literature [70–73], and three main approaches are used for the assessment of biogenic carbon (i.e., the −1/+1 approach, the 0/0 approach, and the dynamic approach of biogenic carbon calculation) [73]. The updated version of the EN 15804+A1:2019 reports this as an optional phase but, nevertheless, it suggests the −1/+1 approach whenever biogenic CO₂ is considered. This implies that the uptake of biogenic CO₂ during the forest growth is transferred to the building elements and reported as a negative emission in module A (−1 kgCO₂-eq/kg CO₂ of biogenic origin) and, subsequently, released in the EoL scenario of the building or, in case of recycling, transferred to another product system (+1 kgCO₂-eq/kg CO₂ of biogenic origin) [45,73]. The dynamic approach for biogenic carbon calculation is reported in scientific papers only, while EPDs mainly follow the 0/0 approach [73]. Given the as-of-yet blurred and non-agreed-upon approach to the topic, we preferred to adopt a conservative attitude, not including biogenic CO₂ in the A1–A3 stage.

5. Results

5.1. Energy Simulation Results

The first outcome of the described simulation process was the thermal energy need profile for heating and cooling, for both scenarios. These data have been used to calculate the overall electrical energy use, along with the natural gas one.

5.1.1. Heating and Cooling Energy Needs

Figure 7 shows the daily thermal energy needs calculated for the two scenarios, according to Section 4.3. It is possible to observe that the heating performance of the CNB is much better than the one of the nZEB, whereas the cooling performance is comparable. The adoption of the design strategies previously described leads to an annual thermal energy need reduction of approximately 31% from the nZEB to the CNB scenario.

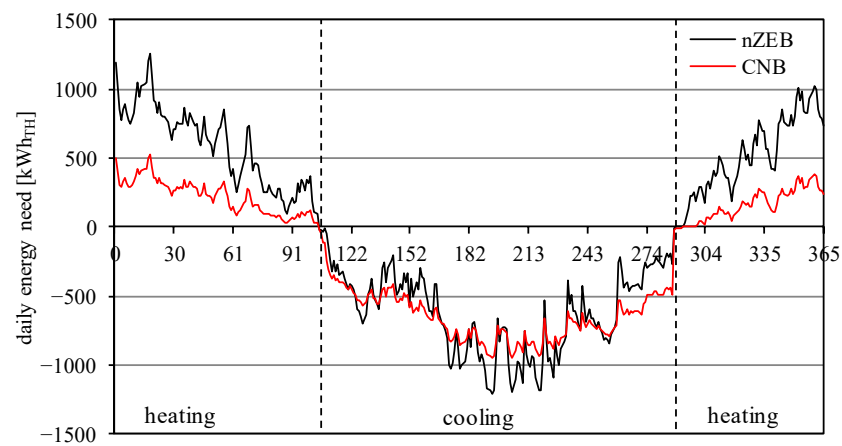


Figure 7. Net and gross daily thermal energy need profiles for the nZEB and CNB building models.

The energy delivered by the generation system was obtained, adding to the thermal energy needs all the losses related to the distribution, control, and emission systems, through the efficiencies reported in Table A2. Finally, the outcome of this process led to the monthly electrical energy uses reported in Figure 8. Concerning the annual values, a total electrical energy use of 161.60 MWh_{EL} and 89.52 MWh_{EL} was calculated for the nZEB and the CNB, respectively, corresponding to a 44.6% reduction.

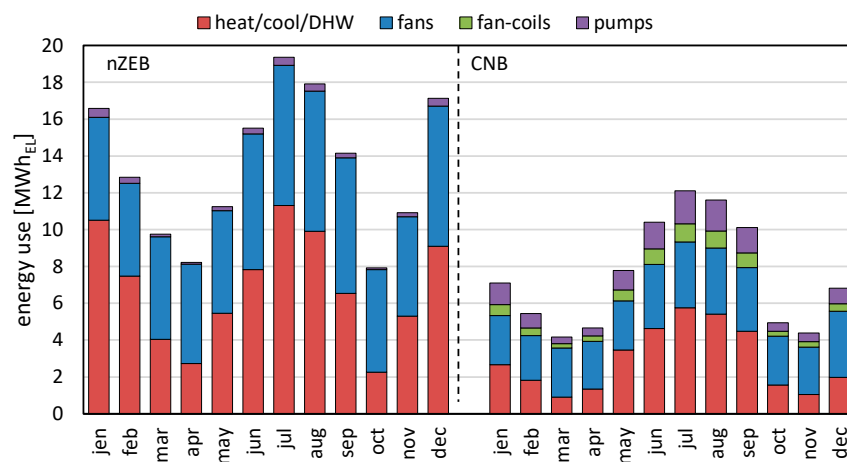


Figure 8. Overall monthly electric energy uses for heating and cooling, for nZEB (left) and CNB (right) buildings.

5.1.2. DHW Energy Use

The electrical energy use related to the production of DHW was calculated starting from the load curve reported in Figure 6. The hourly coefficients were then multiplied by the overall daily water need corresponding to the considered scenario. As far as the nZEB was concerned, a baseline of 33,228 L/day was set, corresponding to a hot water need of 130 L/day for each bed, with a contemporaneity factor of 0.9. This value was also used to calculate the corresponding quantity for the CNB; nevertheless, in order to reduce the water consumption and the corresponding energy use, in the CNB scenario, water mist nozzles were considered as water taps and showers in every room, allowing a reduction in the water requirement. Even though commercial products declare a reduction between 65% and 98%, a more conservative value of 30% was assumed in this work, leading to a daily overall water need of 23,260 L/day for the CNB. Once the DHW daily load profile was obtained for both scenarios, the corresponding annual curve was achieved considering the yearly occupancy profile for the whole building and, finally, the corresponding thermal energy need, with the assumption of a cold-water supply temperature of 10 °C, and a set-point temperature of 42 °C. For each scenario, the corresponding generation system was then considered to achieve the overall electrical energy and natural gas use, according to the technology involved. Moreover, the energy consumption related to circulation pumps was considered, with the weighting factor calculated as the ratio between the instantaneous and the daily maximum water need.

In the nZEB scenario, the electrical energy use related to hot water production comes from the electric heat pump (SCOP 2.8) and the circulation pump to the users (0.9 kW). In the CNB scenario, the base heat source to produce hot water consists of the 9 micro-CHP, with a total nominal thermal output of 8.1 kW, while the rest of the energy is provided by the GWHP (SCOP 4.3). Moreover, the circulation pumps were considered both for the CHPs and the users' sides (0.6 kW and 0.9 kW, respectively). According to these data, the overall electrical energy needed to produce DHW in the nZEB was 196.12 MWh_{EL}, whereas in the CNB, there was a combined consumption of electric energy and thermal energy (to run the CHPs), with annual total values of 80.46 MWh_{EL} and 265.77 MWh_{TH} (corresponding to an annual natural gas consumption of 19,710 m³).

5.1.3. Lights and Appliances

The electric energy use related to lights and appliances was based on the data reported in Table A3. These values lead to a total electric energy use of 28.66 MWh_{EL}, which was considered for both scenarios.

5.1.4. Onsite Energy Production

Both scenarios rely on a PV plant to locally produce electric energy from renewable sources. For the nZEB, the regulation limit peak power of 17.8 kW_p has been met, providing a useful production of 18.46 MWh_{EL}/year. For the CNB, the PV consists of a grid of 72 horizontal panels able to produce 0.3 kW_p each, corresponding to a total of 21.6 kW_p, with a yearly useful production of 22.34 MWh_{EL}/year, overcoming the minimum requirements of the nZEB. Because of the small geometrical footprint of the building, and the urban density determining the constant shading from other buildings, it is not economically feasible to increase the PV system dimensions above this limit.

For this reason, in order to increase the local energy production in the CNB scenario, the 9 CHPs previously presented were implemented. Each of them can produce 0.9 kW_{TH}, used for domestic hot water production, as discussed above, and 1.5 kW_{EL} each, with an hourly natural gas consumption of 0.25 m³/h. Therefore, the overall 19,710 m³ natural gas consumption previously mentioned allows for the production of 118.26 MWh_{EL}/year.

5.1.5. Overall Energy Balance

All of the calculations previously discussed led to the overall electric energy use for both scenarios. In Figure 9, each electric energy and natural gas use considered is depicted, along with the local energy production (represented with negative values), and the overall nonrenewable primary energy need.

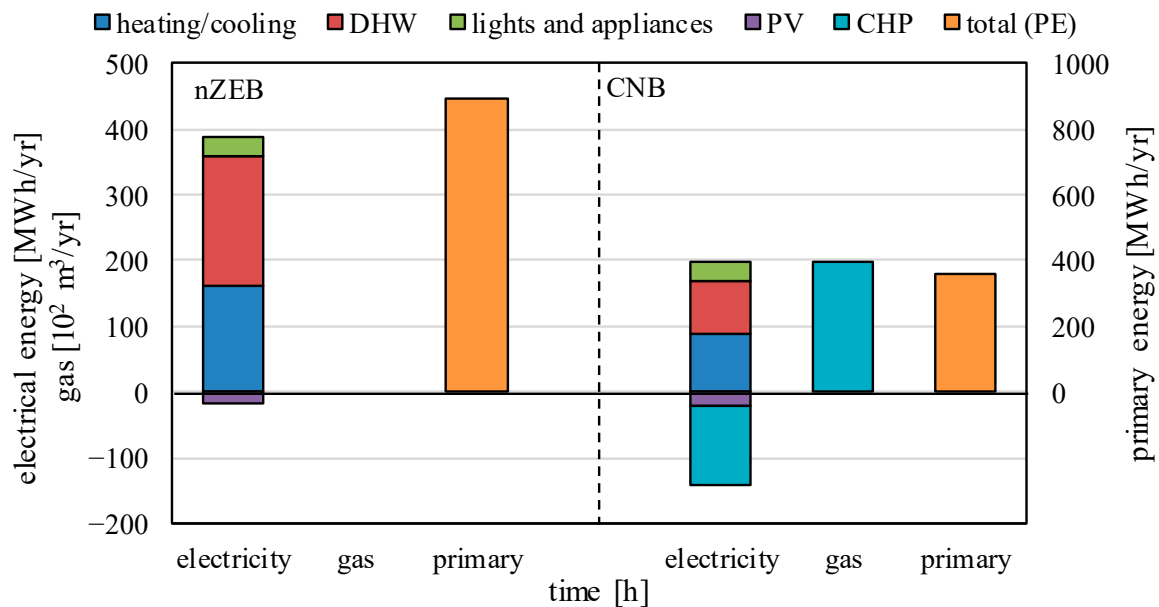


Figure 9. Overall consumption and production.

The annual electric energy use for all the services of the building is 386.4 MWh_{EL}/year and 198.6 MWh_{EL}/year for the nZEB and the CNB, respectively, while the natural gas consumption for the operation of the CHPs in the CNB scenario is equal to 210.7 MWh/year. The local energy production is 18.5 MWh_{EL}/year and 140.6 MWh_{EL}/year, corresponding to 4.8% and 70.8% of the total use. It is important to notice that, in both scenarios, the electrical energy uses related to lights and appliances are comparable to the local production through PV, due to the limited roof area available and the projected shadows typical of a congested urban context. This demonstrates that it is important to take this element of the energy balance into consideration when dealing with the operational phase of a building in urban environment. Moreover, in terms of primary energy, considering that the national average conversion factors are equal to 2.42 and 1.05 for electricity and natural gas, respectively [49], along with a conversion rate of 10.6 kWh/m³ for the latter, the overall nonrenewable primary energy for the nZEB is 890.4 MWh_{PR}/year, while for the CNB, it is 361.7 MWh_{PR}/year (140.5 MWh_{PR}/year from electricity use and 221.2 MWh_{PR}/year from gas). This means that the design process that led to the CNB scenario allowed for a reduction in the primary energy of about 59%, compared to the nZEB scenario (Table 4).

Table 4. nZEB and CNB energy performance per year.

End-Uses Electric Energy Use per Year				
End-Use	nZEB Scenario	CNB Scenario	Unit	Difference CNB vs. nZEB %
Bedrooms	14.4	14.4	MWh _{EL} /year	
Common areas lighting	7.5	7.5	MWh _{EL} /year	0%
Common areas (appliances, etc.)	6.8	6.8	MWh _{EL} /year	
DHW	196.1	80.5	MWh _{EL} /year	−59%
Heating/cooling	161.6	89.5	MWh _{EL} /year	−45%
Total electric energy use per year	386.4	198.6	MWh _{EL} /year	−49%
Natural gas consumption per year (not available for the nZEB scenario)				
CHP		19,710.0	m ³ /year	
CHP	n.a.	210.7	MWh/year	n.a.
Electric energy produced on site per year				
Photovoltaic production	18.5	22.3	MWh _{EL} /year	+21%
CHP production	0.0	118.3	MWh _{EL} /year	n.a.
Total electrical energy produced on site	18.5	140.6	MWh _{EL} /year	+662%
Thermal energy produced by CHP				
Thermal energy produced by CHP	n.a.	47.3	MWh _{TH} /year	n.a.
Electrical energy supplied by the electricity grid per year				
	367.9	58.0	MWh _{EL} /year	−84%
Nonrenewable primary energy demand per year				
	890.4	361.7	MWh _{PR} /year	−59%

5.2. Environmental Impacts Results

The environmental impacts were calculated according to the approach and hypothesis described in Section 4.4, through One Click LCA and SimaPro software, and according to the standardized methodology developed for construction products and defined by EN 15978.

5.2.1. Operational Energy Use Stage B6 Environmental Impacts

As shown in Table 4, in the CNB scenario, the electric energy supplied by the power grid is equal to 58.05 MWh_{EL}/year, or 2902.5 MWh_{EL} during the entire life of the building (50 years). In terms of the CO₂-eq emissions, a factor equal to 0.414 tonCO₂-eq/MWh_{EL} [67,69] was used. Therefore, the environmental impacts due to the electric energy use are equal to 1201.6 tonCO₂-eq. In this scenario, in addition to the emissions related to the electricity supplied by the national grid, CO₂-eq emissions due to the natural gas consumption for the operation of the micro-CHP systems should be considered. Adopting the value reported in Table 4 for electricity and natural gas, and the two allocation scenarios described in Section 4.4.3, the total tonCO₂-eq emitted during the entire life of the building were calculated and are presented in Table 5. To assess the CHP impacts on the production of electric and thermal energy, the emission factors presented in Section 4.4 were used according to the exergetic (1), and electricity allocation (2), scenarios. The latter is the worst and the more conservative scenario; for this reason, a total environmental impact of the use phase (B6), equal to 3980.7 tonCO₂-eq_{50 years}, was considered for the CNB scenario.

Table 5. Total impact during the project building use phase (B6) for the CNB scenario.

Impacts Due to the Electric Energy Supplied by the Electricity Grid		
Annual electric energy supplied by the electricity grid	58.05	MWh/year
Electricity emission factor from the national grid	0.414	tonCO ₂ -eq/MWh
Impact of electric energy from the national grid (50 years)	1201.6	tonCO ₂ -eq _{50 years}
CHP Impacts		
Annual electricity produced	118.3	MWh/year
Annual thermal energy produced	47.3	MWh/year
CHP emission impact Scenario 1 (50 years)	2743.6	tonCO ₂ -eq _{50 years}
CHP emission impact Scenario 2 (50 years)	2779.1	tonCO ₂ -eq _{50 years}
Total Environmental Impacts of the Building Use Phase (B6)		
Impacts of CHP (Scenario 1) + impacts due to the electric energy supplied by the electricity grid (50 years)	3945.3	tonCO ₂ -eq _{50 years}
Impacts of CHP (Scenario 2) + impacts due to the electric energy supplied by the electricity grid (50 years)	3980.7	tonCO ₂ -eq _{50 years}

Concerning the nZEB scenario, as shown in Table 4, the onsite production of electric energy is equal to 18.5 MWh/year, and the electric energy use is 367.9 MWh/year. Therefore, considering the same emission factor for electric energy supplied as in the CNB scenario (0.414 tonCO₂-eq/MWh_{EL}), and a service life of the building of 50 years, the environmental impact of the use phase in the nZEB scenario is equal to 7615.9 tonCO₂-eq_{50 years}.

5.2.2. Whole-Building Lifecycle Environmental Impacts

According to the hypotheses and the calculations described so far, the environmental impacts of both scenarios are presented in Table 6. The CNB demonstrates its capability to reduce overall CO₂-eq emissions by 55%, compared to the nZEB scenario. The use phase of the building (B6) has the highest impact in terms of emissions in both scenarios, accounting for 79% of the total emissions in the CNB scenario, and for 68% of the total emissions in the nZEB scenario. The second most impactful phase is the one related to the production of construction materials (A1–A3), which accounts for 14% of the total emissions in the CNB scenario, and for 26% of the total emissions in the nZEB scenario. Details about this phase are reported in Table 7. The remaining life cycle phases, i.e., transportation, construction and installation, replacement, and disposal of material, have an overall impact of 7% in the CNB scenario, and 6% in the nZEB scenario.

Table 6. Building carbon footprint for the analyzed scenarios (CNB vs. nZEB) in the whole lifecycle.

Life Cycle Phase	nZEB		CNB		Difference CNB vs. nZEB [%]
	[tonCO ₂ -eq]	[%]	[tonCO ₂ -eq]	[%]	
A1–A3	2910.0	26%	727.4	14%	−75%
A4	57.1	1%	31.1	1%	−46%
A5	52.1	1%	52.1	1%	0%
B4–B5	361.8	3%	130.4	3%	−64%
B6	7615.9	68%	3980.7	79%	−48%
C1–C4	135.3	1%	94.5	2%	−30%
Total (A1–C4)	11,132.1	100%	5016.2	100%	−55%

Table 7. Material construction phase analysis and impact comparison (A1–A3) for the CNB and the nZEB scenarios (see Tables A4 and A5, in the Annex, for further details).

Technological Unit Classes	nZEB [tonCO ₂ -eq]	CNB [tonCO ₂ -eq]	Difference CNB vs. nZEB [%]
Load-bearing structure	2430	562	−77%
Vertical envelope	102	42.4	−59%
Horizontal envelope	62.9	7.84	−88%
Internal partitions	225	39.7	−82%
Systems/Plants	90.6	75.7	−16%
Total	2910	727	−75%

5.2.3. Carbon Offset

Although extremely performing, the CNB still reports emissions equal to 5016.2 tonCO₂-eq along its service life. Since the building performance may not be further improved to pursue the carbon-neutral target, a carbon offset strategy needs to be established. An effective way to compensate for emissions is via local actions, visible to the citizenship and producing local advantages [74]. To this purpose, an area of 9850 m² adjacent to the building has been identified, and a project of requalification has been proposed. The area is currently a boulevard made of two roadways for cars and a central parking lot. The new project considers a redesign of the local mobility, reducing the section of the roadways, imposing low-velocity limits, installing pervious paving, and limiting the parking area. The intervention includes a green area of about 2400 m², with about 90 new trees selected among indigenous species, with limited need for watering, and a high-carbon capture capability. Calculations, run with i-Tree Eco v6 software [75], report that, in 30 years of development, the 90 trees will be able to locally capture about 300.4 tonCO₂-eq and, moreover, they will provide collateral benefits, such as outdoor air quality and thermal comfort improvement, and other ecosystem services.

Because of the limited space, a whole local carbon offset is not feasible (to do so, about 1400 additional trees would be required). Thus, the remaining 4715.8 tonCO₂-eq emissions may only be offset via the acquisition of voluntary carbon funds on the carbon market, and the provision of energy supply contracts with guaranteed renewable origins.

6. Discussions and Conclusions

The case study reported in this paper showed that, in order to deliver a carbon-neutral building compliant with a methodologically sound definition, as the one proposed in Section 3, a massive performance improvement is necessary when typical urban conditions are considered, both in terms of operational and embodied emissions. The nZEB objective, as defined in recent years in Italy, and in a large part of the EU [76,77], is far from what is required to deliver a CNB (the case study shows a reduction of 59% in terms of primary energy, compared to the nZEB threshold). Moreover, a reduction in the operational energy is not sufficient to reach carbon neutrality, but a parallel effort should be made in the selection of materials that feature the best performance in the overall life cycle, including, therefore, construction, installation, and disposal (the case study is characterized by a reduction of 75% in terms of emissions related to construction, of 46% in terms of transport, of 64% in terms of replacement, and of 30% in terms of disposal/deconstruction). This means not only substantially changing the normal practice for design offices (architecture and engineering firms), but also for the construction industry, that appears to be unprepared for this change, since it is still often struggling with the requirements of the nZEB wave [78].

The final performance of real buildings depends, further, on: (i) Occupant behavior and systems management and; (ii) Construction site management (the quality of the construction phase). Both of these aspects are not under the control of the designer and cannot be easily modeled; thus, carbon neutrality might require even more effort than so far reported. All of this may have direct economic consequences, i.e., a CNB may

require, at least in the initial market phase, more capital investments than an nZEB. The major costs may include: (i) The design; (ii) The materials; (iii) The construction site. Economic savings might be reached in the operational phase if the building is properly operated, monitored, and maintained. Thus, in order to enable a market uptake of CNBs, it is necessary to include (and make mandatory) the environmental costs in the overall economic evaluation of a project. This requires a new methodology and a brand-new vision for the construction market.

The case study also shows that carbon neutrality can be a difficult goal to achieve by a building, depending on its characteristics (i.e., geometry, destination, location), and, in some cases (typically urban buildings), it can only be reached through a careful carbon offset plan, which either requires additional economic commitments (i.e., the acquisition of voluntary carbon funds on the carbon market, and the provision of energy supply contracts with guaranteed renewable origins), or space (and money) to deliver a vegetation project. Moreover, in many cases, such as the one investigated in this work, urban lots might be too small to provide space for vegetation to completely offset the building's emissions, or a large enough exposed area to install renewable energy generation systems to cover the overall building energy use [1]. A possible solution could see the involvement of municipalities (or regions) to find the spaces dedicated to carbon offset, through the definition of a vegetation plan as part of the city land use and development plan, along with actions to coordinate the private funding to enable it. The Municipality of Milan opened, indeed, a fund of investments to support the forestation project of the city [79], and this is a promising approach to challenge carbon neutrality at the city level while achieving other goals at the same time (e.g., heat island mitigation, particulate pollution mitigation, etc.).

Buildings could more easily reach the carbon-neutral objective when large lots at the city boundaries are used, where a lot of vegetation may be planted. However, this approach may be risky. Dislocating office and retail buildings, as well as homes (i.e., promoting the urban sprawling), may indeed increase emissions due to transport, whereas a major benefit might be obtained by having buildings close to each other, so that people's movements in the city may be limited, preferably along pedestrian and cycling paths or with the use of public mobility. A real carbon neutrality approach cannot be limited to buildings, but it should also include the city transportation plan.

This paper also highlights some major methodological gaps existing in the calculation procedure for CNB. The most relevant flaw is the lack of a shared definition of what a CNB is, and what emissions should be considered (referring only to the operational phase may be misleading). If a common carbon-neutral objective is to be achieved, cities and nations should agree on what this objective is, and how to assess it. Otherwise, each one will reach its own carbon neutrality. This paper provides a possible operative definition for carbon neutrality associated with a clear methodological approach.

Standards do exist, and they are continuously being upgraded; however, a lot of work is still required to assess the emissions from products and materials (e.g., paints, carpets, etc.) during the normal operation of the building, the emissions of all ordinary maintenance activities (e.g., cleaning), and of the repair of the relevant building components, before the end of their service life. Biogenic CO₂, and the ways to account for it, should also be further studied in order to reach a consensus on the methodology (0/0 approach, -1/+1 approach, dynamic approach) to be used for its assessment and integration within a whole-building LCA.

Author Contributions: Conceptualization, F.C.; methodology, F.C.; software, F.C., A.T. and A.A.; formal analysis, F.C., A.T. and A.A.; resources, F.C.; writing—original draft preparation, F.C., A.T. and A.A.; writing—review and editing, F.C., A.T. and A.A.; project administration, F.C.; funding acquisition, F.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Rete fra Imprese B.Smart.

Acknowledgments: We wish to acknowledge Eng. Stefano Rondo of TECNEAS Integrated Building Design, Arch. Ambrogio Risari, Arch. Emanuela Cidri, Arch. Giulia Pannella, Arch. Lapo Soldano for the design process, and Eng. Jacopo Famiglietti for the support on CHP analysis.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

The simulations aimed at calculating the operational energy used were performed on a building numerical model divided into 23 thermal zones. Their sizes and features are summarized in Table A1. The resulting thermal energy needs were then manipulated in order to take into account the energy losses due to distribution, control and, emissions, according to the national technical standards [63,64], through the efficiencies reported in Table A2. Finally, the electrical energy needs related to lights and appliances were calculated on the basis of the assumptions described in Table A3.

Table A1. Characterization of the thermal zones in the numerical model of the project and the BAU scenario, in terms of gross floor surface (S_{gross}), gross internal volume (V_{gross}), overall internal gain contributions, ventilation technology, and emission system.

Storey	Thermal Zone	S_{gross} [m ²]	V_{gross} [m ³]	Internal Gains/Loads	Ventilation	Heating/Cooling Supply
Basement	Bar	211	611	120+ people, lights, appliances	AHU	supply air
	Stairs/Corridors	76	222	lights	AHU	supply air
	Sleeping Rooms	125	363	24+ people	AHU ¹ /BW ²	fan coil
Ground floor	Reception	178	515	120+ people, lights, PCs	AHU	supply air
	Stairs/Corridors	93	270	lights	AHU	supply air
	Sleeping Rooms	93	271	18+ people, lights	AHU ¹ /BW ²	fan coil
First	Stairs/Corridors	59	171	lights	AHU	supply air
	Sleeping Rooms	203	588	34+ people, lights	AHU ¹ /BW ²	fan coil
Second	Stairs/Corridors	59	171	lights	AHU	supply air
	Sleeping Rooms	203	588	34+ people, lights	AHU ¹ /BW ²	fan coil
Third	Stairs/Corridors	59	171	lights	AHU	supply air
	Sleeping Rooms	203	588	34+ people, lights	AHU ¹ /BW ²	fan coil
Fourth	Stairs/Corridors	59	171	lights	AHU	supply air
	Sleeping Rooms	203	588	34+ people, lights	AHU ¹ /BW ²	fan coil
Fifth	Stairs/Corridors	59	171	lights	AHU	supply air
	Sleeping Rooms	203	588	34+ people, lights	AHU ¹ /BW ²	fan coil
Sixth	Stairs/Corridors	59	171	lights	AHU	supply air
	Sleeping Rooms	203	588	34+ people, lights	AHU ¹ /BW ²	fan coil
Seventh	Stairs/Corridors	59	171	lights	AHU	supply air
	Sleeping Rooms	203	588	34+ people, lights	AHU ¹ /BW ²	fan coil
Penthouse	Flat	118	343	4+ people, lights	AHU ¹ /BW ²	rad. pan.
	Kitchen	17	48	appliances, lights	BW ² /hood	rad. pan.
Total		2778	8051			

¹ only in the nZEB scenario, ² only in the CNB scenario.

Table A2. Efficiencies of the distribution, control, and emission subsystems used for both scenarios investigated.

	nZEB			CNB		
	Common Spaces	Bedrooms	Penthouse	Common Spaces	Bedrooms	Penthouse
HEATING SEASON						
distribution	0.993	0.993	0.995	0.993	0.993	0.995
control	0.960	0.950	0.950	0.995	0.995	0.990
emission	0.950	0.980	0.980	0.970	0.960	0.990
COOLING SEASON						
distribution	0.980	0.990	0.990	0.980	0.990	0.990
control	0.950	0.950	0.950	0.995	0.995	0.990
emission	0.970	0.970	0.970	0.970	0.980	0.970

Table A3. Data and parameters for electrical appliances energy needs.

Use	Specific Absorption	Daily Working Time	Total per Year
	sleeping rooms		
lighting (3 lights per room)	50 W	3 h/day	55 kWh _{EL} /room
small devices (smartphones, PCs, etc.)	125 W	2 h/day	91 kWh _{EL} /room
vacuum cleaner	1800 W	0.2 h/day	131 kWh _{EL} /room
	total per room total (73% occupancy rate)		277 kWh _{EL} /room 14.43 MWh _{EL}
	common spaces		
lighting (corridors—5 lights per floor)	14 W	2.52 h/day	450 kWh _{EL}
lighting (ground floor entrance—60 lights)	14 W	8 h/day	2453 kWh _{EL}
lighting (underground floor entrance—60 lights)	14 W	8 h/day	2453 kWh _{EL}
lighting (various rooms—40 lights)	14 W	8 h/day	1635 kWh _{EL}
lights (stairs—2 lights per floor)	36 W	2.52 h/day	463 kWh _{EL}
vacuum cleaner (common spaces)	1800 W	2.5 h/day (working days) 3 h/day (weekends) 3 h/day (vacations)	1762 kWh _{EL}
vacuum cleaner (corridors)	1800 W	2.5 h/day (working days) 3 h/day (weekends) 3 h/day (vacations)	1762 kWh _{EL}
elevators	4000 W	2 h/day (working days) 2.5 h/day (weekends) 3 h/day (vacations)	3262 kWh _{EL}
	total		14.24 MWh _{EL}

With regard to the environmental impacts analysis, the following tables report details on the environmental impacts of each technological unit and the material considered in the analysis for the nZEB and CNB scenarios.

Table A4. Material construction phase impacts (A1–A3) for the nZEB scenario.

Technological Unit Classes	Technological Unit	Technical Element Details/Materials	Quantity [ton]	Stage A1–A3 [tonCO ₂ -eq]
Load-bearing structure	Foundations, beams, pillars	Cement, sand, and aggregates	294.0	45.4
		Steel reinforcements	12.6	17.9
	Slabs and walls	Cement, sand, and aggregates	9430.0	1640.0
		Steel reinforcements	467.0	665.0
	Steel beams	Steel	52.6	61.1
Vertical envelope	Vertical façade	Interior/exterior finishes (painting and plaster)	84.3	15.4
		Rock wool/EPS insulation and vapor barrier	16.3	18.2
		Brick blocks	106.0	39.1
		Plasterboard sheets and metal substructure	15.6	3.9
	Transparent façade	Double glazed façade windows/doors and aluminum frames	8.4	25.8

Table A4. Cont.

Technological Unit Classes	Technological Unit	Technical Element Details/Materials	Quantity [ton]	Stage A1–A3 [tonCO ₂ -eq]
Horizontal envelope	Attic terrace, top floor roof	Exterior finishes (outdoor tile paving, gravel, waterproofing membranes, and vapor barrier)	16.6	5.0
		EPS Insulation	1.0	9.0
		Plasterboard sheets	3.8	0.5
		Screeds	5.7	0.9
	Ground floor slab and external paving	Interior finishes (painting)	0.1	0.0
		Finishes (internal and external paving, membranes)	23.9	35.8
		Screeds	28.0	3.5
Internal partitions	Vertical internal partitions	EPS Insulation	1.4	8.1
		Interior finishes (painting, tiles)	22.1	13.9
		Plasterboard sheets and metal substructure	45.9	12.2
	Interior doors	Insulation (rock wool)	14.3	7.9
		Interior doors and fire-resistant doors	6.3	26.7
	Horizontal internal partitions	Interior finishes (painting, plaster, paving)	81.2	161.0
		Screeds	125.0	2.0
Insulation		8.7	1.5	
Systems	Lifts	Lifts	1.0	4.3
	Heat and energy generators and circulators	Heat pumps, photovoltaic panels, pipes, circulators, thermal storage tank	23.2	86.3

Table A5. Material construction phase impacts (A1–A3) for the CNB scenario.

Technological Unit Classes	Technological Unit	Technical Element Details/Materials	Quantity [ton]	Stage A1–A3 [tonCO ₂ -eq]
Load-bearing structure	Foundations, beams, pillars	Cement, sand, and aggregates	202.0	15.7
		Steel reinforcements	3.7	2.6
	Slabs and walls	Cement, sand, and aggregates	2.4	321.0
		Steel reinforcements	163.0	111.0
	Steel beams	Steel	32.2	47.1
Wooden elements	CLT and structural wood materials	341.0	63.9	
Vertical envelope	Breathing wall and vertical façade	Interior and exterior finishes (painting)	0.3	0.3
		Façade panel in wood fibres	2.9	0.4
		OSB panels and plasterboard slabs	40.5	3.3
		Insulation (rock wool and wood-based)	13.9	6.3
		Other (wooden substructure, vapor barrier, bedding mortar, etc.)	35.1	11.6
	Transparent vertical façade	Double-glazed façade windows/doors and wooden frames	14.1	20.6

Table A5. Cont.

Technological Unit Classes	Technological Unit	Technical Element Details/Materials	Quantity [ton]	Stage A1–A3 [tonCO ₂ -eq]		
Horizontal envelope	Green roof, attic terrace, top-floor roof	Exterior finishes (wood paving, green roof, gravel, waterproofing membranes and vapor barrier)	5.4	2.7		
		Insulation (wood-based)	2.9	0.5		
		Plasterboard slabs	5.9	0.4		
		Dry screeds	1.8	0.4		
		Interior finishes (paint and paving)	2.3	1.3		
	Ground-floor slab and external paving	Finishes (internal and external paving)	0.2	0.5		
		Dry screeds	9.6	1.9		
		Insulation (wood-based)	2.8	0.1		
		Internal partitions	Vertical internal partitions	Interior finishes (painting, tiles)	17.5	9.8
				Interior-treated wooden slabs + wooden substructure	42.2	5.9
Insulation (wood-based)	9.2			1.6		
Interior doors	Interior doors and fire-resistant doors		4.4	4.6		
	Horizontal internal partitions		Interior finishes (painting)	10.3	6.0	
Dry screeds		38.5	7.8			
Insulation (wood-based)		11.3	2.0			
Plasterboard slabs		28.4	1.9			
Systems/plants	Lifts	Lifts	1.4	4.3		
		Heat and energy generators and circulators	Heat pumps, CHP system, circulator pumps, pipes, photovoltaic panels, thermal storage tank	16.5	71.4	

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