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Net-Zero Climate Emissions Districts: Potentials and Constraints for Social Housing in Milan

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Abstract: Net-zero climate districts are gaining wide attention at the European and international levels. Urban regeneration competitions have been launched recently to stimulate development; nevertheless, the literature does not yet provide a shared scope definition (i.e., product system). Using the process-based life cycle assessment method, the authors evaluate the climate profile of a new district in Milan (14 buildings with 36,000 m^2 of gross surface area in total) aiming to become the first net-zero social housing project in Italy. The authors show in the results section how climate neutrality is achieved on the part of the real estate operator by varying the scope. The most conservative scenario (including all the emission sources considered in the analysis) indicates that the net-zero climate target is reached only by purchasing voluntary carbon credits. The authors also highlight: (i) a district composed of nearly-zero energy buildings is far from the definition of a net-zero climate emissions district; (ii) a net-zero climate emissions district may not be a positive energy district and vice-versa; and (iii) constraints linked with the lack of space in a densely populated city due to insufficient area to install renewables on site.

Keywords: net-zero emission districts; life cycle assessment; climate neutral; MILP; greenhouse gas emissions; level(s) framework

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1. Introduction

The recent European and international objectives towards complete decarbonization have paved the way for various projects aimed at finding solutions to reach net-zero operating emissions by 2050 [1]. Cities, or even smaller districts, are the core of this transition. They represent communities in which different elements and energy systems are interconnected, with arising potential opportunities for carbon neutrality that may not be feasible in individual buildings [2]. Moreover, because of the links among multiple buildings and different sectors, districts and cities reflect on the global community. They stand at the base of the wider regional, national, and international policy areas, being sources of viable solutions, common practices, and lessons learned that can be adapted and transposed to a broader scale of analysis. In addition, according to Famiglietti et al. [3], cities represent the major cause of global environmental impact, accounting for 75% of greenhouse gases emitted and 70% of energy consumed.

Studies aimed at reducing their environmental burden are therefore very relevant and more and more diffused to achieve greenhouse gas (i.e., climate) neutrality on a global scale, according to the Paris Agreement. In particular, the focus is on the entire building sector, which is responsible for nearly 40% of energy consumption and CO_2 eq emissions [4]. It is in this context that in recent years the European guidelines aimed at reducing the environmental burden of the construction sector have moved from the scale of buildings to groups of buildings, hence districts, and from a “nearly-zero energy” approach to the more challenging and stringent concepts of “positive energy” and “climate neutral” [5]. Reviews of these different terms and requirements, which still lack clarity and may generate confusion, are presented in Causone et al. [1], Lützkendorf, Frischkenecht [6], and Brozovsky et al. [7]. Similar to what is done in Ala-juusela et al. [8], a sort of timeline of definitions is presented in the following.

The nearly zero-energy building (nZEB) objective was introduced in Europe in 2010 within the legislative framework that includes the Energy Performance of Buildings Directive 2010/31/EU [9] and the Energy Efficiency Directive 2012/27/EU [10]. It stated that by the end of 2020, all new buildings should have nearly zero or very low energy needs to be covered to a significant extent by renewable energy sources. Guidelines for calculating the buildings' energy performance were also defined. In December 2021, a revision of the Energy Performance of Buildings Directive was proposed. It set ambitious objectives to achieve a zero-emission, fully decarbonized building stock by 2050. Therefore, it introduced the zero-emission building (ZEB) [11].

The positive-energy building (PEB) gives an additional step, which indicates buildings are so efficient that they can produce more energy than they consume. It translates into energy produced in excess, which leads to another fundamental aspect of this concept. It is possible to efficiently convey this exceeding amount of energy to the surrounding environments and thus to neighboring buildings or other energy-consuming sectors, e.g., the power and transportation sector. Eventually, this led to the concept of a positive-energy district (PED). It is defined as an "energy-efficient and energy-flexible urban area which produces net-zero greenhouse gas emissions and actively manages an annual local or regional surplus production of renewable energy" [12]. The authors of the present paper would like to point out that in this definition, the requirement of net-zero GHG emissions should be considered limited to the operative phase. The definition may not be valid when considering the product and construction stage. This means that a zero-emission building (ZEB) may not be a positive-energy building (PEB), and vice-versa.

1.1. Previous Works on the Topic

To widen the scale of analysis, the environmental assessment that is made of a single building must be applied to a subset of neighboring buildings, interconnected from an energy point of view. However, the wider scale of analysis may imply some adaptation of the approaches generally used at the building level and may lead to different considered boundary conditions and, therefore, to a subset of possible alternatives. This variety leads to not-yet-harmonized methods (i.e., system boundaries, changes in technologies, etc.) to deal with districts' environmental profile assessment [13], identifying an open field of research. The study presented in this paper fits into this research topic, being one of the few articles that can be found in the literature in which the life cycle assessment (LCA) method is applied at a level of analysis broader than a single building. LCA (process-based) is a product-based valid scientific methodology, internationally standardized [14,15] and used to assess specific environmental profiles of goods and services. However, the necessity of many specific and very detailed input data, together with the required long computational time, makes it difficult to use at a higher level of analysis without incurring uncertainties in results. Evidence of this is also given by the literature review conducted by Mirabella et al. 2019 [16], from where it can be derived that comprehensive LCA at an urban scale does not exist to date.

To the best of the authors' knowledge, only three scientific articles applied to two Norwegian case studies (located in Bergen and Elverum) are present at the district level. As described by Lausselt et al. in 2019 and 2020 [17] for the district located in Bergen and by Lausselt et al. in 2021 [18,19] for the district located in Elverum, five contributors of greenhouse gas (GHG) emissions were investigated: buildings (residential and non), mobility, open spaces, networks, and on-site energy infrastructure. The authors of the articles focus their analysis on: (i) the LCA modeling, analyzing five structures of ambition level linked with the system boundaries; (ii) the temporal analysis of materials and emissions; and (iii) mobility and surplus energy from photovoltaic modules. As implicative policies, the articles point out: (i) the installation of photovoltaic modules is more suitable for low-rise buildings where roof space is proportionately larger than for tall buildings; (ii) strategies related to reducing floor area per inhabitant are very significant; and (iii) the scope (which life cycle stages and physical elements to include in the analysis) pointedly influences the final results for the set target.

The authors would also like to stress that, at present, there are no standards and guidelines at the European level regulating this aspect when using the process-based LCA method, other than the Norwegian pilot project guideline "The Zero Emission Neighborhood definition" [20]. Previous work addresses [21–23] the topic not with a life cycle approach but at the organization level in line with ISO 14064 [24] (i.e., scope 1, 2, and 3).

1.2. Focus and Aims of the Research

In the present paper, similar to Lausselt et al., the authors use the LCA method to assess the climate (not only CO_2 but all the GHG emissions generated) profile and the benefits used to achieve the target of net-zero climate emissions of a social housing district in Milan. The novelty of the work not only stands in designing and modeling a net (obtained through a balance) zero climate emission district (NZCED), an innovative and more ambitious concept than a PED, but also in analyzing possible mitigation and offset solutions for a cluster of social housing buildings never investigated before. The PED may not be an NZCED if within the system boundaries are included construction materials or others. Indeed, the term NZCED indicates a district whose net climate impact is zero; thus, its GHG emissions generated for construction materials and operational energy in the life cycle (according to a defined time horizon) are equal to the amount of GHG avoided through reduction solutions implemented within or outside the district's sphere of influence, real estate operator, residents, etc.

The main goal of this paper Is to preliminarily design an NZCED and to assess its climate impact by applying the life cycle assessment method following EN 15978 [25]—"Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method". More specifically, the aims are:

- Assessing the climate profile of the district over 50 years (defined as the reference study period—RSP) considering in the analysis both the embodied emissions of the construction materials and the emissions generated during the operational phase of the buildings located in the district (for space heating, space cooling, domestic hot water, mechanical ventilation, artificial lighting, and home appliances);
- Evaluating the mitigation solutions provided to reduce the footprint of the buildings. Thus, (i) a fifth-generation district heating and cooling network (also called ambient loop or ultra-low-temperature district heating) supplied by a groundwater large-scale heat pump is used. The latter is powered by electric energy produced by a photovoltaic solar array installed on the building roofs and the canopy nearby the railway station, covering approximately 3700 m^2 (740 kWp), and (ii) vertical structures made of reinforced concrete with blast furnace slag (40%) and recycled steel (95%) are also used;
- Investigating potentials and constraints of additional mitigation and offset solutions to reach net-zero climate emissions, i.e., (i) purchasing renewable energy certificates for the amount of electricity provided by the national grid; (ii) changing the structural system from reinforced concrete to mass timber; and (iii) purchasing credits from voluntary carbon funds (i.e., economic compensation).

The first novelty of this article is the application of the net-zero climate emission approach at the district level. While most previous studies focus on one building [1,6,26], this work examines an entire district composed of 14 buildings with a total gross area of 36,000 m^2. In addition, the detailed input data reported may also serve as a source for similar applications. Moreover, unlike previous studies, the energy management strategy at the district level is optimized through a mixed-integer linear program (MILP) developed in Matlab [16] in combination with an LCA model developed in Python [17]. The production and exploitation of renewable energy are maximized based on the specific boundary conditions of the area under study, minimizing the climate profile of the district. Thus, the second novelty of the work involves applying the LCA method at the district level and combining it with a MILP optimization. Few studies dealing with LCA in combination with optimization techniques can be found in the literature [27–29]. Thirdly, among the mitigation solutions considered, there is a very innovative technology for the distribution of the heat generated by renewable sources: the fifth-generation district heating and cooling (DHC) network. According to Buffa et al. [30], over a sample of 40 reviewed networks of this type, only 5 are currently in operation in Europe.

The analysis thus will make it possible to address two main research questions that currently lack standardized answers. They are:

- Understanding whether a district made up of nearly-zero-energy buildings can also be defined as a net-zero climate emissions district. This paper will highlight how relevant the definition of the scope of the analysis is. Indeed, the climate neutrality of a district can be achieved or not according to what is considered in the product system, e.g., construction materials, home appliances, artificial lightning, etc. Additionally, a district can be defined as PED and NZCED based on that.
- Evaluating whether climate neutrality can be reached in densely populated urban settings and how. In [31], three main issues in potential conflict with climate neutrality are envisaged for highly populated cities: high total energy consumption, limited space available for renewable energy sources (RES) installation and exploitation, and lack of green open space to stock carbon dioxide.

2. Materials and Methods

This section explains the methodology used to assess the climate profile (greenhouse gas emissions) of the district and the benefits used to achieve the target of net-zero climate emissions within the time boundaries of the present study, from now on also referred to as the reference study period (RSP). The product system, system boundaries, functional unit, characterization method, and options for reaching net-zero climate emissions proposed by Lützkendorf and Frischkenecht are explained [6]. The LCA results were calculated using specific codes developed using the Python programming language, reproducing the computational structure explained by Heijungs and Suh [32].

2.1. Product System

The product system was defined following the "from cradle to grave" approach explained by the European Committee for Standardization with EN 15978 [25] and EN 15804 +A2 [33]. The modules of the standards considered for the evaluation were: (i) A—product and construction stage, (ii) B—use stage (B4—replacement and B6—operational energy use), (iii) C—end of life stage, and (iv) D—reuse–recovery–recycling potential. Figure 1 shows the modules evaluated and excluded.

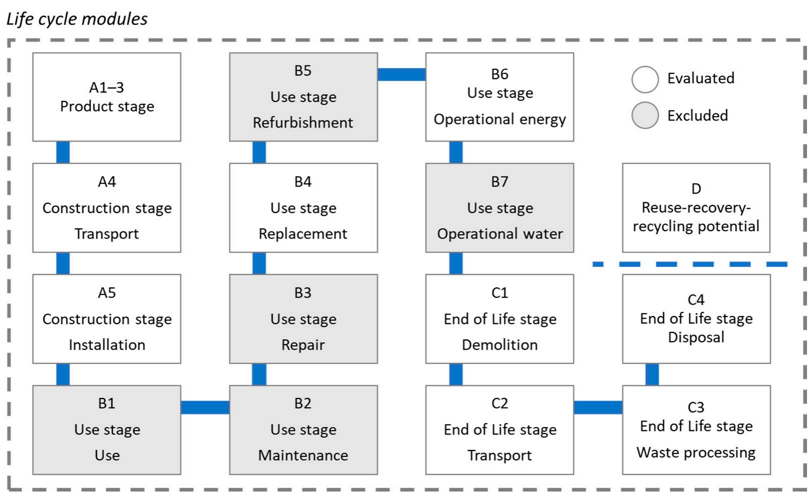

Figure 1. Modular approach for collecting information on the climate profile of the building district.

The following components and elements were studied for each module of Figure 1:

- Construction of the buildings within the district:
  - Load-bearing structural frames, basements, and vertical structures;
  - Non-load bearing elements, basement and internal slabs, balconies, stairs, and internal partitions;
  - Roofs;
  - Façades, opaque and transparent envelopes.
- Fifth-generation district heating and cooling network (DHC network):
  - Heat pumps;
  - Heat exchangers;
  - Network (pipes);
  - Thermal storages tanks;
  - Consumption of electricity during the operational phase.
- Consumption of electricity at the building level for parasitic (i.e., the demand for electricity from substations to buildings and mechanical ventilation), home appliances, and artificial lighting.

The life cycle phases considered for the DHC network are aligned with Famiglietti et al. [34]. Table 1 shows in detail the model implemented.

Table 1. Life cycle phases assessed per energy system.

Heat Pumps	Heat Exchangers	Network and Thermal Storage Tanks [1]
• Component production (raw material, supply, production). • Assembling (manufacturing with energy and water consumptions, welding, waste, transport of components). • Distribution. • Use stage (energy vector consumptions, maintenance,and replacement). • End-of-life stage (transport, waste processing for reuse, recovery or/and recycling, and disposal).	• Component production (raw material supply and production). • Transportation from the producer to the installation site. • Use stage (maintenance and replacement). • End-of-life stage (transport, waste processing for reuse, recovery or/and recycling, and disposal).	• Component productions (raw material supply and production). • Transportation from the producer to the installation site. • Installation work (energy vector consumptions). • Use stage (maintenance and replacement). • End-of-life stage.

[1] Excluding the amount of water inside pipes and storage tanks.

2.2. System Boundaries

The environmental burdens of co-production and end-of-life treatment processes were assessed utilizing attributional modeling compliant with the interpretation of EN 15804, using the library ecoinvent 3.8—EN 15804 [35]. For modeling the end-of-life scenarios, waste producers bear the burden of waste treatment based on the "polluter pays" principle; consumers of recycled products receive them without charge. The cut-off rule was set at 1% in terms of the total mass input, and the whole neglected amount per module was not over 5% of the mass. The model did not include inputs and outputs (carbon dioxide equivalent emissions) below these thresholds, i.e., tiles, roof tiles, shutters, plant equipment (buildings' internal piping, ducts, terminal units, control devices for air conditioning and ventilation systems, and electrical cables), the packaging of construction materials, and the transport of packaging materials to the manufacturing sites.

Time boundaries were set considering the reference study period (RSP), the required service life (ReqSL) of buildings in the district, and the estimated service life (ESL) of each product, component, or element. The RSP was deemed equal to a 50-year time horizon, as indicated by the Level(s) framework [36] for the minimum useful life for non-provisional buildings [37]. The ReqSL was set equal to 60 years according to the ESL of vertical structures of reinforced concrete. The number of replacements considered in Module B4 was evaluated following the Equation (1):

$$NR_{(i)} = rounded\ up \left(\frac{ReqSL}{ESL_{(i)}} - 1 \right) \quad (1)$$

where:

- $NR_{(i)}$ is the number of replacements of the product, component, or element (i);
- $ReqSL$ is the required service life of the product, component, or element;
- $ESL_{(i)}$ is the estimated service life of the item (i).

Module B4 was evaluated, and no change in the mechanical and thermo-physical performance of the replaced elements is considered. Table 2 shows the ESL for each product, component, and element.

Table 2. Estimated service life.

Items	ESL [Years]	Source
Load-bearing structural frames.	60	Level(s) framework [9]
Slabs, balconies, stairs, and internal partition—bricks, concrete, reinforcing steel.	60	
Slabs and internal partition—mortar, insulations (acoustic and thermal), gypsum plasterboard (with steel frame), and vapor and water barriers.	30	
Façades—bricks.	60	
Façades—cement plaster, thermal insulation, gypsum plasterboard (with steel frame), and windows.	30	
5GHDC—heat pumps.	21	Kemna et al. [38]
5GHDC—heat exchangers.	25	Danish Energy Agency [39]
5GHDC—network (i.e., pipes).	35 (plastic)	Famiglietti et al. [34]
5GHDC—thermal storage tanks.	60 (in reinforced concrete) 40 (steel)	Level(s) framework [9] Danish Energy Agency [40]
Photovoltaic panels.	30	ecoinvent library

According to the procedure reported in EN 15978, each contribution for Modules B and D_B (benefits and loads that come from Modules B4 and B6), in terms of CO_2 eq emissions, was scaled up by multiplying with the ratio of the RSP and ReqSL, which in this case is equal to 0.83.

The benefits of exported energy produced by photovoltaic panels (PV) installed/mounted on the buildings (building-integrated generation) and located within the district site boundaries (generation within the district site) were included as additional information in Module D, as indicated by Satola et al. [26]. The benefits were assessed by multiplying the amount of energy exported by the difference between the climate profile of 1 kWh_{el} from PV and the climate profile of the residual Italian electricity mix. The residual mix is a virtual mix representing the electricity consumption that is not explicitly tracked through mechanisms such as guarantees of origin (GO). The residual mix was calculated utilizing a report provided by the Association of Issuing Bodies (AIB) [41] based on the dataset provided by the ecoinvent library, as explained in Section 3.4 of the article.

2.3. Functional Unit and Characterization Method

The functional unit (FU) for the analysis was set as 1 m^2 of useful floor area of the buildings located in the district over a reference study period of 50 years (of the use stage). The functional unit was defined following the indications reported in the technical report of the Level(s) framework "Indicator 1.2: Life cycle Global Warming Potential (GWP)" [36]. As a useful area, in line with Italian legislation, the authors mean the net area within buildings excluding the surface occupied by walls, uncovered parts (i.e., balconies, terraces, roofs, etc.), stairwells, and common hallways.

The climate profile of the district is expressed considering the GWP impact category, following the environmental footprint (EF) method 3.0 [42] aligned with EN 15804 +A2, highlighting the contribution of the GWP total, fossil, biogenic, land use, and land use change.

2.4. Options for Reaching Net-Zero Climate Emissions

According to Lützkendorf and Frischkenecht, and Satola et al., the typology approaches to reaching net-zero climate emissions are: (i) the net-balance approach, (ii) economic compensation, (iii) technical reduction, and (iv) a combination of all of them. The net-balance approach is composed of two steps. In the first step, the footprint of the product system is determined. In the second step, the net-zero emission balance is obtained by subtracting the benefit of the exported energy from the footprint value. The economic compensation approach involves offsetting residual emissions (the footprint value) by purchasing CO_2 eq emission certificates. Technical reduction occurs with negative-emission technologies, biological fixation (i.e., afforestation, etc.), or carbon dioxide removal (i.e., direct air capture with carbon separation and storage, etc.) [43].

A fifth approach is described in the two scientific articles mentioned above, the "Absolute zero". It is feasible when all the production processes for construction materials and energy systems are based on renewables and no CO_2 eq emissions are generated during the production activities by chemical reactions (i.e., cement carbonization, etc.).

The authors propose a sixth approach, described in 2009 as "insetting" by Tipper et al. [44] and most recently analyzed by Noor et al. in 2017 [45] and Gallemore et al. in 2019 [46]. The approach is similar to offsetting (economic compensation), but in this case, the reduction of the CO_2 eq emissions (benefits) is taken outside the immediate confines of the product system, i.e., neighborhoods, activities within the district not considered in the product system (e.g., mobilities), etc. Insetting, unlike offsetting, promotes explorations and partnerships to identify opportunities for emissions' reduction within the sphere of influence of the district, real estate operator, residents, etc.

In summary, the types of approaches to reaching net-zero climate emissions are (excluding the absolute zero):

- Type A—net-balance approach;
- Type B—economic compensation (or offsetting);
- Type C—insetting;
- Type D—technical reduction;
- A combination of all of them.

Figure 2 shows the location of the sphere of influence of each approach described to reaching net-zero climate emissions.

In this article, the authors investigate the net-balance approach, providing the results obtained for a social housing district in Milan. The other procedures, as described in the following sections of the paper, are just emphasized as additional options for achieving the set target of zero climate emissions.

3. Life Cycle Inventory Analysis—Case Study

The case study is a district composed of 14 buildings, currently under construction, destined to become a social housing neighborhood in Milan, Italy. In this section, the authors explain the life cycle inventory (LCI) based on primary data used to implement the assessment, considering the scope described in the "Material and Methods" section. In particular, this section explains: (i) the construction technologies with the characteristics of the envelopes (i.e., type of construction materials, amount of construction materials, thermal transmittances, and end-of-life scenarios), (ii) the energy needs of the operational phase, (iii) the energy system installed (i.e., DHC network) to provide space heating (SH), domestic hot water (DHW), and space cooling (SC), and (iv) the photovoltaic solar array installed on the building roofs and the canopy used to supply the DHC network and to export the electricity to the national grid. Figure 3 provides a representation of the positions of the buildings in the district (red shapes).

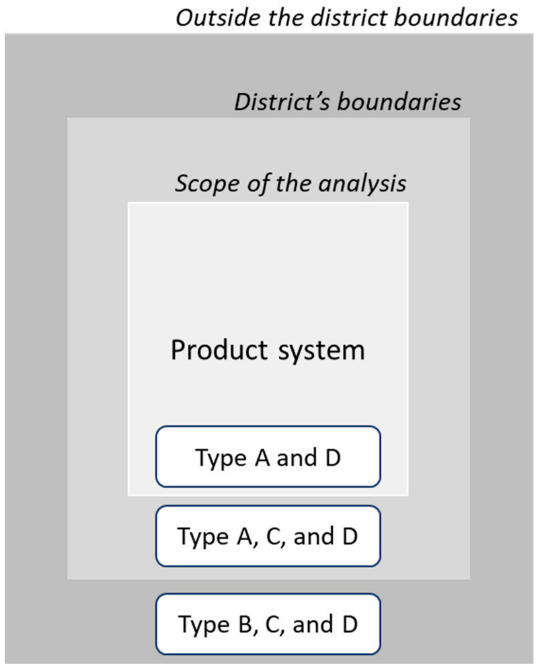

Figure 2. Sphere of influence of types of approaches.

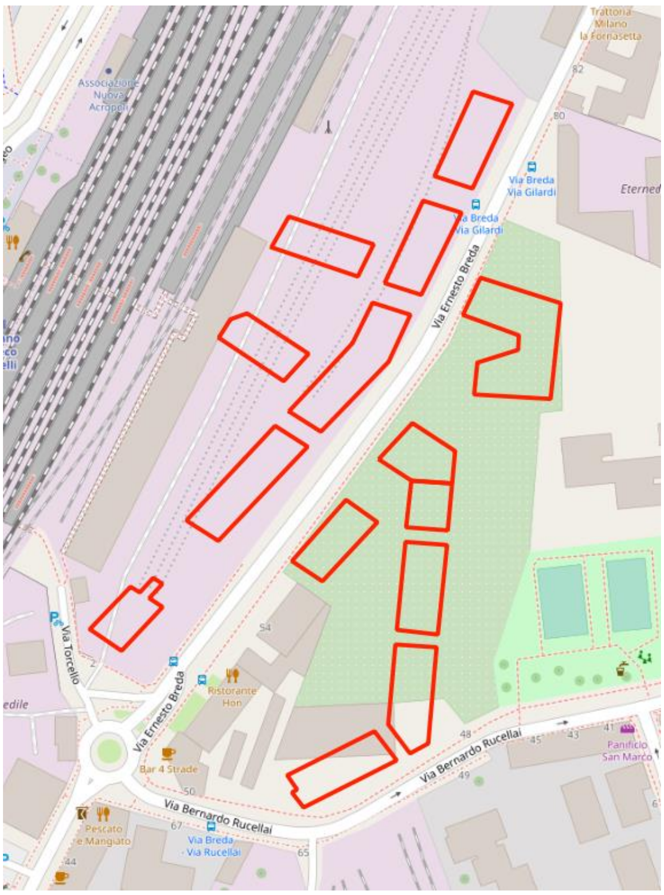

Figure 3. Representation of the positions of the buildings in the district (red shapes).

3.1. Buildings in the District

The buildings have an average height of five stories with a total district area of:

- 36,000 m^2 of gross area;
- 24,000 m^2 of available area;
- 20,870 m^2 of net floor area coinciding with the air-conditioned area.

The authors, in line with "The Zero Emission Neighborhood definition" and the planning parameters of the Municipality of Milan, consider: (i) the gross area, i.e., the total area of the buildings excluding the roof area; (ii) the available area, which is the gross area excluding the surface occupied by external walls, uncovered parts (i.e., balconies, terraces, etc.), stairwells, and common hallways; and (iii) the net area, i.e., the available area excluding internal walls.

The construction technologies used for the buildings are the following:

- Foundation, underground, and vertical structural systems are made of cast-in-place reinforced concrete (37 MPa), using blast furnace cement at 40%, and reinforcing bars with 95% recycled steel content;
- Basement, floor, and roof slabs are made of masonry and reinforced concrete. Also, blast furnace cement at 40% and reinforcing bars with 95% recycled steel content were used in this case. The inner surface of the floor and roof slabs includes a metal ceiling with gypsum plasterboard. The outer surface of the slabs includes mortar with acoustic carpet (for floor slabs), thermal insulation in polyurethane and a vapor barrier (for basement and roof slabs), and waterproofing (for roof slabs);
- External transparent envelopes are made using a polyvinyl chloride (PVC) frame with triple glazing and argon gas;
- External opaque envelopes are traditional masonry made of half-full brick blocks with an insulated internal false wall (double layer of gypsum plasterboard, glass wool, steel metal frame) and expanded polystyrene (EPS) insulation;
- Internal walls consist of a double layer of gypsum plasterboard cladding, a steel metal frame, a layer of glass rock wool insulation, and bricks;

Table A1 shows the used construction technologies, highlighting the amounts of material for square meters of net area for a reference study period (RSP) of 50 years. The table also provides the thermal transmittances.

The authors assessed Modules A4 (transport to the construction site), A5 (installation), C1 (demolition and deconstruction), and C2 (transport to the end-of-life treatment plant) using literature data. In particular, data provided by Rasmussen et al. [47], Asdrubali et al. [48], Weiler et al. [49], and Zabalza Bribián et al. [50] were selected as a reference for:

- Module A4, a distance of 50 km for inert materials and 300 km for additional materials [47];
- Module A5, a climate impact equal to 2% of Modules A1–3 [47,48];
- Module C1, energy consumption in kWh/m^2 of the net area for demolition of 14.45 (electricity) and 26.83 (diesel) [49];
- Module C2, a distance of 50 km [48] for massive materials and 100 km for other materials [50].

Table A2 summarizes the scenarios adopted to model Modules C3 (waste processing), C4 (disposal), and D (benefits and loads beyond the system boundaries). The percentages for disposal destinations (recycling, incineration, and landfill) are reported in the first column. The table shows, in the second column, the efficiencies of the recycling processes (selection and reprocessing) and the waste-to-energy plant of Milan in producing electricity and heat due to the combustion of solid wastes. The third column reports the substitution ratios, describing the quality of the outgoing material with respect to the substitute. The last column describes the substituted production (average suppliers, attributional modeling) thanks to recycling and incineration with energy recovery activity. The disposal destination, recycling efficiency, substitution ratio, and avoided burden values were assumed in line with Baldassarri et al. [51], Rigamonti et al. [52], and Ghose et al. [53]. In this article, the authors used mechanical compressive strength to evaluate the substitution ratio of concrete and bricks compared with gravel, equal to 37, 5, and 150 mPa. The efficiencies of the waste-to-energy (WTE) plant of Milan were found by consulting the report of the Italian Association of the Urban Heating (AIRU) [54].

3.2. Energy Modeling of Buildings

The building energy needs for heating, humidification, cooling, and dehumidification are calculated according to the standard EN ISO 52016:2017 [55] (hourly method) using typical hourly schedules for occupation (crowd ratio of 0.04 people/m^2) and electric appliances (installed power of 4 W/m^2). Ventilation is set to a constant value of 0.4 vol/h. The heating system is active from 15/10 to 15/04. Outside this interval cooling is permitted. To limit cooling energy needs, blinds are used when the global solar radiation on a transparent surface exceeds 300 W/m^2. The estimated building energy needs for heating, cooling, and domestic hot water are in line with the data reported in recent studies on a nZEB located in Northern Italy [56,57] and thus implemented according to the same energy requirements prescribed by Italian law on the energy efficiency of buildings.

The thermal energy supplied to the heating, ventilation, and air conditioning (HVAC) distribution system depends not only on theoretical energy needs but also on the type of HVAC system used. For low energy consumption, which is a requirement typical of social housing, and improved indoor air quality, which is a compelling need in air-tight buildings, a suitable choice is fan coils for heating and cooling with mechanical ventilation. Mechanical ventilation with heat recovery is particularly suited to limit the heating energy demand, thanks to the high effectiveness achieved by new, high performing, air-to-air heat exchangers (75%). Fan coils are selected because they can be used for both heating and cooling, can perform dehumidification, and can operate in heating mode at relatively low temperatures (45 °C). The building thermal energy needs and the associated energy demands of the distribution system are reported in Table 3, along with heat demand for domestic hot water (calculated assuming 50 l/day/person).

Table 3. Building energy needs and energy demand of the distribution system.

Name	A_{net} (m^2)	$Q_{nd,h}$ (kWh/m^2)	$Q_{nd,c}$ (kWh/m^2)	$Q_{dst,SH}$ (kWh/m^2)	$Q_{dst,SC}$ (kWh/m^2)	W_{dst} (kWh/m^2)	Q_{DHW} (kWh/m^2)
A01	1250	32.1	15.1	16.5	23.9	4.4	24.1
A02	1190	32.3	15.1	16.7	23.9	4.4	24.1
A03	1061	33.0	15.4	17.4	24.4	4.5	24.1
A04	1865	31.3	15.6	15.8	24.7	4.5	24.1
A05	960	33.1	15.6	17.5	24.7	4.5	24.1
A06	2525	30.4	15.7	14.9	24.9	4.4	24.1
A07	1628	31.8	15.8	16.2	25.0	4.5	24.1
A08	1836	34.4	15.7	18.7	24.8	4.5	24.1
A09	1009	33.0	15.6	17.4	24.6	4.5	24.1
A10a	648	34.6	14.7	18.9	23.4	4.5	24.1
A10b	3113	31.3	16.1	15.8	25.5	4.5	24.1
A11	1223	32.0	14.9	16.4	23.7	4.4	24.1
A12	1343	31.6	15.0	16.1	23.7	4.4	24.1
A13	1219	32.7	15.7	17.1	24.9	4.5	24.1

3.3. Fifth-Generation District Heating and Cooling Network

The heating and cooling energy system of the whole district is schematically represented in Figure 4. A two-pipe bidirectional DHC network interconnects building substations (one for each building) with the central energy system, constituted by groundwater wells, a heat exchanger, a central heat pump, and thermal storage (balancing unit). Building substations can either extract or reject heat from the balancing unit, which shall be maintained within suitable temperature levels for efficiency. For cooling, heat exchange with groundwater is sufficient, while for heating, a central heat pump is used to extract heat from groundwater and increase the balancing unit temperature.

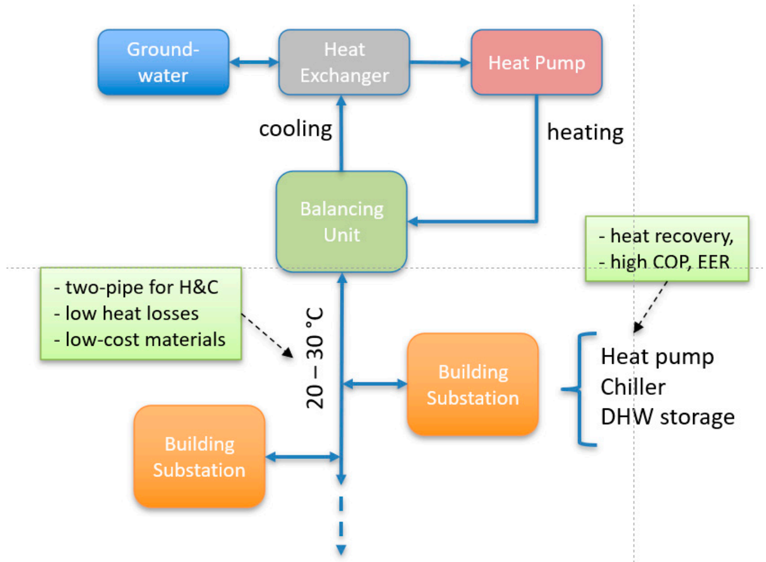

Figure 4. District heating and cooling based on fifth-generation thermal micro-grid.

The building substations are conceived to supply heating or cooling to a two-pipe fan-coil system and to charge the domestic hot water storage. As shown in Figure 5, the substation comprises a DHW tank, a heat pump (HP) to supply heat to fan coils, and a reversible heat pump chiller (HPC) to cool fan coils and charge the DHW tank. The HPC can perform DHW heating and space cooling simultaneously, thus enhancing the seasonal energy efficiency. Two heat exchangers allow bidirectional thermal energy exchange with the DHC network, alternating heat extraction (right) and rejection (left) depending on the operation conditions.

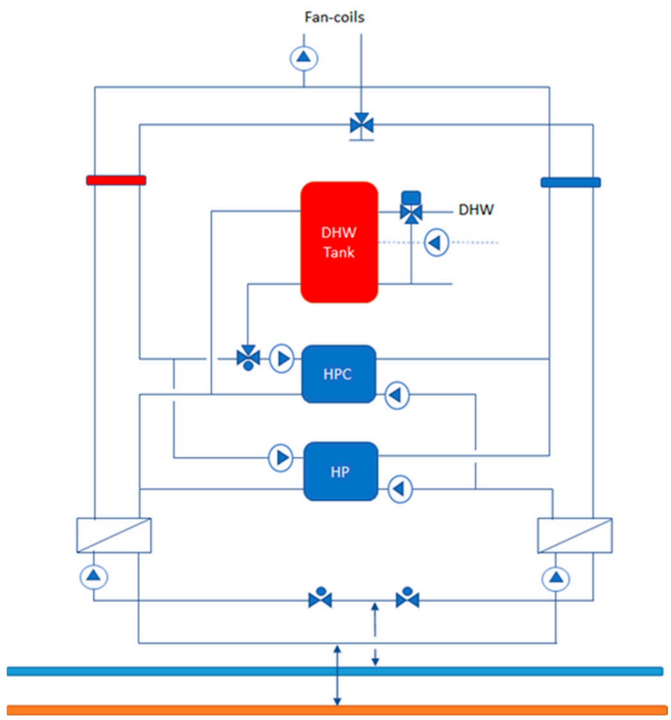

Figure 5. Schematic of a building substation.

With the objective of minimizing the electricity demand of the thermal micro-grid, a two-level optimization procedure is set, aiming to (1) minimize the electricity consumption of each building's substation (level-1 optimization) and (2) minimize the overall electricity consumption of the whole district by adjusting the temperature of the balancing unit (level-2 optimization). Optimization is implemented using mixed-integer linear programming (MILP) in Gurobi [58] and, to keep the problem manageable for a laptop computer, is performed at hourly timesteps for a few representative days, one day at a time. To cover one year, the yearly energy demand calculated for each building with hourly time steps is aggregated into 12 representative days, one for each month, providing a 12 × 24 matrix.

3.3.1. Modeling of the Substation

At a given time step, the substation works in one of the following operating modes (see also Table 4):

1. Only space heating (DHW storage fully charged, space heating demand > 0);
2. Only space cooling (DHW storage fully charged, space cooling demand > 0);
3. Only DHW (DHW storage requires charging, space heating, and cooling demand = 0);
4. Space heating and DHW (DHW storage requires charging, space heating demand > 0);
5. Space cooling and DHW (DHW storage requires charging, space cooling demand > 0)
    - DHW controlled (the source HX provides an artificial cooling demand);
    - SC controlled (the sink HX provides an artificial DHW demand).

Table 4. Association of substation, HPC, and HP operation modes.

Substation	$\delta_{HPC,1}$	$\delta_{HPC,2}$	$\delta_{HPC,3}$	$\delta_{HPC,4}$	$\delta_{HP,1}$
1	0	0	0	0	1
2	1	0	0	0	0
3	0	1	0	0	0
4	0	1	0	0	1
5.a	0	0	1	0	0
5.b	0	0	0	1	0

Because the MILP implementation requires linear energy-flow models for a substation's HP, HPC, and DHW tank (see Figure 5), constant COP and EER values for HP and HPC are desirable. In principle, COP and EER vary with the source and sink temperature for a heat pump/chiller. However, setting their values to be constant is not a limitation at this stage because: (1) the delivery temperatures for SH, DHW, and SC must be set to the values requested by the distribution system, which are respectively 45, 55, and 7 °C; and (2) the network temperature is considered as an exogenous, constant parameter that influences the temperature of the source and sink heat exchangers (level-1 optimization is performed for different values of the network temperature, employing each time the proper values of COP and EER and "preparing the ground" for level-2 optimization at the district level). The operation modes of the substation can be reproduced by setting four operation modes for the HPC ($\delta_{HPC,j}$, $j = 1..4$) and one for the HP ($\delta_{HP,1}$), as illustrated Table 4. The HPC modes indicate the combination of a source and sink respectively connected to the HPC evaporator and condenser:

- SC distribution as source, DHC network as sink;
- DHC network as source, DHW tank as sink;
- SC distribution and DHC network as source, DHW tank as sink;
- SC distribution as source, DHC network and DHW tank as sink.

Clearly, at a given time step, only one HPC operation mode can be active:

$$\sum_{j=1}^{4} \delta_{HPC,j} \leq 1 \quad (2)$$

The mathematical expressions for the thermal energy flows generated by the HPC are defined hereafter.

Heat generated at the HPC condenser and used to charge the DHW storage:

$$Q_{h,HPC,DHW} = COP_{HPC,2}W_{HPC,2} + COP_{HPC,3}W_{HPC,3} + COP_{HPC,4}W_{HPC,4} - Q_{h,HPC,SNK,4} \quad (3)$$

Heat generated at the HPC condenser and discharged to the DHC network through the substation's sink heat exchanger:

$$Q_{h,HPC,SNK} = COP_{HPC,1}W_{HPC,1} + Q_{h,HPC,SNK,4} \quad (4)$$

Cool generated at the HPC evaporator and used to fulfill space cooling load:

$$Q_{c,HPC,SC} = EER_{HPC,1}W_{HPC,1} + EER_{HPC,3}W_{HPC,3} + EER_{HPC,4}W_{HPC,4} - Q_{c,HPC,SRC,3} \quad (5)$$

Cool generated at the HPC evaporator and subtracted from the DHC network through the substation's source heat exchanger:

$$Q_{c,HPC,SRC} = EER_{HPC,2}W_{HPC,2} + Q_{c,HPC,SRC,3} \quad (6)$$

where:

$$0 \le Q_{h,HPC,SNK,4} \le COP_{HPC,4}W_{HPC,4}$$

$$0 \le Q_{c,HPC,SRC,3} \le EER_{HPC,3}W_{HPC,3}$$

$$0 \le W_{HPC,j} \le \delta_{HPC,j}W_{HPC,j,MAX} \; j = 1..4$$

The thermal energy flows generated by the HP are straightforward because the HP is dedicated to space heating only:

$$Q_{h,HP,SH} = COP_{HP,1}W_{HP,1} \quad (7)$$

$$Q_{c,HP,SRC} = EER_{HP,1}W_{HP,1} \quad (8)$$

where:

$$0 \le W_{HP,1} \le \delta_{HP,1}W_{HP,1,MAX}$$

Equalities are imposed to fulfill the thermal energy demand of the distribution system of the building:

$$Q_{h,HP,SH} = Q_{dst,SH} \quad (9)$$

$$Q_{c,HPC,SC} = Q_{dst,SC} \quad (10)$$

$$U^{t}_{DHW} = U^{t-1}_{DHW} + \tau\, Q_{h,HPC,DHW} - \tau\, Q_{dst,DHW} - \tau\, Q_{DHW,loss} \quad (11)$$

The last equality represents the energy balance across the DHW storage, which includes heat losses, $Q_{DHW,loss} = UA_{DHW}\left(T_{DHW} - T_{Ref}\right)$. The average storage temperature (T_{DHW}) is calculated as a linear function of the storage internal energy and constrained within a suitable interval:

$$T_{DHW,MIN} \le T_{DHW} \le T_{DHW,MAX} \quad (12)$$

The objective function to minimize at the building level (level-1 optimization) is the electricity consumption of the substation:

$$obj = \sum_{j=1}^{4} W_{HPC,j} + W_{HP,1} \quad (13)$$

3.3.2. Modeling of the Network

The thermal energy exchanged at the source and sink heat exchangers of each substation is aggregated to calculate the net thermal energy flow transferred to the balancing unit ($Q_{NTW,BU,nT}$). Similarly, the electricity of all substations is aggregated ($W_{NTW,nT}$). Because level-1 optimization is performed for different values of the average network temperature (supposed to be equal to the average balancing unit temperature thanks to negligible heat losses), both the net thermal energy flow and substations' electricity consumption become matrices of size 12 × 24 × nT, where nT is the number of discretized network temperatures. The exact values of thermal energy flow and electricity consumption depend on the temperature of the balancing unit. In respect to this, linearization will be assumed as a valid approximation.

3.3.3. Modeling of the Energy Center

The energy center transfers heat in and out of the balancing unit ($Q_{EC,BU}$) to counterbalance the heat transferred from all substations through the network ($Q_{NTW,BU}$). Therefore, the energy balance across the balancing unit reads:

$$U_{BU}^{t} = U_{BU}^{t-1} + \tau\, Q_{EC,BU} + \tau\, Q_{NTW,BU} - \tau\, Q_{BU,loss} \tag{14}$$

The energy center can operate either in heating or cooling mode. To consider the effect of the storage temperature on the efficiency of the energy center, the nT discretized values of the balancing unit temperature are used to assess the heating and cooling efficiency corresponding to each temperature interval, and $Q_{EC,BU}$ is calculated as the overall contribution of an equal number of virtual energy centers:

$$Q_{EC,BU} = \sum_{k=1}^{nT} \eta_{h,EC,k} W_{h,EC,k} - \sum_{k=1}^{nT} \eta_{c,EC,k} W_{c,EC,k} \tag{15}$$

For heating, the efficiency is set equal to the COP of the central heat pump, while for cooling it is calculated based on the cooling exchanged by the groundwater heat exchanger and the associated power consumption of the groundwater pump, both assumed to be linearly related with the groundwater flow rate. The electricity consumed for heating and cooling is constrained as follows:

$$0 \leq W_{h,EC,k} \leq \delta_{h,EC,k} W_{h,EC,MAX}$$

$$0 \leq W_{c,EC,k} \leq \delta_{c,EC,k} W_{c,EC,MAX}$$

where $\delta_{h,EC,k}$ and $\delta_{c,EC,k}$ are the disjunctive variables introduced to activate the virtual energy center corresponding to the current balancing unit temperature.

The optimization goal for the DHC network (level-2 optimization) is the overall electricity consumption:

$$obj = \sum_{k=1}^{nT} W_{h,EC,j} + \sum_{k=1}^{nT} W_{c,EC,j} + W_{NTW} \tag{16}$$

Concerning $Q_{NTW,BU}$ and W_{NTW}, they are the linearized versions of $Q_{NTW,BU,nT}$ and $W_{NTW,nT}$, respectively. Piecewise linearization is performed with respect to T_{BU} using disjunctive variables and the associated constraints, as explained by Rardin [59].

3.4. Photovoltaic Solar Array and Residual Mix

Suitable surfaces to install photovoltaic (PV) modules are the building roofs (14) and the canopy of the nearby railway station. Thus, the installation of a large PV system comprising 15 subfields with a total area of 3696 m^2 is foreseen. The hourly generation profile of each PV subfield is calculated based on the available solar radiation and considering the module efficiency at standard conditions (20%), a nominal operating cell temperature

(NOCT) of 45 °C, and system losses (14%). The PV subfields installed on the buildings' roofs are assumed to contribute to the electricity demand of the related building substation, whereas the PV field on the station canopy contributes to that of the energy center.

To properly weigh the environmental impact of the district considering the benefits obtained from the electricity exported from the PV modules, the residual electricity mix of the Italian national grid was investigated. As stated, the residual mix is a virtual mix representing the electricity consumption that is not explicitly tracked through mechanisms such as guarantees of origin (GO). Thus, its climate profile (approximately 616 g CO_2 eq/kWh_{el} for low and medium voltage) was considered more consistent than the actual electricity mix (475 g CO_2 eq/kW for low voltage and 484 g CO_2 eq/kW for medium voltage) to evaluate (i) the operational phase (Module B6) and (ii) the outcomes from recovery potentials and exported electricity (Module D). The electricity mix was assessed considering the European Commission's data in the EU Reference Scenario [60] open-source database based on EU PRIMES 6 in 2020 for Italy and importing countries (France, Austria, Slovenia, and Greece). The residual mix was calculated utilizing the report provided by the Association of Issuing Bodies (AIB). Both models were developed by integrating the production percentages by source and technology in the ecoinvent library (version 3.8 EN 15804) with the Italian electricity activity process. Table 5 shows the compared percentages of the energy sources considered in the two scenarios (mix and residual mix in 2020).

Table 5. Comparison of the Italian mix vs. the residual Italian mix.

Source	Mix 2020 (%)	Residual Mix 2020 (%)
Nuclear energy (import)	6.19%	6.03%
Coal	0.01%	13.28%
Oil	0.17%	4.55%
Gas	30.03%	65.29%
Biomass	13.67%	2.34%
Hydropower	13.76%	2.49%
Wind	15.76%	0.76%
Solar	19.14%	5.26%
Geothermal	1.27%	0.0%
Total	100.00%	100.00%

3.5. Energy Modeling Results

The main results of the energy modeling are briefly presented in the following. It is worthwhile to mention that the balancing unit temperature did not vary notably during the year, with optimal values ranging between 20 and 22 °C. The optimized electricity consumption is reported in Figure 6, along with the electricity generated by PV. The data are broken down into four categories based on point of delivery (energy center vs. substations) and type of supply (grid vs. local PV system). The data for the substations here include only the consumption of compressors (heat pump and heat pump chiller) and the pumping work. In winter, approximately one-third of the overall electricity is consumed by the energy center, while in summer, the contribution of the energy center is quite modest because only electricity for groundwater pumping is required. Moreover, the share of electricity consumption fulfilled by local generation (PV) in summer is nearly 100% for the energy center and approximately 70% for the substations.

The thermal energy demand at the distribution system and the total energy ratio (TER), defined as the ratio of total thermal energy demand to overall electricity consumption, are presented in Figure 7.

In summer, the DHC system is very efficient thanks to the direct use of groundwater to cool the balancing unit, which collects the heat of condensation of the different substations, and the inherent efficiency of the substations, which can simultaneously generate cooling and heating for DHW preparation. In winter, the DHC efficiency is penalized by heat losses in the balancing unit and by the electricity requested by the central heat pump to elevate the temperature of the balancing unit with respect to groundwater temperature. Overall, a yearly average total energy ratio (TER) of 3.3 is achieved.

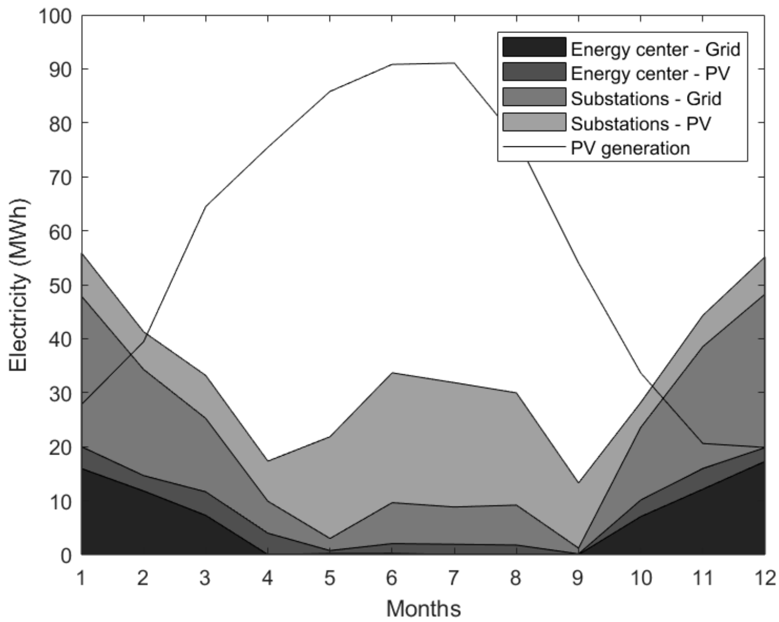

Figure 6. Electricity consumption and generation.

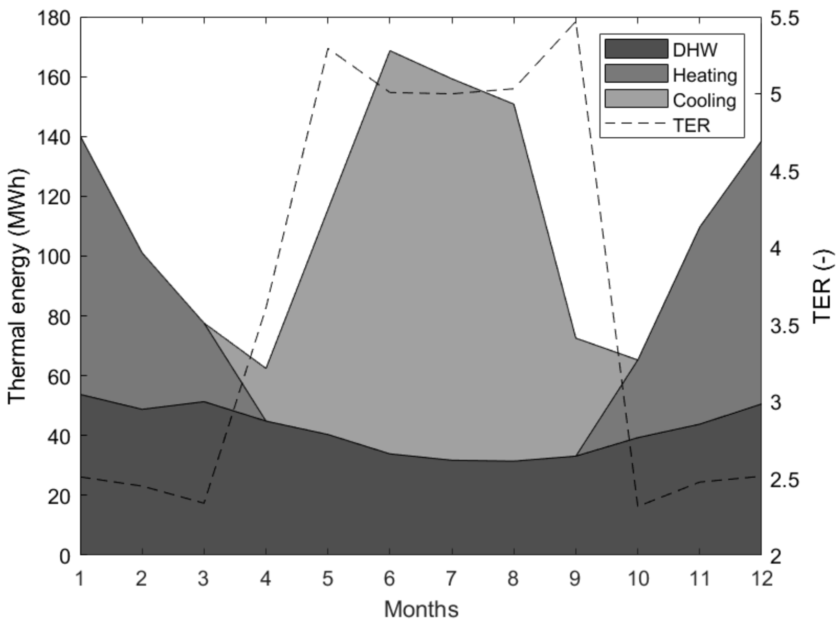

Figure 7. Thermal energy demand and TER.

4. Results

The results are provided: (i) for the functional unit (FU) described in Section 2.3, the net area for a reference study period of 50 years (Table 1), and (ii) for the total emissions generated by the district over those 50 years (Figures 8–10). A detailed view of the origin of global warming potential (GWP) emissions is also presented (Table 6), reporting for each module the emissions in: (i) GWP—fossil, (ii) GWP—biogenic, (iii) GWP—land use and land use change, and (iv) GWP—total as a sum of the previous contributions.

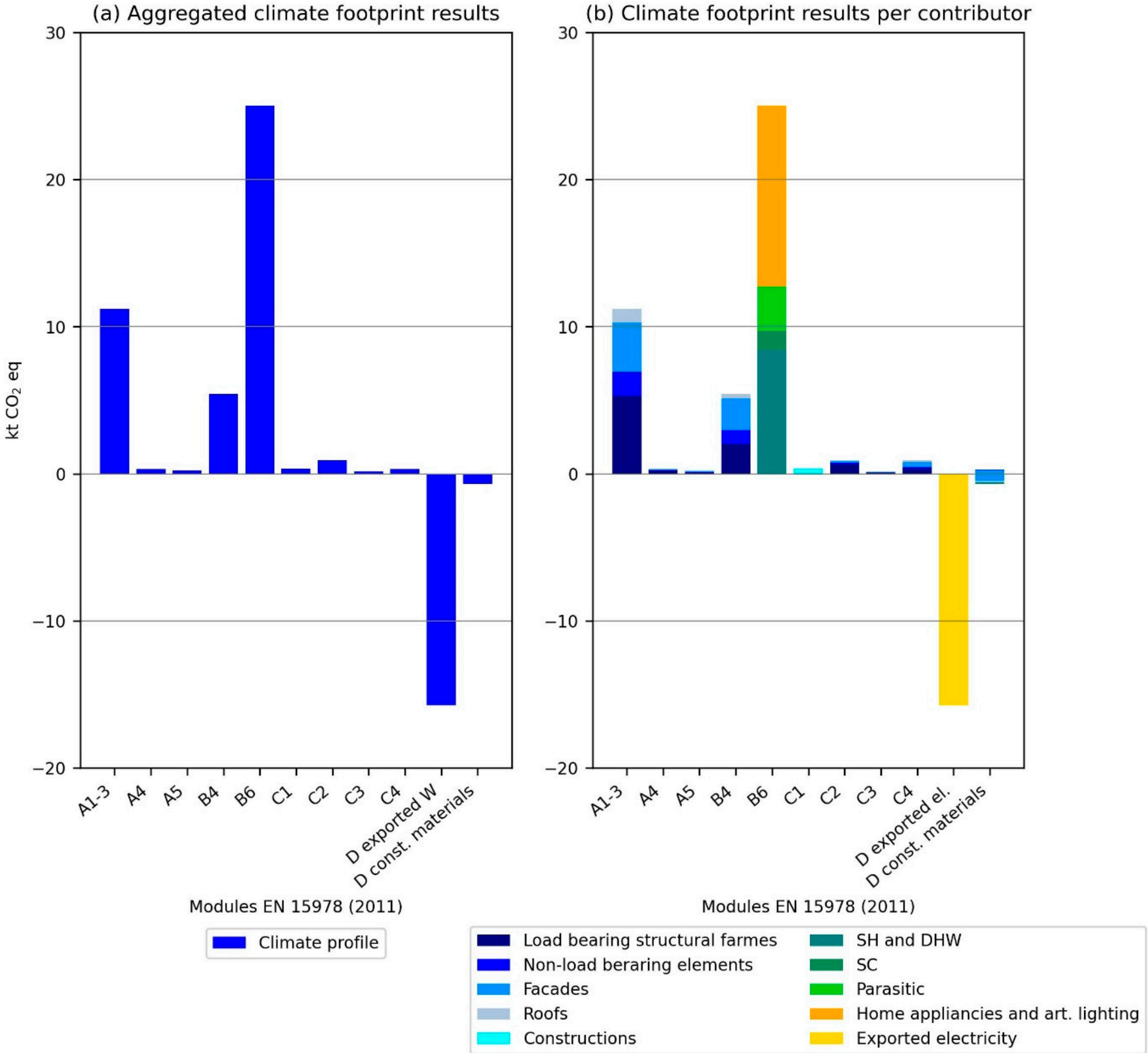

Figure 8. Climate footprint results—of each module (**a**) and of each module divided according to the parts described in the scope (**b**).

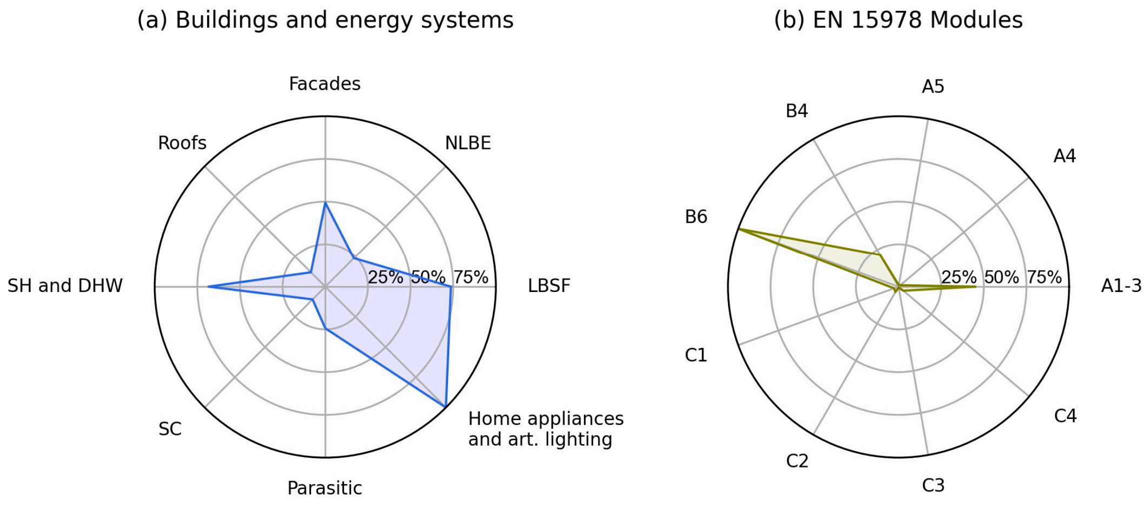

Figure 9. Percentage results by (**a**) contributors and (**b**) modules.

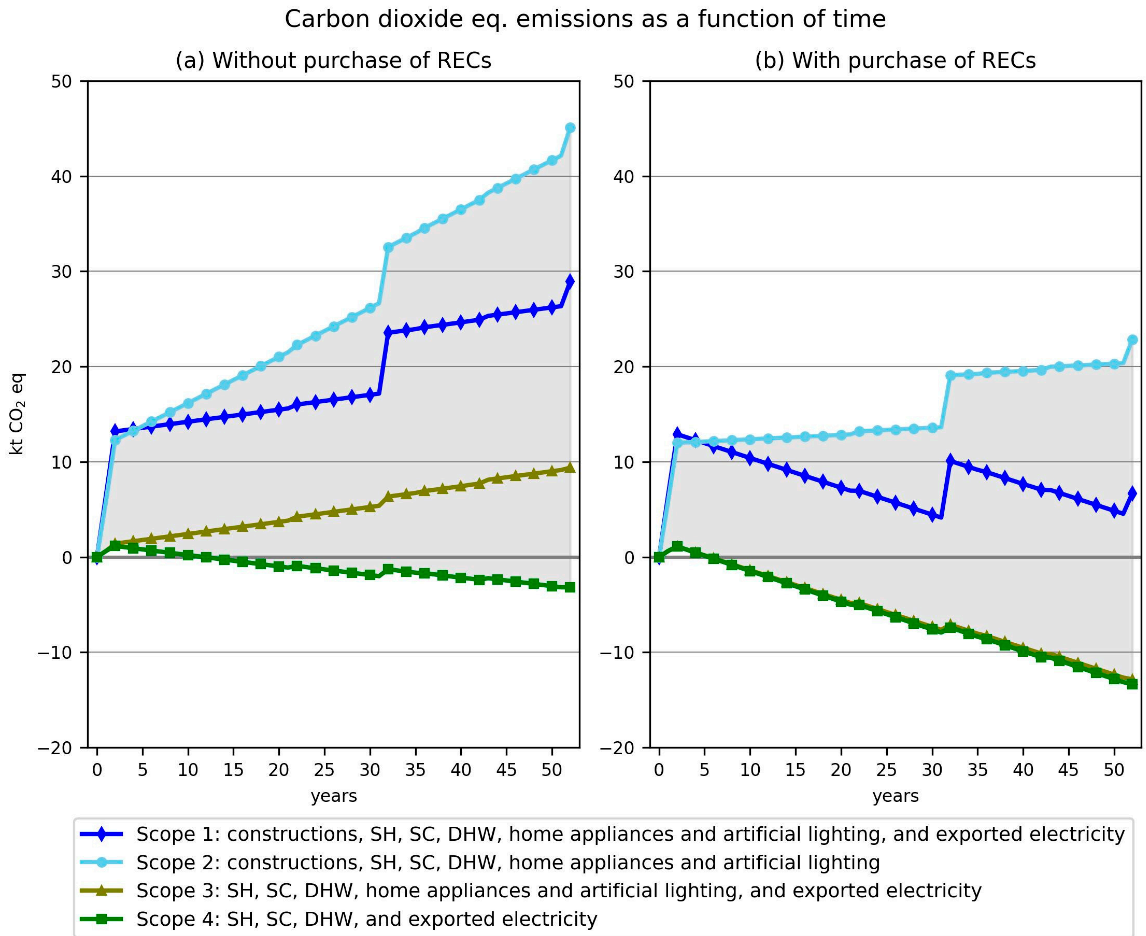

Figure 10. Climate footprint of the district as a function of time concerning four different scopes—without purchase of RECs (**a**) and with purchase of RECs (**b**).

Table 6. Origin of GWP emissions in kg CO_2 eq/m^2 of net area for an RSP equal to 50 years.

GWP Emissions	A1–3	A4	A5	B4	B6	C1	C2	C3	C4	Total	D Exported Electricity	D Const. Materials
GWP fossil	528.9	15.8	10.6	254.0	1,195.4	14.9	43.8	6.7	44.4	2114.3	−753.1	−29.7
GWP biogenic	8.5	0.1	0.2	5.5	4.6	1.9	0.2	0.0	0.1	21.2	−1.5	−8.6
GWP land use and land use change	0.6	0.0	0.0	0.3	0.2	0.0	0.0	0.0	0.0	1.0	0.1	0.0
GWP total	538.0	15.8	10.8	259.8	1,200.1	16.8	44.0	6.7	44.5	2136.4	−754.5	−38.3

The GWP total results of each module (EN 15978) evaluated in this study for an FU of 1 m^2 of net area are provided in Table 7. The table also shows the contribution of each part of the assessed buildings. As indicated, Module B6 (operational energy) is the main contributor (56% of the emissions of the total of Modules A1–5, B4 and B6, and C1–4), followed by Modules A1–3 (product stage) and Module B4 (replacement), which had contributions of 25% and 12% respectively. The other modules are negligible (7%). In the same way, looking at the evaluated parts, the authors assert that electricity consumption for home appliances and artificial lighting (HAAL) is the main contributor (28%), followed by space heating (SH) and domestic hot water (DHW) (19%), internal slabs (10%), opaque envelopes, transparent envelopes, and electricity consumption for parasitic (equal to 7% each). The other parts contribute to the remaining 22%. The results can be divided into two types of emissions: those embodied in building materials (Modules A1–5, B4, and C1–4) and those which are directly and indirectly operational (related to Module B6). The direct and indirect operational emissions consider: (i) the emissions related to the production of electricity, (ii) direct emissions of leakage of refrigerant gas, and (iii) embodied emissions (i.e., from the construction of heat pumps, distribution systems, thermal storage, etc.). The contributions are 936 (embodied) and 1200 (operational) kg CO_2 eq/m^2 for an RSP of 50 years, respectively.

Table 7. Emissions of GWP total in kg CO_2 eq/m^2 of net area for an RSP equal to 50 years.

-	A1–3	A4	A5	B4	B6	C1	C2	C3	C4	Total	D Exported Electricity	D Const. Materials
Basements	33.1	2.1	0.7	0.0	0.0		6.4	0.9	1.4	44.5	0.0	4.3
Vertical structures	63.4	3.7	1.3	0.0	0.0		11.4	1.5	2.4	100.6	0.0	9.3
Basement slabs	37.6	0.9	0.8	28.0	0.0		2.7	0.2	5.1	75.3	0.0	−4.7
Internal slabs	123.7	3.6	2.5	72.9	0.0		11.1	1.0	7.6	222.4	0.0	−1.5
Roof slabs	45.9	0.9	0.9	13.8	0.0		2.6	0.2	5.8	70.2	0.0	−4.4
Opaque envelopes	82.8	1.9	1.7	45.9	0.0	16.8	3.9	0.8	9.3	146.2	0.0	−9.5
Transparent envelopes	76.6	0.2	1.5	58.3	0.0		0.7	1.3	7.1	145.6	0.0	−26.8
Internal walls ([1])	39.6	1.7	0.8	15.7	0.0		2.5	0.6	0.7	61.6	0.0	0.4
Balconies	32.9	0.8	0.7	25.3	0.0		2.3	0.1	5.1	67.2	0.0	−1.8
Stairs	2.2	0.1	0.0	0.0	0.0		0.4	0.1	0.1	2.9	0.0	0.3
Space Heating and DHW	0.0	0.0	0.0	0.0	404.0	0.0	0.0	0.0	0.0	404.0	0.0	−2.9
Space Cooling	0.0	0.0	0.0	0.0	62.2	0.0	0.0	0.0	0.0	62.2	0.0	−1.1
Parasitic (i.e., pumps and ventilation)	0.0	0.0	0.0	0.0	143.8	0.0	0.0	0.0	0.0	143.8	0.0	0.0
Home appliances and lighting	0.0	0.0	0.0	0.0	590.2	0.0	0.0	0.0	0.0	590.2	0.0	0.0
Exported energy from PV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−754.5	0.0
Total	538.0	15.8	10.8	259.8	1200.1	16.8	44.0	6.7	44.5	2136.5	−754.5	−38.3

[1] Considered only between heated and unheated spaces.

The results obtained were consistent, as an average, with what was found in previous studies. For embodied and operational emissions, the order of magnitude was in line with Asdrubali et al., Causone et al. [1] (average of the two assessments given), and Rasmussen et al. These three studies were selected because they focused on locations in Italy (north, two studies, and north-center, one study) and accounted for residential/hospitality (hostel) use of buildings. In summary, the scientific documents report the following value range:

- From approximately 1400 to 450 kg CO_2 eq/m^2 of net area for embodied emissions;
- From approximately 3600 to 600 kg CO_2 eq/m^2 of net area for operational emissions.

The authors of this article scaled up the emissions reported in the cited scientific papers to the net area and the RSP of 50 years. In the latter case (operational emissions), the high variability can be justified by the large differences among services provided (i.e., home appliances, lighting, space heating, etc.) and asset classes investigated (i.e., residential and hospitality). It is important to underline that Rasmussen et al. evaluated only space heating and domestic hot water demand, excluding cooling, home appliances, and artificial lighting. Causone et al. assessed a building with hospitality (hostel) as the intended use, which was thus characterized by higher demand for energy than residential buildings.

Figure 8 shows the total emissions generated by the district over 50 years. Figure 8a presents the contribution of each module listed in EN 15978. In Figure 8b, the same results are divided according to the parts described in the scope (product system). The authors, in line with the Level(s) framework, consider: (i) load-bearing structural frames (LBSF), basements, vertical structures (pillars, beams, and concrete walls), internal slabs, and balconies; (ii) non-load-bearing structural elements (NLBSE), basement slabs, internal walls, and stairs; (iii) façades and opaque and transparent external envelopes; and (iv) roofs and roof slabs. The climate footprint related to building demolition is reported under the "Constructions" label.

Figure 9 presents the results by contributions described in the scope (Figure 9a) and by modules (Figure 9b). In Figure 9a, the results are shown in percentage values relative to the contribution of home appliances and artificial lighting (HAAL), as indicated previously to be the most significant. The figure shows that LBSF has a climate footprint value of about 75% of the value of HAAL; SH and DHW have a value of approximately 70%, façades about 50%, etc. Figure 9b presents the percentage results for the modules. As already highlighted, Module B6 appears to be the most significant contributor, followed by Modules A1–3, which are approximately 50% lower than it, Module B4 (22%), etc.

In Figure 10, the total emissions generated by the district over the 50 years are shown as a function of time. The figure, in addition to the product system described (scope 1), shows another two different scopes (scope 3 and 4) and a baseline (scope 2) where the benefit of the exported electricity is not allocated to the district. In this way, the authors demonstrate how the achievement of net-zero climate emissions is closely related to both the environmental performance of the building materials and energy systems and the scope of the analysis (what is and what is not considered in the product system). In summary, the four different scopes analyzed by the authors are the following (for Figure 10a without the purchase of renewable energy certificates—RECs):

- Scope 1, with a score of +28,780 t CO_2 eq, represents the product system described in Sections 2 and 3, called the full life-cycle-based GHG emissions of buildings by Lützkendorf and Frischkenecht. In scope 1, the benefit from exported electricity produced by the PV array (Module D) installed in the district is considered in the balance;
- Scope 2, with a score of +44,589 t CO_2 eq, represents the product system described in Sections 2 and 3. In this case, no benefit was shown, as additional information in Module D was considered;
- Scope 3, with a score of +9237 t CO_2 eq, represents the evaluation of the operational emissions only, where the embodied emissions of the construction materials are excluded. In this case, the benefit of exported electricity from the PV array is taken into account;
- Scope 4, with a score of −3079 t CO_2 eq, considers the operational emissions and the benefit from exported electricity, excluding the contribution of home appliances and artificial lighting.

In the first 2 years, the construction of the district buildings and the DHC network was assumed. At the end of the second year, the operational phase begins, and it ends at year 52, reaching the 50-year operating horizon as stated in the reference study period (RSP) definition. The replacement of building components (Module B4) and PV panels (i.e., at year 32) and the end-of-life stage of buildings (i.e., Modules C1–4, at year 52) are well highlighted in the figure with increased emissions. The replacement of energy system components based on the expected useful life (shown in Table 2) is also evaluated. However, these contributions are less significant for the climate footprint than the operational phase of the energy systems (i.e., electricity consumption and leakages of refrigerant gas) and, therefore, less apparent. Nevertheless, Figure 10 reports small steps in all four scopes (e.g., at years 21, 32, 42, etc.). It confirms the findings of previous authors [3,61,62] regarding the climate profile of energy systems, i.e., the operational phase contributes more to CO_2 eq emissions than the capital equipment (construction and end of life of appliances).

Figure 10a clearly shows how product systems 1 and 3 do not achieve net-zero emissions despite performing well from an emission viewpoint. The photovoltaic-powered DHC network has a very low climate profile compared to individual vapor compression systems [3] (157 vs. approximately 200 g CO_2 eq/kWh_{th} for SH and DHW and 64 vs. approximately 250 g CO_2 eq/kWh_{th} for SC). The construction was implemented using reinforced concrete with 40% blast furnace slag cement with a climate profile (Modules A1–3) of 204 vs. 295 kg CO_2 eq/m^3 of conventional Portland cement and 95% recycled steel bars (0.77 vs. 2.18 kg CO_2 eq/kg). In addition, the district, thanks to the photovoltaic array installed on the roofs of the buildings and the canopy nearby the railway station, produces 581 MWh_{el}/year that is exported to the national grid. Net-zero climate emissions are reached only when considering the scope 4 scenario, where the contributions of both the construction of buildings and home appliances and artificial lighting (HAAL) are excluded.

In this context, it is clear that an additional mitigation strategy must be defined to achieve net-zero climate emissions considering scenario 1 (full-life-cycle-based GHG system, as described in Section 2.4) and scenario 3 (direct and indirect operational emissions). A first solution, agreed upon with the real estate operator, could be to purchase renewable energy certificates (RECs), as shown in Figure 10b, to mitigate the footprint associated with grid electricity consumption; thus, the district's climate profile would drop from +28,780 to +6839 t CO_2 eq in scenario 1. This solution would be effective for scenario 3, reaching zero climate emissions for the operational phase (from +9237 to -12,704 t CO_2 eq) and making it approximately equivalent to scenario 4 (−13,187 t CO_2 eq). The value was calculated by changing the electricity emission factor from the national grid by considering electricity from hydroelectric, wind, and photovoltaic plants in equal proportions (33.3%). This allows decreasing the value from 616 (for the residual mix) to 24 g CO_2 eq/kWh_{el}.

5. Discussion

In this section, the authors discuss the outcomes obtained and presented in Section 4. The results from the case study are considered in the context of the aims and research questions presented in Section 1.2. Limitations and further recommendations are also analyzed in the field of designing NZCEDs.

Figure 11 shows the workflow steps to be followed in creating an NZCED. As can be seen, the work steps are iterative (a closed loop) in line with ISO 14000 standards (i.e., 14040-44, 14001, etc.). In addition to the steps discussed in this article, it is necessary to monitor the forecast emissions over time and implement potential preventive and corrective actions (additional insetting and offsetting solutions) to maintain the set goal of zero emissions.

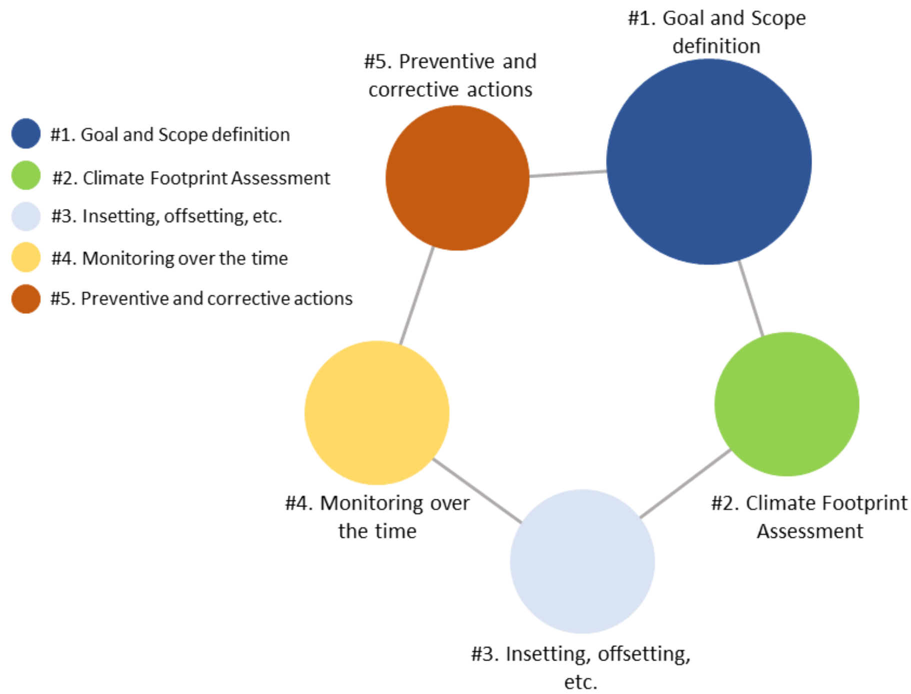

Figure 11. Workflow for defining net-zero climate emission districts.

5.1. Additional Mitigation and Offset Solutions to Reach the Zero Emissions Target

In addition to purchasing energy from RECs, other solutions could involve: (i) increasing the installed capacity from photovoltaics, making the district a positive-energy district (PED). The case study shows that the 14 buildings consume 919,044 kWh_{el}/year, and the solar array produces 759,184 kWh_{el}/year, so it would need at least 156 kWp to be installed, considering an annual value of 1034 kWh_{el}/kWp. Through this solution, the balance for scenario 1 would drop to +3417 t CO_2 eq (considering both RECs and additional PV). This solution, however, was not implemented by the real estate operator because the available space was already fully allocated to the solar array. This highlights how difficult it is to implement PEDs in a densely populated city like Milan. (ii) Another solution involves improving the embodied carbon dioxide of construction materials, as the building performances of the external envelopes may hardly be improved because they were already designed with low transmittances, as reported in Table A1, and are nearly zero-energy buildings (nZEB). Mass timber could be used for the vertical structures, and floor and roof slabs could be used instead of the adopted construction solution (reinforced concrete with eco-cement and recycled steel bars). Mass timber (i.e., cross-laminated timber—CLT, etc.) will mitigate about 4000 t CO_2 eq, achieving zero CO_2 eq emissions (net-balance approach), including RECs and an extra 156 kWp of photovoltaic modules. This solution was also investigated in the design phase by estimating the required amount of CLT for a prototype building. However, this solution was also not pursued by the real estate operator because it was considered too expensive for social housing units. An extra cost of 340 EUR/m^2 of gross area was calculated, amounting to about EUR 12,000,000 over the entire district. Due to impracticality, other solutions, such as small wind turbines, were not considered in the design phase. Small wind generators' benefits would be limited given the low productivity in kWh/kW achievable from systems installed in Milan [63] and generally within cities.

Because of the constraints described, achieving zero climate emissions (offsetting the remaining +6839 t CO_2 eq) is feasible for the case study only via additional insetting (e.g., redesigning local mobility and producing local benefits, etc.), economic compensation, and technical reduction (e.g., afforestation) solutions. For this case study, the real estate operator purchased credits from voluntary carbon funds (i.e., economic compensation).

5.2. Limitations and Further Work

The outcome of this work could be further improved by extending the evaluation to include long-term changes in technologies (i.e., PV modules, the climate profile of the electricity grid, and appliances supplying the DHC network) and also by making predictions about energy demand during the operational phase in the coming years, such as by using external temperatures and relative humidity concerning the representative concentration pathway (RCP) of the Intergovernmental Panel on Climate Change [64]. Insetting and technical reduction solutions should be further investigated. In this article, the authors mention the possibility without analyzing them. This decision is related to the substantial work needed to discuss the topics that would have lengthened the paper adequately and partly departed from its intended goals. In particular, the direct benefits associated with afforestation are limited in a densely populated area such as the one studied. A single tree can only store approx. 1.5 t CO_2 [65,66]. Furthermore, the dry matter content of rooftop gardens and wall gardening is limited, thus providing little CO_2 eq benefit. More significant potential benefits would occur through urban-scale projects achieving other climate mitigation advantages simultaneously (i.e., heat islands, particulate matter, etc.).

In this context, at the policy level, there is an urgent need to define appropriate performance thresholds (in terms of CO_2 eq footprint per square meter) according to the asset class of buildings in the district and for a hierarchy of solutions to achieve the net-zero climate target (i.e., insetting, offsetting, etc.) to hold real estate operators as accountable as possible.

Moreover, the outcome of this work could be further improved by extending the climate profile assessment to other environmental indicators, e.g., acidification, eutrophication, water depletion, resource use of mineral and metal resources, etc. As declared by Laurent et al. [67,68] for electricity production, a potential burden shift may occur in reaching net-zero climate emissions. Furthermore, other aspects beyond the environmental perspective could be included in the investigation; adding the life cycle cost and the social life cycle assessment to the environmental life cycle assessment would allow the obtaining life cycle sustainability analysis. To date, the implementation of a net-zero climate district, as highlighted, creates consequential economic and social effects, which could generate barriers to some segments of the population (i.e., the poorest). These consequential effects shall be further investigated in detail.

6. Conclusions

In this work, the authors evaluate the climate profile of a new district in Milan (14 buildings with 36,000 m^2 of gross surface area in total), aiming to become the first net-zero social housing project in Italy. The greenhouse gas emissions generated over a reference study period of 50 years are evaluated considering the direct and indirect emissions generated during the operational phase (for space heating, space cooling, domestic hot water, and electricity demand for parasitic, artificial lighting, and home appliances), following EN 15978. The embodied emissions of the construction materials are also included in the evaluation. At the same time, the authors exclude other emission sources, such as inhabitants' mobility, food consumption, and waste management. Mitigation solutions are provided by: (i) a fifth-generation district heating and cooling network powered by the Italian national grid and photovoltaic panels with a full capacity of approx. 740 kWp; (ii) vertical structures made of reinforced concrete with blast furnace slag (40%) and recycled steel bars (95%); and (iii) the purchase of renewable energy certificates for the amount of electricity provided by the national grid. The target of climate neutrality is reached by offsetting the residual emissions (equal to +6839 t CO_2 eq) by economic compensation. The evaluation of the case study allowed the authors to derive the following conclusions:

- The operational emissions are the main contributor (56%) compared with embodied emissions (44%). These percentages are assessed without considering the benefits of purchasing renewable energy certificates. Considering the purchase of renewable energy certificates, embodied emissions become the most significant contributor (86%) compared to operational emissions (14%).
- The definition of the product system with the scope of the analysis is a crucial component that significantly affects the final results, i.e., whether or not the district achieves climate neutrality. The authors show in the results section how climate neutrality is achieved on the part of the real estate operator by varying the scope. Therefore, this aspect will need to be more thoroughly researched and standardized in future regulations and guidelines that are released on the topic.
- The use of building materials with low primary non-renewable energy and CO_2 eq emissions is a key step in achieving the set neutrality goals. However, such materials are difficult to find on the market except at a significant cost increase (e.g., mass timber, etc.). Therefore, the decarbonization of the industry is a necessary step to follow.

Moreover, the authors highlight in relation to the research questions:

- A district composed of nearly zero-energy buildings is far from the definition of a net-zero climate emissions district, as previously highlighted by Causone et al. Even a positive-energy district can be a distant goal if, within the scope, construction materials are considered in the climate balance;
- Implementing positive-energy districts and reaching climate neutrality may not be feasible in densely populated urban settings without outsourcing the benefits (i.e., insetting, offsetting, etc.). There is insufficient space on building rooftops to produce enough electricity to offset demand. Ground spaces within the district must be used, even though they are often inadequate. Using district heating networks (of the latest generation, fourth or fifth) at the city level instead of at the district level could optimize space by allowing more photovoltaic modules to be installed and thus reaching the target set. In other words, the goal of climate neutrality must be pursued from the point of district master plan definition to leave adequate space for photovoltaic modules and analyze appropriate solutions.

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Abbreviations

Nomenclature	
Q	Heat transfer rate or thermal energy, kW or kWh
T	Temperature, °C
t	Time index
U	Internal energy, kWh
UA	Heat transfer coefficient—area product, W/K
W	Electric power or electricity consumption, kW or kWh
δ	Binary variable
τ	Time step, set to 1 h
Subscripts	
BU	Balancing unit
c	Cooling
DHW	Domestic hot water
dst	Distribution
EC	Energy center
el	Electric
h	Heating
loss	Thermal losses
nd	Building energy needs
NTW	Network
Ref	Reference value for heat losses calculation
th	Thermal
Abbreviations	
AIRU	Italian Association of the Urban Heating
CC	Climate change
CLT	Cross-laminated timber
COP	Coefficient of performance
CO_2 eq	Carbon dioxide equivalent
DHC	District heating and cooling
DHW	Domestic hot water
EER	Energy efficiency ratio
EF	Environmental footprint
EoL	End of life
EPS	Expanded polystyrene
ESL	Estimated service life
FU	Functional unit
GHG	Greenhouse gas
GO	Guarantees of origin
GWP	Global warming potential
HAAL	Home appliances and artificial lighting
HPC	Heat pump chiller
HVAC	Heating, ventilation, and air conditioning
HP	Heat pump
LCA	Life cycle assessment
LBSF	Load-bearing structural frames
MILP	Mixed-integer linear program
NLBSE	Non-load-bearing structural elements
NOCT	Nominal operating cell temperature
NZCED	Net-zero climate emission district
nZEB	nearly zero-energy building

PEB	Positive-energy building
PED	Positive-energy district
PV	Photovoltaic
PVC	Polyvinyl chloride
RCP	Representative concentration pathway
REC	Renewable energy certificate
RES	Renewable energy sources
ReqSL	Required service life
RSP	Reference study period
SC	Space cooling
SH	Space heating
TER	Total energy ratio
WTE	Waste to energy
ZEB	Zero-emission building

Appendix A

Table A1. Construction technologies, amounts, and thermal transmittances.

Component	Element	Amount (kg/m^2 of Net Area)	Thermal Transmittances U $\left(\frac{W}{m^2K}\right)$
Foundation and underground	Concrete Reinforcing steel	231.84 17.39	-
Vertical structures (beams, pillars, and concrete walls)	Concrete Reinforcing steel	408.66 37.19	-
Basement slabs	Mortar Polystyrene Concrete Light bricks Reinforcing steel	45.78 1.31 40.61 16.31 2.01	0.188
Floor slabs	Mortar Polystyrene Concrete Light bricks Reinforcing steel Metal ceiling Gypsum plasterboard	183.14 1.21 162.43 65.23 10.32 2.42 8.05	0.351
Roof slabs	Bitumen Polystyrene Vapor barrier in PVC Mortar Concrete Light bricks Reinforcing steel Metal ceiling Gypsum plasterboard	0.43 1.21 0.23 38.74 40.61 16.31 2.58 0.60 2.01	0.150
External transparent envelopes	Frames in PVC Glass Argon	18.97 4.02 0.01	1.250

Table A1. *Cont.*

Component	**Element**	**Amount (kg/m^2 of Net Area)**	**Thermal Transmittances U $\left(\frac{W}{m^2K}\right)$**
External opaque envelopes	Cement plaster EPS Light bricks Rock wool Metal ceiling Gypsum plasterboard	12.47 2.60 124.70 2.77 2.08 6.93	0.120
Internal walls between heated and unheated spaces	Bricks Rock wool Metal ceiling Gypsum plasterboard	74.97 1.67 2.50 16.66	0.427
Balconies	Mortar Polystyrene Concrete Welding mesh Light bricks EPS Cement plaster	31.64 0.77 35.04 1.09 15.99 0.61 3.13	-
Stairs	Concrete Reinforcing steel	13.65 1.38	-

Table A2. EoL scenarios, benefits, and loads.

Material	**EoL Scenario**	**Values (%)**	**Recycling and WTE Efficiency**	**Substitution Ratio**	**Avoided Burdens**
Reinforced concrete	Recycling Incineration Landfill	61.2% 0.0% 38.8%	70% for steel	1:0.25 concrete 1:1 steel	Gravel extraction for road filling. Primary production from pig iron.
Polystyrene	Recycling Incineration Landfill	0.0% 100.0% 0.0%	20.70% for electricity 27.20% for heat	-	Residual electricity from the national grid and heat production from a natural gas boiler.

Table A2. *Cont.*

Material	EoL Scenario	Values (%)	Recycling and WTE Efficiency	Substitution Ratio	Avoided Burdens
Steel	Recycling Incineration Landfill	97.0% 0.0% 3.0%	81.45%	1:1 steel	Primary production from pig iron.
Light bricks	Recycling Incineration Landfill	60.0% 0.0% 40.0%	100%	1:0.03	Gravel extraction for road filling.
Gypsum plasterboard	Recycling Incineration Landfill	15.0% 0.0% 85.0%	-	1:1	Primary gypsum production.
Bitumen	Recycling Incineration Landfill	0.0% 100.0% 0.0%	20.70% for electricity 27.20% for heat	-	Residual electricity from the national grid and heat production from a natural gas boiler.
Vapor barrier in PVC	Recycling Incineration Landfill	0.0% 100.0% 0.0%	20.70% for electricity 27.20% for heat	-	Residual electricity from the national grid and heat production from a natural gas boiler.
Windows frame in PVC	Recycling Incineration Landfill	5.4% 15.0% 74.6%	55.71% for recycling 20.70% for electricity 27.20% for heat	1:1	Primary production of PVC granulate. Residual electricity from the national grid and heat production from a natural gas boiler.
Glass	Recycling Incineration Landfill	10.0% 0.0% 90.0%	90.1%	1:1	Primary production of glass from sand. Residual electricity from the national grid and heat production from a natural gas boiler.
Cement plaster	Recycling Incineration Landfill	0.0% 0.0% 100.0%	-	-	-
EPS	Recycling Incineration Landfill	0.0% 100.0% 0.0%	20.70% for electricity 27.20% for heat	-	Residual electricity from the national grid and heat production from a natural gas boiler.
Rock wool	Recycling Incineration Landfill	0.0% 0.0% 100.0%	-	-	-

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