Innovative tools and protocols for the regeneration of urban and peri-urban districts towards climate neutrality

Prof. Arch. Fabrizio Tucci, Arch. Valeria Cecafosso, Arch. Gaia Turchetti, Arch. Marco Giampaoletti, Arch. Chiara Mastellari

University of Rome, Sapienza, Department of Planning, Design, Technology of Architecture, Via Flaminia 72, Roma, Italy

fabrizio.tucci@uniroma1.it, valeria.cecafosso@uniroma1.it, gaia.turchetti@uniroma1.it, marco.giampaoletti@uniroma1.it, chiara.mastellari@uniroma1.it

Abstract. Cities represent the foremost contributor to the escalating growth in energy consumption, constituting a substantial portion of global greenhouse gas (GHG) emissions. In the face of climate change and the heightened frequency and severity of extreme events, urgent policies and actions are imperative for cities to enhance resilience and instill a sense of responsibility among their inhabitants. Additionally, establishing monitoring and reporting models to track progress in implementing sustainable urban development measures is crucial.

The calculation of CO2 emissions in cities demands a multidimensional approach, encompassing sectors such as energy, buildings, water, green spaces, transport, waste, and others. Models and diagnostic tools are available for the different fields of interest. These are valuable elements; however, they often necessitate specialized expertise and prolonged processing times for accurate result interpretation, sometimes conflicting with the need for prompt, reliable guidance.

This contribution aims to define innovative tools and protocols, along with a specific performance verification model (easy model), concerning mitigation and adaptation to climate change. These tools are designed to be easy to apply and usable from the preliminary project stages for the redevelopment/regeneration of existing architecture and urban districts.

Keywords: Climate change-Retrofitting-Decarbonization-Resilient-Energy efficiency-Easy model-Simulation process.

1. Introduction

The city, defined as a global center of communication, trade, and culture, constitutes the most significant component of energy consumption growth, accounting for 36% of global greenhouse gas (GHG) emissions. [1] They must deal with ever-increasing climate-related risks, such as heat waves, prolonged droughts, and floods, in interaction with non-climate risk factors such as ecosystem fragmentation, pollution, unsustainable agricultural practices, water management, land use settlement patterns, and social inequalities. These factors generate public health, ecosystem, infrastructure, and economic impacts that can spread like a waterfall from one system or region to another, leading to system-wide challenges affecting entire societies, with vulnerable social groups particularly affected. [2] [3]

In this context, the city must carry out a key role in combating the effects of climate change with mitigation and adaptation actions aimed to achieving zero emissions. Implementing circular economy principles allows cities to accelerate decarbonization while addressing long-standing issues such as resilience and quality of life. [3]

This contribution proposes to analyze planning strategies, actions, and solutions aimed to raising the performance level of building constituting urban and peri-urban districts. It suggests using simplified support models for planning, design, management, and maintenance phases, with a perspective of interoperability, multifunctionality, and multi-scalarity.

The function of verifying (testing) the technological solutions adopted in urban regeneration projects is delegated to innovative protocols and tools. These tools can provide useful answers to stakeholders in the sector from the preliminary phases of the project. They allow for rationalization of the building form, user needs, plant systems, environmental elements, and their dynamic interactions in the building context with a high level of precision and reliability that is difficult to replicate with traditional analogue techniques. [4]

Architectural modification of existing urban morphology can sometimes improve the functional characteristics of open spaces but may lead to potential loss of well-being for the resident population if poorly governed. The adoption of ex-ante/ex-post simulation processes allows the assessment, through a dedicated methodology, of the maximization of the physiological well-being of the users. [5]

The simplified models adopted in this contribution interact directly with the original data defined for the analyzed context area. They define, as the primary objective, the same logic of design management of environmental and thermodynamic parameters. They provide fully integrated flow simulations that can be compared and implemented with the possible variants of solutions adopted. [6] These models are themselves the subject of research and implementation, evaluating the integrative potential in the performance process of the building and any interactions. [7]

The new protocols and tools are intended to support the generation of innovative modules through analytical design processes. They go beyond the 'synthesis-analysis-evaluation' sequence, which has been supported and elaborated in numerous scientific researches so far, and connect with recent advances in architectural calculation, simulation, and parametric design.

2. Methodology and operational stages of the research

Quantifying CO2 emissions associated with urban metabolism, particularly Energy, Water, Green, Waste, and Mobility consumption, involves assessing the various sources and activities that contribute to them.

The research is developed in three stages:

Stage 1 – Analyzing the reference framework and classifying related emissions that occur. The model adopted is that of the IPCC (Intergovernmental Panel on Climate Change). [8] Identify the emissions to be considered, including both embedded emissions (generated by the demolition and reconstruction process) and operational emissions (generated directly within the neighborhood).

Stage 2 – Developing a reference framework by identifying specific models and methodologies to calculate the operational CO2 equivalent emissions of each analyzed system:

- Energy: Simulation models are adopted to assess energy consumption of buildings and urban areas, considering energy efficiency and the use of renewable sources. CO2 emissions are calculated based on the type and amount of energy consumed.
- Water: The consumption model in the district is examined, and associated emissions with water treatment and distribution are assessed, including electricity for lifting, treatment, and network feeding.
- Green: Building a framework of CO2 sequestration capacity of green areas and trees in relation to species.
- Waste: Calculation of emissions associated with waste collection, transport, and disposal based on the amount and types produced in the district.
- Mobility: Assessing public and private transport, traffic congestion, and flow patterns. The calculation of emissions takes into account the number of vehicles, kilometers traveled, and the type of fuel used.

Stage 3 - Elaborating the emission assessment framework applied to a pilot district. It consists of:

- Emission inventory: Examination of the current state of art with identification of strengths and weaknesses to define the baselines against which the process is measured. Identifying emission sources and quantifying them for each category.
- Develop a master plan: Developing an action plan to reduce emissions by optimizing key actions and setting priorities.
- Evidence reduction: Evaluating the implementation of measures taken to ensure the reduction of CO2 emissions to zero.

3. Pilote case

3.1. Geographical background and analysis of state of art

The pilot case involves an intervention of urban regeneration with a sustainable focus in Tiburtino Sud, a neighborhood initially developed as an economic and popular housing plan. It is located in the eastern part of Rome, within the GRA and belongs to the IV municipality. The neighborhood covers an area of 187 hectares and, as of 2023, has a population of 21,976 inhabitants. [9]

The area represents one of the largest Area Plan realizations in the capital city. Its urbanization began between the 1970s and 1990s with building cooperatives following the provisions of the 1962 Regulatory Plan, which envisaged an expansion to the east of the city.

The intervention area is equipped with a well-developed hierarchical infrastructure system that connects it both longitudinally and transversally to the rest of the city through two main horizontal axes (Via Tiburtina to the north and Via Collatina to the south) and a central vertical axis (Viale Palmiro Togliatti). Public transport accessibility is also effective, with two subway stops on the B line, the Togliatti railway station, and three bus lines servicing the main roads.

A critical aspect is the almost complete absence of a soft mobility system. The limited road network winds through a fabric of 20th-century expansion characterized by curvilinear buildings, which give the area its planimetric identity. Numerous urban voids within the fabric accommodate green spaces, some of which contain historical artifacts.

The predominantly high-density residential buildings range in height from 24 to 30 meters. Basic services are located on the ground floor of buildings facing the main roads and are generally reachable within a 15-minute walk.

The residential buildings were constructed according to low-cost housing criteria, with a load-bearing structure in reinforced concrete composed of pillars and beams arranged in a "trestle" pattern, supporting load-bearing slabs. Prefabricated concrete panel claddings with a thin layer of insulation are used, though they do not adequately improve the building envelope's performance. Internally, the distribution of space is replicated on each level, with a mix of medium to large housing units.

The urban pattern includes several green spaces, both public and residential, with parks concentrated along the edges of the built-up area. These include the Acea Park, which acts as a buffer for the Roma Est water purification plant, and the Cervelletta Park, appreciated for its ecosystem services. The presence of a rich environmental system also results in significant vegetation, with a reported mapping of all tree species in the area to assess their greenhouse gas absorption rate, currently estimated at about 2 million KgCO2eq/a

3.2. Definition of a reference framework

The examined district comprises 24 buildings from the economic and popular housing plan, totaling 210,097 square meters of residential and green areas. Among these, two buildings are undergoing deep renovation as part of the housing complex located at the junction of the district's two arterial roads. For these buildings, the weight, volume, and embodied carbon of the components have been calculated. It is believed that the planned actions on them could potentially be applied to all other existing buildings to limit land consumption and transform the buildings, ensuring thermohygrometric comfort and reusing demolished materials.

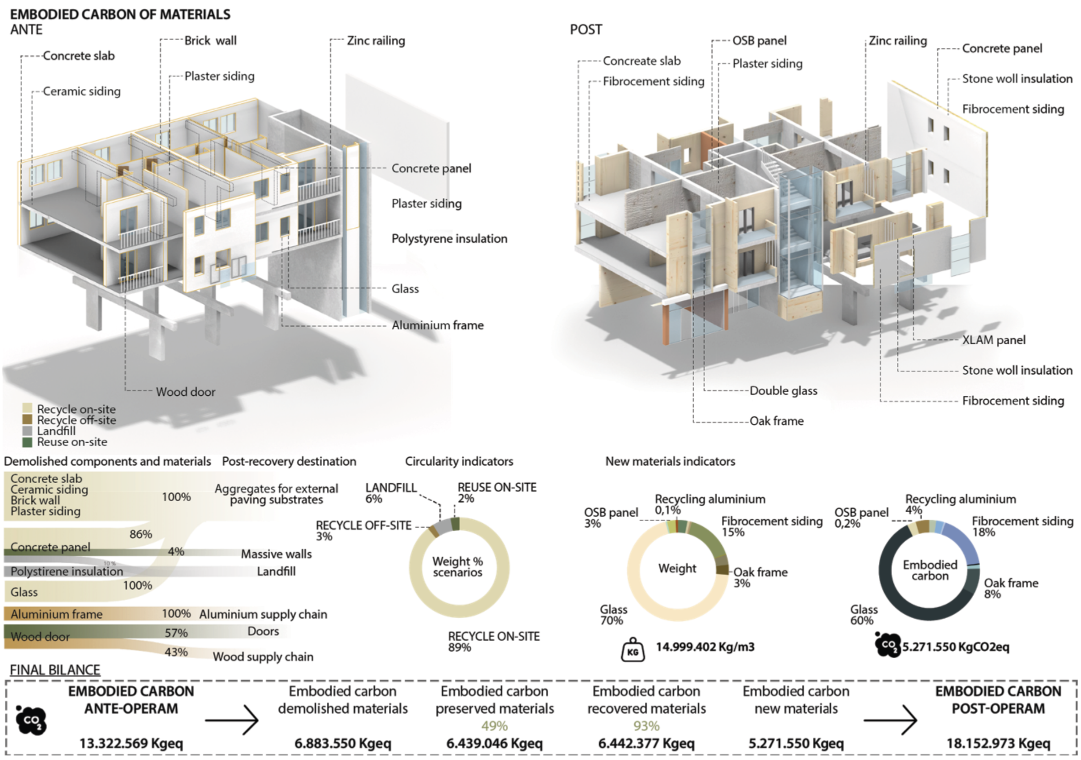

Figure 1. Definition the destinations of demolished materials and calculation of the weight and embodied carbon of new materials with final comparison between ante operam and post operam.

The entire intervention has been planned with the idea of limiting raw material consumption and minimizing the materials resulting from the demolition and reconstruction process. Initially, it was assessed that approximately 13,322,597 kgCO2eq is the starting point, with 6,883,550 kgCO2eq designated for demolition, the largest share of which consists of internal partitions, external concrete panels, and window fixtures. According to the building CAM (D.M.11/10/17), at least 70% of disused materials must be recovered. Therefore, possible destination scenarios have been identified for each type to minimize the portion sent to landfill.

Material recovery amounts to 93%, with 89% allocated for on-site recycling. Brick partitions, concrete screed, plaster, and part of the prefabricated panels will be used as aggregates for the subfloors of the new external flooring. The remaining panels will serve as solid walls for bioclimatic systems, and glass will be used as a draining subfloor on the roof. When choosing the type of cladding for newly built walls, materials with selected embodied carbon for the same thermal performance were preferred. Xlam panels were chosen for external cladding, and OSB panels with wooden frames were selected for internal partitions (see Figure 1).

Operational emissions within the district are divided into thematic classes: water, mobility, energy, and waste networks, based on emission indices indicated by respective research institutions.

Currently, municipal solid waste production per capita stands at 615 kg, with a collection rate of 47% [10]. The associated CO2 emissions, including the collection system, amount to 13,225,368 KgCO2eq/year. On another front, the water requirements exclusively for drinking water, encompassing internal uses for daily activities and external uses for irrigation [11], contribute to greenhouse gas emissions production totaling 84,526 KgCO2eq/year. Emissions from energy consumption, covering domestic uses such as indoor air conditioning, domestic hot water, electrical appliances, and lighting, as well as public lighting, total 12,800,195 KgCO2eq per year, based on an energy consumption of 49,630,161 kWh/year [12].

Regarding mobility, emissions are considered from traffic induced by residential and ancillary activities, including emissions from public and private means of transport, based on the average number of bus passages at bus stops and the quantity of private vehicles owned relative to the number of users in the area, with an average distance traveled per year of 11,744 km per car [13]. Estimating that 54% of vehicles are powered by petrol, the corresponding CO2 emissions amount to 7,739,316 kgCO2eq per year.

In total, operational emissions amount to 33,857,023 KgCO2eq per year.

3.3. Masterplan development and strategies in place regarding resource flows

Based on the analysis conducted, the existing weaknesses and strengths offered by the intervention area have been highlighted. A regeneration model has been developed to achieve decarbonization through the adoption of a series of strategies focused on improving environmental quality, bioclimatic well-being, energy efficiency, and the circular management of natural capital and resources. Additionally, the model aims to enhance the livability and usability of spaces for citizens. [14]

These strategies are evaluated based on the multi-scalar dimension of the analyzed district. Furthermore, they aim to enhance the response to climate change events by implementing mitigation and resilience skills to climate change at the urban level. This includes interventions in green and paved public areas, water infrastructures, transport and mobility infrastructures, and the waste management network. At the level of the individual building complex, interventions focus on energy efficiency.

For green areas, it is established that they will be redeveloped both at ground level and in elevated areas. This will involve introducing the planting of new trees and tree species that perform better in CO2 storage. Additionally, green spaces will be increased by removing impermeable soil where possible, creating corridors to connect pre-existing ecosystem services. This will allow them to contribute more to emission abstraction (see Figure 2).

The green spaces also create an excellent combination with natural ventilation in terms of microclimatic well-being as they ensure evapotranspiration cooling and strategic positioning of tree masses according to wind flows within the neighborhood. They can act as a barrier during the winter season and a directional filter during the summer season (see Figure 3).

In addition, a cycle-pedestrian ring is adopted with the task of unifying the entire area plan and improving accessibility by thematizing each stage of the path according to the implemented services of the missing functions. These functions will play the role of poles of attraction of the path itself. From this ring, cycle paths run along the main roads to reconnect with existing sections that are part of the city's system. At the infrastructural level, carriageways that are not relevant to the road system are converted into pedestrian areas, while at ground level, parking areas are replaced with pavements with draining characteristics, and underground parking spaces are provided to reduce the amount of open-air asphalt. This would contribute to an increase in heat and difficulty in rainwater runoff.

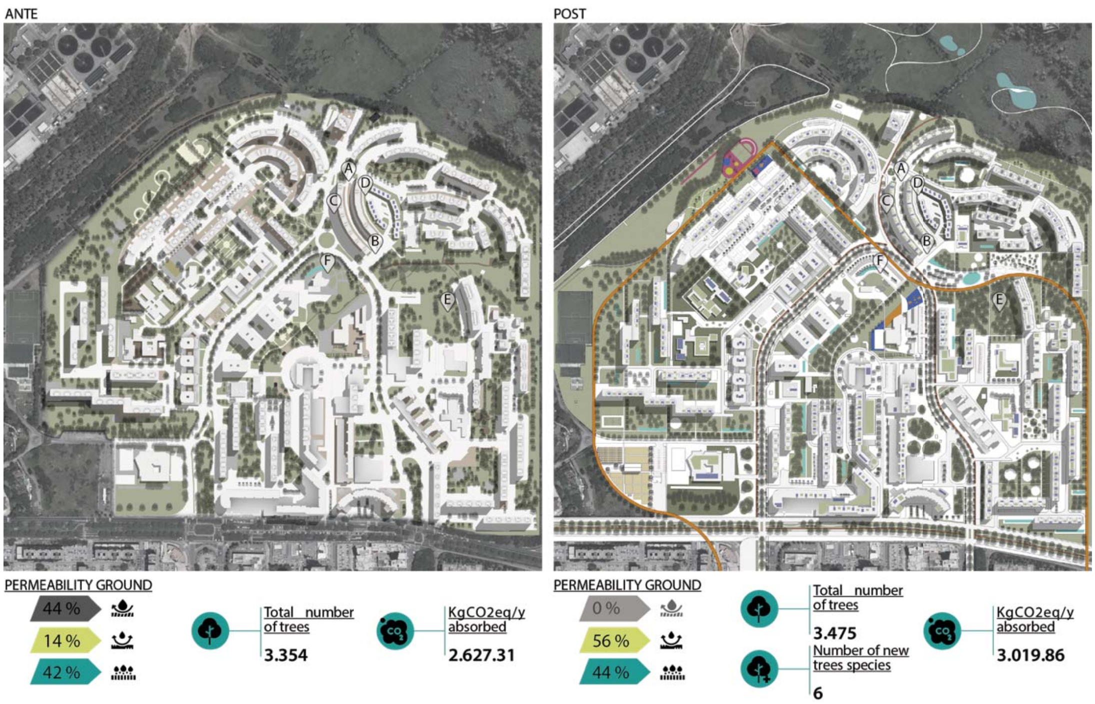

Figure 2. Masterplan ante and post operam comparison based on soil permeability and quantity of tree species and identification of six points of interest subject to the micri-climate monitoring stage.

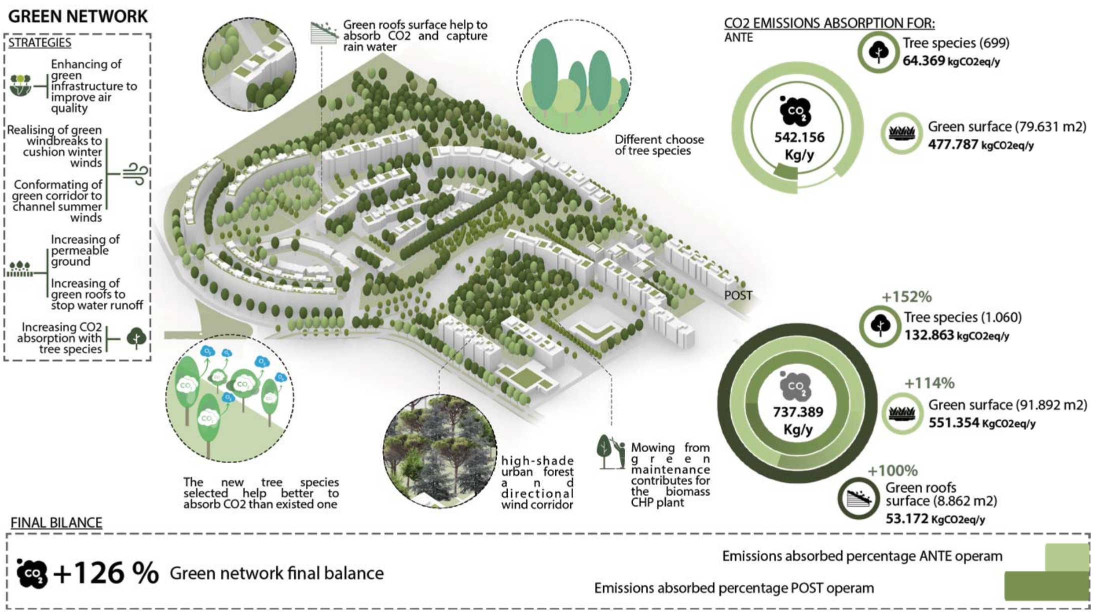

Figure 3. Green network in the district with declaration of strategies and calculation of CO2 emissions comparing ante operam and post operam.

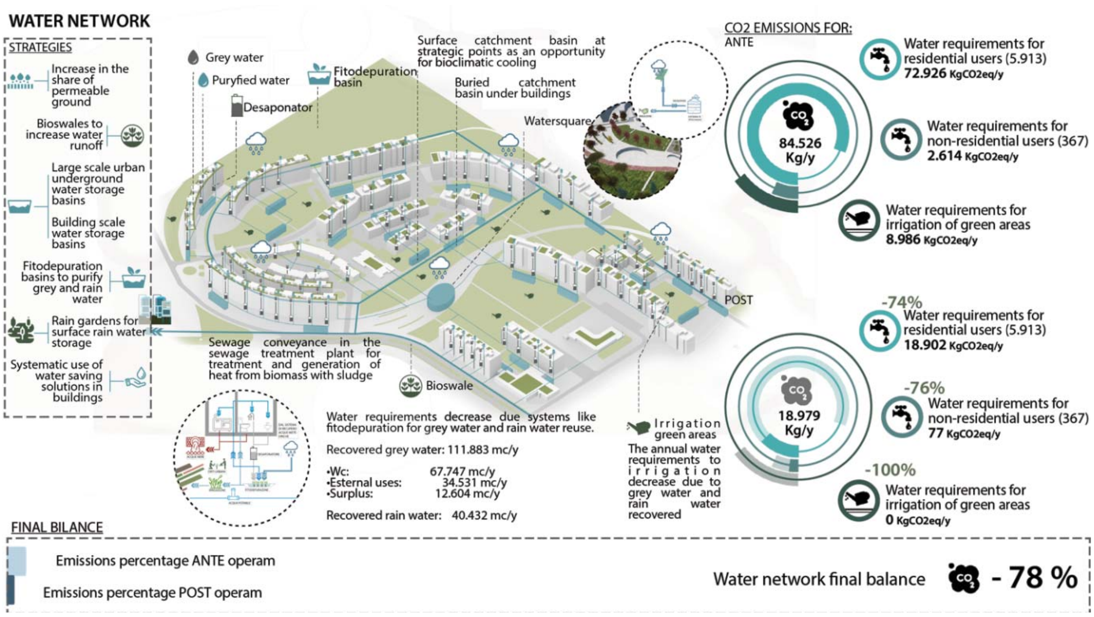

Figure 4. Water network in the district with declaration of strategies and calculation of CO2 emissions comparing ante operam and post operam.

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Therefore, paved public areas are redeveloped, making them semi-permeable and using cool materials that, combined with the control of ventilation flows, help to reduce heat islands and affect the local outdoor climate with positive effects on CO2 emissions. In fact, external comfort has an impact on the energy consumption of indoor confined spaces by limiting the energy requirements for heating and cooling.

Improving soil permeability through the use of paving with draining characteristics is useful in the perspective of circular resource management and for the adaptation of the city to extreme events by avoiding runoff phenomena. In this sense, the realization of devices such as rain gardens and bioswales is planned to be located at the main roadways.

Outdoor interventions are completed by also acting on buildings with deep renovation actions for energy efficiency. This involves improving the building envelope performance with ventilated walls and new wall packages that boost transmittance. Passive contributions are maximized through integrated technological solutions, including direct gain systems (such as solar loggias) and indirect gain systems (like Trombe walls). Ventilation towers are utilized to decrease consumption for cooling the environment and facilitate the exchange of indoor air. Additionally, renewable sources with active systems (such as solar photovoltaic and solar thermal) are used to compensate for the remaining energy requirements for heating, cooling, and domestic hot water production.

Integration with vegetation in some significant areas of the façades is also crucial to generate shading. Blue-green roof systems are installed, a particular type of roof that helps reduce the thermal load in the summer period and decrease heat losses in the winter period, thereby reducing energy consumption. Furthermore, interventions focus on water saving by recycling rainwater for irrigation.

The recovery of rainwater from building roofs can take place in surface tanks, as in the case of watersquares, which can transform into socializing places during periods of water scarcity.

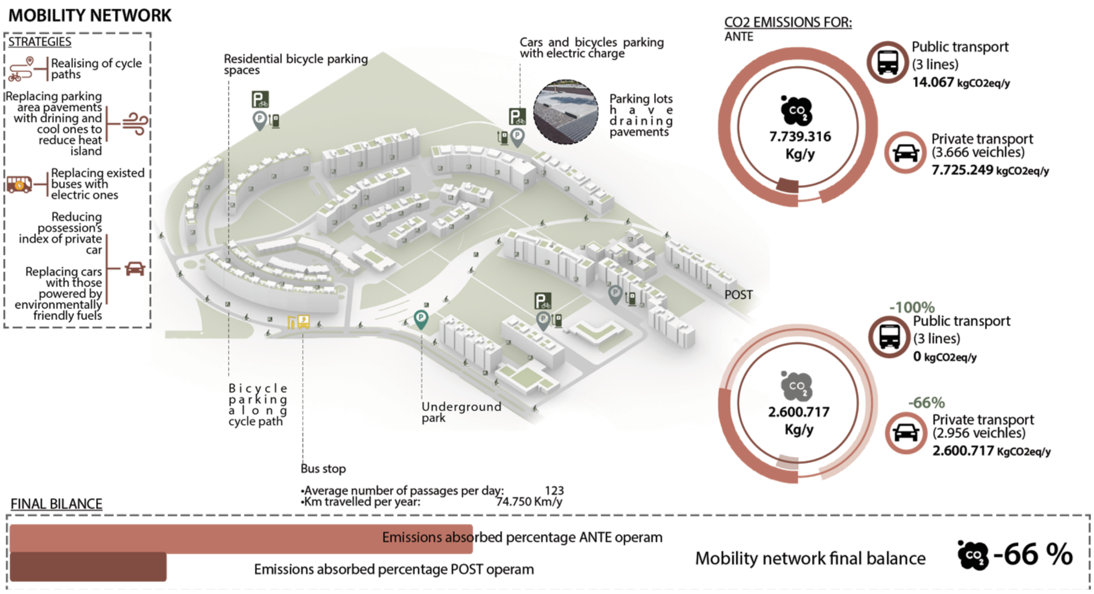

Figure 5. Mobility network in the district with declaration of strategies and calculation of CO2 emissions comparing ante operam and post operam..

The other capted rainwater together witch grey water originating from domestic uses, are conveyed towards undergroung storage basins for their reuse within water circuits after being treated in phyto-purification basins by means of a settling process taking advantages of suitable plants.

Sewege, in the other hand, is directed to towards the water purification plant where the produced sludges are used to generate energy (Figure 4).

With reguard to mobility in the parking lots, electric rechargings are inserted to encourage the uso of sustainable vehicles and it is provided for possible exchange of heat-engined buses with electrically powered ones (Figure 5).

The reduction of emissions for energy production is also applied to outdoor spaces through the use of LED lamps and integrated photovoltaic panels for public lighting to be self-supporting and the use of green maintenance mowings for the production of biomass energy to be realised in the cogeneration plant to upgrade the existing water purification plant (Figure 6).

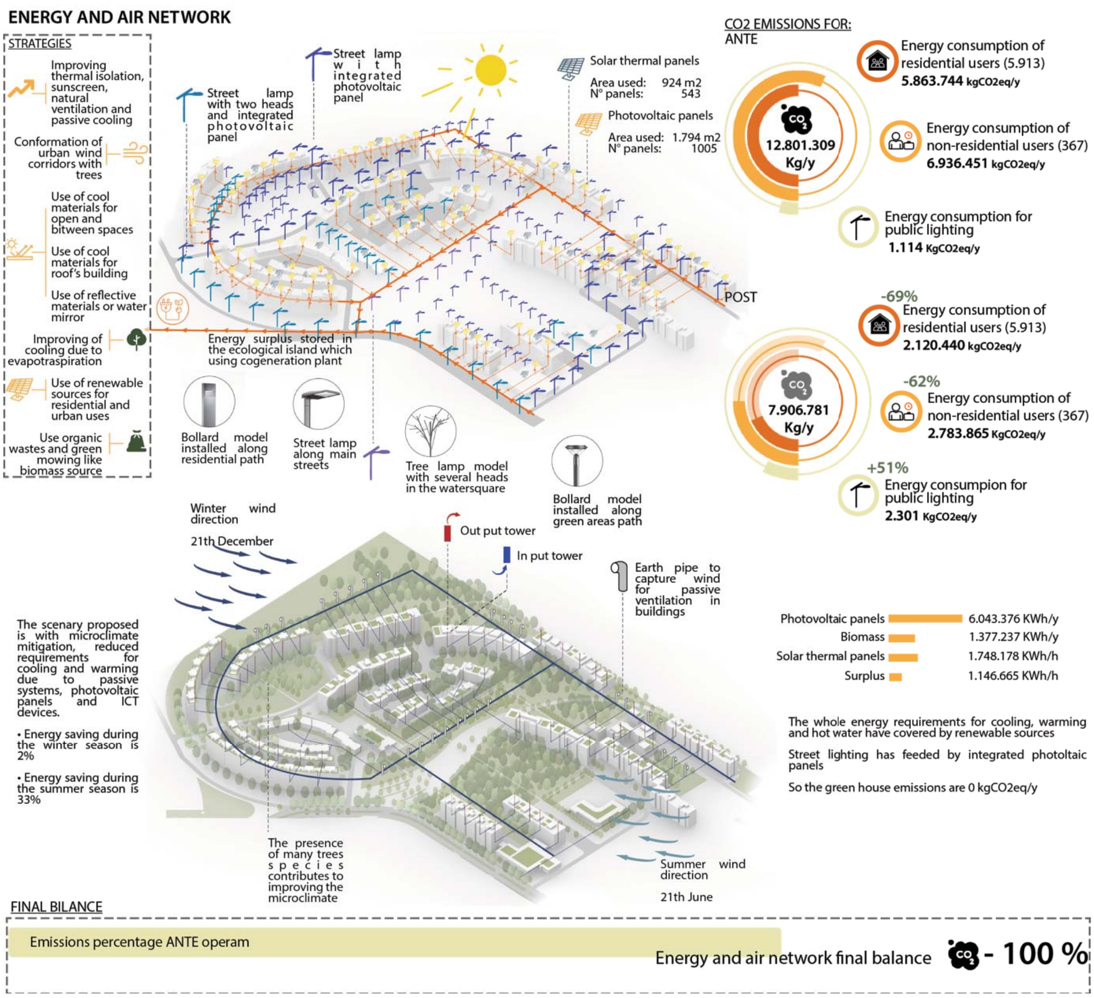

Figure 6. Energy and air networks in the district with declaration of strategies and calculation of CO2 emissions comparing ante operam and post operam.

Wastes also are input into the optimised waste managment cycle: are included collection points in the outdoor areas along the main axis of the neighbourhood where wastes are pushed by means of underground pneumatic systems from differentiaded channels located in common rooms, with which each floor of the buildings is equipped, to, once collected, the treatment centre. This process allows to obtain a benefits in the vision both for emissions reduction due to the greater recovery of materials and the limited movement of collection vehicles in a single pass, and for energetic cause the organic fraction, togheter with green wastes, can be used as a source of biomass (Figure 7).

3.4. Fluid-dynamic simulations and monitoring

Against the planned interventions, the improvement of the local microclimate is verified through fluid-dynamic simulations using the ENVI-met modeling software. Six interest points in the intervention area are selected for monitoring and comparison between ante- and post-operam, indicated by the first six letters of the alphabet: A, B, C, and D located in the built-up area of the two study buildings, E in a green equipped area, and F in the free paved area of the square.

The software, by inputting data about the climate and morphological-environmental characteristics of the area under investigation, allows the extrapolation of climatic and perceptual output parameters to support the definition of appropriate environmental and energy strategies during the design stage.

The results of the simulations are used to calculate energy consumption related to the planned improvement scenario (see Figure 8).

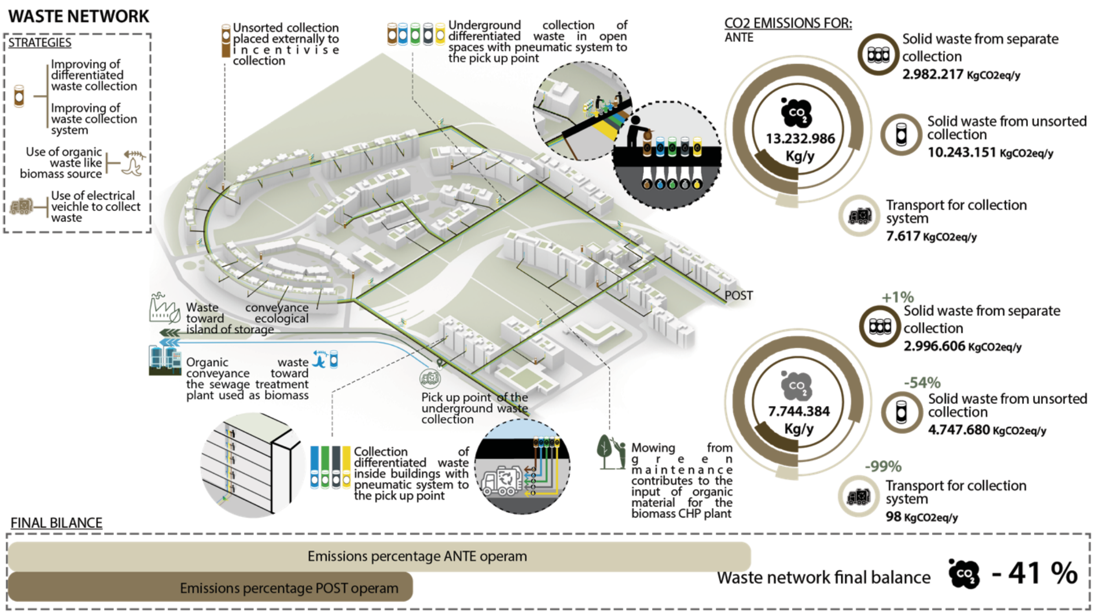

Figure 7. Waste network in the district with declaration of strategies and calculation of CO2 emissions comparing ante operam and post operam..

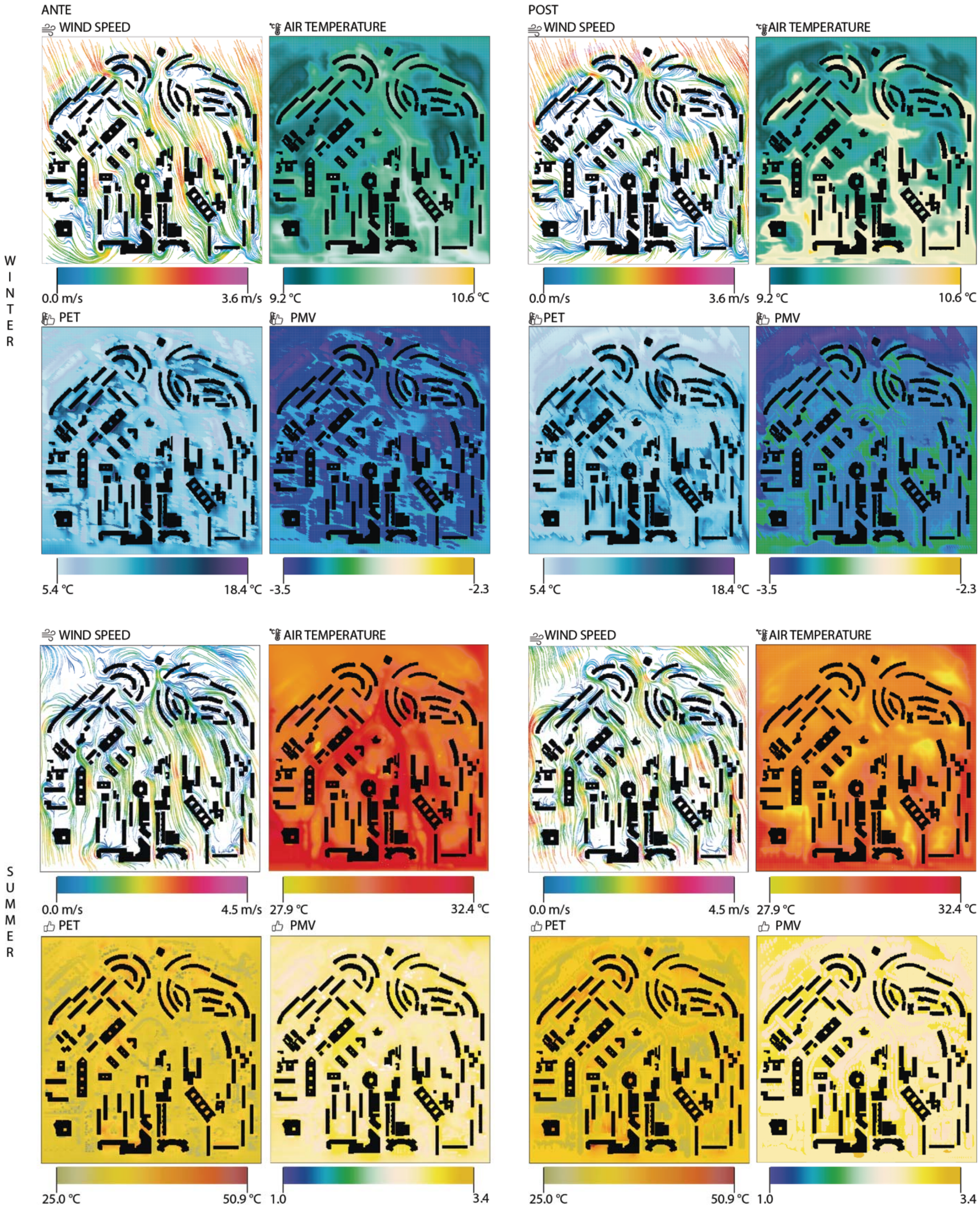

Figure 8. Fluid-dynamic (wind speed), thermophysical (air temperature and mean radiant temperature) and perceptual (PET, PMV and PPD) simulations on 21/12/23 and 21/06/23 comparing the actual and design state.

Due to the measures implemented in winter, a reduction in wind speed of approximately 0.5 m/s is recorded, thanks to the strategic positioning of tree masses acting as a barrier. Additionally, there is an increase in temperature from 9°C to 10°C, with relative humidity rising on average from 73% to 70%. The perceived temperature increases on the paved areas, with points D and E experiencing a 2°C increase, while the average radiant temperature significantly increases at points B, C, D, and F, reaching 22°C during the hottest hours. Consequently, the PMV (Predicted mean vote) improves from values of -4 and -3 to values of -2 and -1, reducing the percentage of dissatisfied individuals from 78% to 65% (see Table 1).

In the summer season, conversely, there is an increase in the intensity of the ventilation flow by 1.9 m/s. Together with gains in shaded and cooled portions, this reduces the average temperature from 32°C to 30°C. Particularly, at point E, where the area is intended to be densely vegetated, the temperature is around 26°C, resulting in a perceived temperature decrease of 5°C. Overall, there is an improvement in all parameters due to the cross effects of the implemented actions: the average radiant temperature is reduced to 35°C from the initial 47°C, thanks to the use of light-colored surfaces on the facades, which reduce the albedo effect. Additionally, the PMV index is lowered, while the relative humidity remains around 45% (see Table 2).

Table 1. Output data from post-operam simulations in the winter season compared with pre-operam data.

	WIND SPEED (m/s)	AIR TEMPERATURE (°C)	RELATIVE HUMIDITY (%)	AVERAGE RADIANT TEMP. (°C)	PET (°C)	PMV	PPD (%)
A	1.2	9.6	71	11.6	9.5	-1.7	60
	1.6	9.7	70	12.1	7.6	-3.0	70
B	0.8	10.2	68	22.5	13.6	-1.4	51
	1.0	9.8	69	12.5	11.5	-2.8	58
C	1.6	10.1	69	20.0	8.6	-1.8	58
	2.0	9.8	69	11.1	6.6	-3.2	67
D	0.4	9.7	70	21.7	11.7	-1.4	57
	0.1	9.7	70	8.3	11.2	-2.9	68
E	1.7	9.4	72	10.7	8.1	-2.9	62
	1.6	9.3	72	9.6	9.7	-3.3	73
F	0.9	10.2	69	18.2	9.6	-1.5	54
	2.0	9.7	71	9.9	9.0	-3.0	68

Table 2. Output data from post-operam simulations in the summer season compared with pre-operam data.

	WIND SPEED (m/s)	AIR TEMPERATURE (°C)	RELATIVE HUMIDITY (%)	AVERAGE RADIANT TEMP. (°C)	PET (°C)	PMV	PPD (%)
A	1.0	29.7	44	39.7	32.8	2.2	80
	1.3	30.5	41	51.2	35.8	2.6	96
B	1.3	29.9	44	40.2	33.7	2.3	86
	0.9	31.0	41	51.2	38.9	2.8	98
C	1.4	29.6	46	46.2	32.0	2.7	77
	2.1	31.2	40	50.3	34.6	2.5	95
D	0.7	29.6	45	38.4	33.3	2.2	90
	0.1	30.4	43	30.9	39.6	1.6	95
E	1.9	28.4	42	34.8	29.3	1.8	61
	1.8	30.8	42	48.6	33.4	2.3	90
F	1.2	30.0	45	42.5	35.0	2.5	91
	1.1	30.8	42	48.5	35.0	2.6	96

3.5. Discussion of the results

Based on the planned indoor and outdoor retrofitting measures, a reduction in the consumption of the examined resources and a corresponding decrease in CO2 emissions are achieved. However, it should be noted that regarding mobility, there is a hypothesis of reducing the private car ownership index to 0.62% per inhabitant and replacing public transport vehicles with heat engines with electric vehicles. This aims to reduce emissions to 2,600,717 KgCO2eq per year, which is 66% of the current level.

At the energy level, improved environmental conditions, the implementation of passive systems in buildings, and the intelligent management of ITC systems allow for a reduction in consumption to 6,757,815 KWh/year [12] and emissions to be reduced to 7,906,781 KgCO2eq per year. This reduction can lead to neutrality thanks to the use of energy from renewable sources.

Furthermore, water usage is rationalized by utilizing rainwater and greywater collection-recovery-reuse systems, and by reducing the use of drinking water for non-hygienic purposes, resulting in a 78% reduction in CO2 emissions. Additionally, waste separation and collection system improvements lead to a 41% reduction in emissions. Ultimately, the calculated CO2 emissions amount to 10,364,080 KgCO2eq per year. To further mitigate emissions, even better-performing tree species are added to increase carbon dioxide storage by 26% compared to current levels. The final balance confirms that the proposed interventions achieve the expected result, as emissions within the examined district are reduced by 71% (see Figure 9).

4. Conclusions

The document focuses on issues related to rising temperatures and CO2 emissions in the city. Firstly, it is important to underline that the district and neighborhood scale represents the optimal perimeter for implementing a circular ecological transition model while enhancing ecosystem quality, environmental performance, and bioclimatic adaptability.

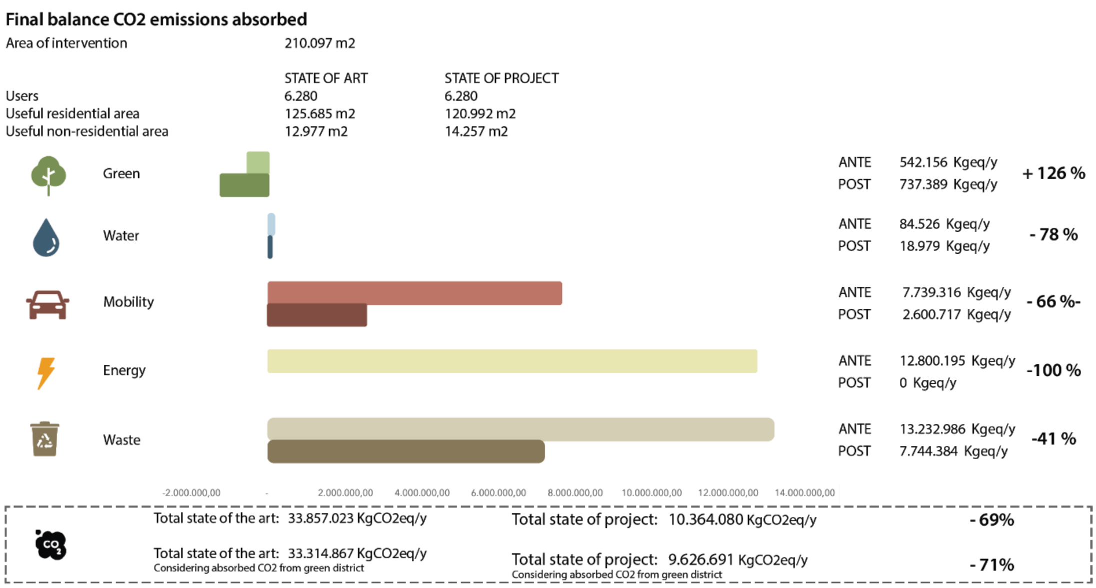

Figure 9. Global overview of final emissions comparing ante operam and post operam and total calculation of CO2 subtraction throughout the district.

Another significant point is the confirmation, after extensive research, of the innovative methodology and the effectiveness of the method adopted (easy model) for assessing climate-changing emissions. This simplified model is not opposed to more structured ones but aims to guide and finalize the necessary deep renovation actions.

The proposed framework of interventions starts from the neighborhood scale and extends to the building-open space dimension, involving the technological systems adopted to ensure high levels of effectiveness. The model, therefore, acts as a holistic framework for assessing emissions by capturing the emission sources of building assets and city resources. Interventions include improving the use of existing resources, transitioning to renewable energy sources and low-carbon materials, and increasing the overall efficiency of energy systems.

The purpose of the study is to monitor these aspects and to initiate transformation processes within the reference context through a consistent framework of actions aimed at reducing emissions, enhancing resilience to rising temperatures and extreme events, and creating conditions for a better livability of the city.

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