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REMOVING AND STORING CARBON IN THE BUILT ENVIRONMENT
Green and grey solutions

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ABSTRACT
This paper investigates the potential of the combined use of ‘green’ and ‘grey’ solutions for removing and storing carbon in the interventions to regenerate the building stock, as relates to the goal, dictated by European policies, of halving carbon emissions by 2030 and achieving carbon neutrality by 2050. The issue is of great scientific importance in light of the European and national strategies and policies illustrated in the Next Generation UE Plan and the National Recovery and Resilience Plan (Piano Nazionale di Ripresa e Resilienza – PNRR). In particular, the paper illustrates the developments of research initiated by the Research Unit at ‘Sapienza’ University of Rome in the context of the PRIN (project of overriding national interest) ‘TECH START’ Research and of the ‘Climate-Pandemic-Proof Design’ Research, funded by ‘Sapienza’ University. This research was carried forward through the experimental application, in a public housing neighbourhood in Rome, of ‘green’ solutions (green infrastructures) and ‘grey’ solutions (CO_2 absorbing and low embodied carbon materials) working in synergy, systematically assessing their impact in terms of reducing climate-altering emissions from the current state.

KEYWORDS
carbon storage, carbon neutrality, carbon capture, embodied carbon, urban redevelopment

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Transforming and regenerating cities and urban areas into resilient, sustainable, and flexible organisms is a condition that can be put off no longer. The quality of living in urban spaces is of fundamental importance, and this includes adapting to and mitigating climate change, thereby contributing, with appropriate measures, to the decarbonization process (Tucci, 2018). The construction industry has a growing need for concrete strategies and actions to offset its emissions: reductions, removals, and/or offsets, to date yet to be systematically used in the built environment, are needed (Hirsch et alii, 2019; UNEP, 2020). This critical condition is the focus of this paper, which illustrates the developments of research carried out in the Rome-Sapienza operating unit of the PRIN (project of overriding national interest) Research titled 'TECH START – Key Enabling Technologies and Smart Environment in the Age of Green Economy – Convergent innovations in the Open Space/Building Systems for Climate Mitigation' (2019-2021) and the context of the Research, funded by 'Sapienza' University, titled 'Climate-Pandemic-Proof Design – Strategie, misure, sistemi tecnologici per la mitigazione climatica e la neutralità carbonica post-Covid' (2021)[1]. In particular, the paper analyzes the experimental application, in a public housing neighbourhood in Rome, of solutions capable of absorbing, removing, and storing carbon emissions from the atmosphere, belonging to two macro-concepts: 'green' and 'grey.' More generally, some of these solutions have already been in use, while others have the potential to be expanded, and others still appear only theoretical at present. The research proposes various solutions, estimating their performance impact on net carbon storage, and verifies their applicability and interaction while assessing their limits and opportunities.

Currently, the processes of capturing, transporting, and storing carbon are subject to continuous implementations to improve the process and contain costs, thus making them more efficient; these aspects are essential for extending these methodologies on a wide scale (Climeworks, 2020). As numerous studies have pointed out, the 'green' and 'grey' aspects are often treated separately, without grasping their interaction and with no unitary vision, while special problems are mostly discussed in greater depth (Kuittinen, 2021a, 2021b; Ariluomaa et alii, 2021; Amiri et alii, 2020). The results of these studies suggest that there is an underutilized potential for the systematic accumulation of atmospheric carbon in the built environment. The prospects, in particular as relates to storage, leave open problems that have yet to find adequate solutions as relates to sustainability, due to unacceptable areas of vulnerability.

The research assesses the tools and materials capable of absorbing and storing carbon from the atmosphere in urban and peri-urban environments, using 'green' and 'grey' procedures. The paper's originality lies in its combined use of 'green' and 'grey' solutions acting in synergy, to halve carbon emissions by 2030 and achieve carbon neutrality by 2050 (Calvo Buendia et alii, 2019). This arrangement aims at defining and cataloguing currently available solutions and strategies for reducing carbon emissions in urban districts, which are responsible for 36% of final energy consumption and 39% of total carbon dioxide emissions worldwide (IPCC, 2022).

Green infrastructure in the urban built space is intensifying as an affordable, long-term measure for mitigating the impacts of climate change, a measure that, thanks to its absorption capacity, contributes towards maintaining the water cycle in equilibrium and protecting the soil (IEA, 2022). Green infrastructure is an actual carbon sink and helps mitigate the greenhouse effect while containing the threats associated with the warming climate (Battisti and Santucci, 2020). The capacity to capture carbon is minimum in the leaves, larger in the branches and sprouts, and maximum in the trunk due to its diameter, and the soil; moreover, it varies depending on the plant species and other parameters that will be examined further on (Keenan and Williams, 2018).

In parallel, the research presented here takes account of another source of greenhouse emissions associated with buildings – a source that is less ‘taken for granted’: embodied carbon, which is to say the total of greenhouse gas emissions associated with construction, and particularly those derived from extracting, transporting, and manufacturing the materials (cradle-to-gate), which represent the main share of total carbon embodied in buildings. With the goal – crucial for decarbonization – of monitoring and mitigating this considerable share of emissions, which represent a total of 11% of global carbon emissions (Pomponi, De Wolf and Moncaster 2018; WGBC, 2019), the research identifies scenarios for intervention that use low embodied carbon materials, relying for example on wood or plant fibres for natural heat insulation, to exploit the carbon emissions stored in species suited to the production of these construction materials. In synergy with this approach, the paper considers experimentation activities based on the reuse and recycling of construction waste which prevent their elimination with the related economic and environmental costs, thereby incentivizing circularity and material resource efficiency and reducing embodied carbon through an improved process that includes design choices and assessments with a view to the life cycle, supported by LCA (Life Cycle Assessment).

Lastly, ‘grey’ solutions take into consideration the systematization of the technologies and processes available today for storing CO_2, for example, CCS (Carbon Capture and Storage), CCU (Carbon Capture and Utilization)m and DAC (Direct Air Capture), in addition to other experimental programmes (D’Olimpio, 2016; Global CCS Institute, 2021; Selosse and Ricci, 2017). As relates to these technologies, elements of use for their concrete integration with respect to natural solutions, and their potential applicability to the built setting are examined, through technologies and products that can be used safely and effectively today, so that they might contribute towards achieving the planned objectives.

Research methodology and operative phases | The paper relies on a review of the main methodologies currently present on the international landscape and capable of removing, absorbing, and reducing CO_2 emissions into the atmosphere, by assessing their aspects in terms of functionality, setting of use, production and cost/efficiency ratio, while carrying out interpolated comparisons among the various researched types.

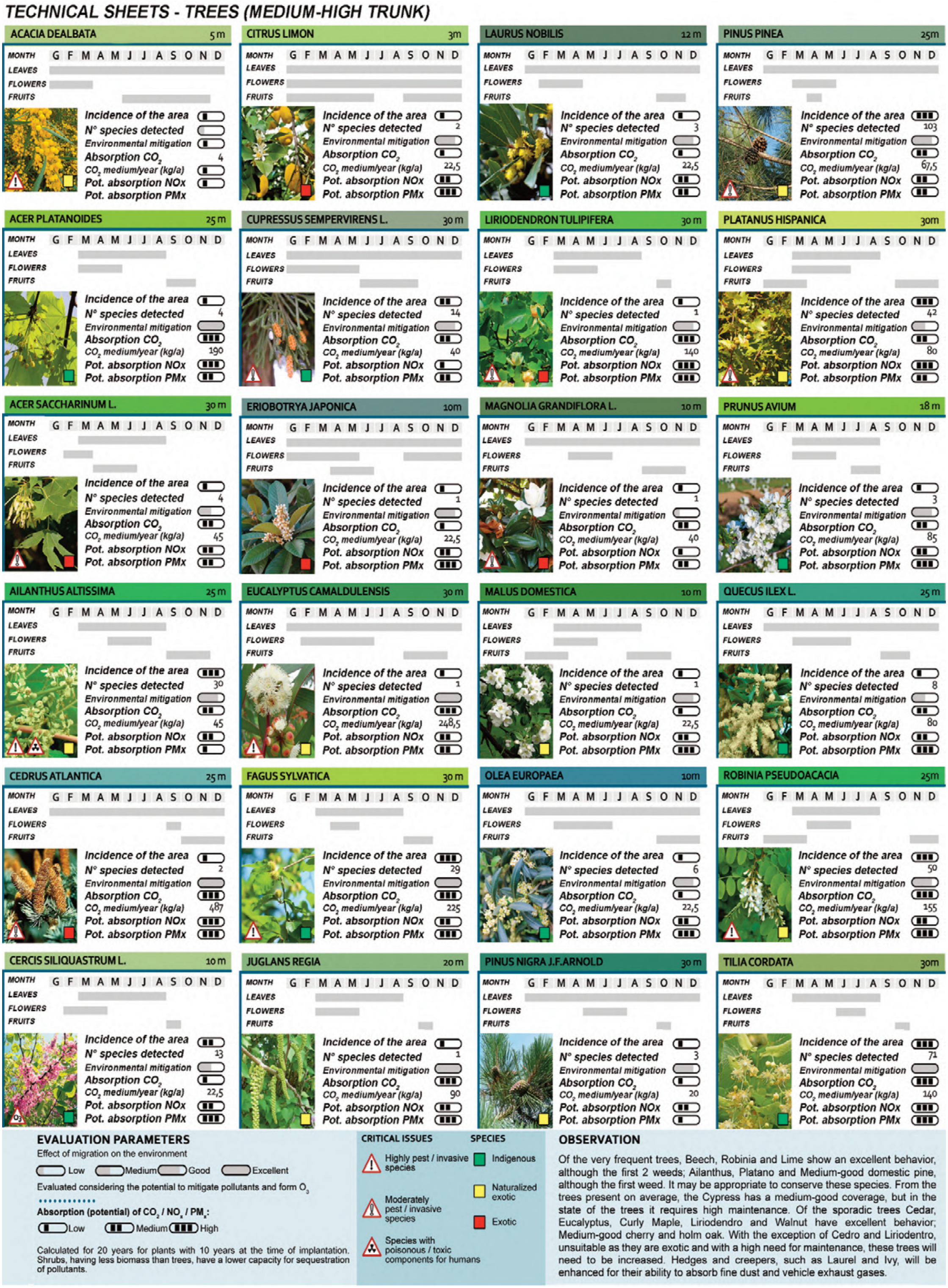

Fig. 1 | Data sheets of surveyed medium and tall tree species (credit: F. Tucci, P. Altamura, V. Cecafosso, M. Giampaoletti, 2022).

The analysis process is developed in three phases. The first is reserved for quantifying CO_2 emissions for the investigation settings in accordance with the area's current state. The second analyses the advanced design options. The third takes stock of the examined issues.

The methodological approach applied for the ecosystemic assessment involves an analytic/evaluational examination, carried out also through an on-site survey and by systematizing the possible 'green' and 'grey' solutions, with the definition of two intervention scenarios. In this regard, important support was the tree census performed by the Municipality of Rome in June 2016 for each municipality, an implementation of the large tree survey that expresses a high value not only from the strictly botanical standpoint but in historical/cultural and scenic terms as well. This stock of knowledge, combined with direct surveys, provides a complete picture of the tree species that are present in the Mediterranean basin and have the highest carbon absorption capacity, thereby making the following possible:

– analysis of trees and species in accordance with specific parameters (autochthonous or naturalized, chorotype, biological form, use) with greater capacity for environmental mitigation to absorb and store CO_2 throughout the entire life cycle (Region of Tuscany, 2018);
– mapping of green surfaces;
– a survey of the vegetation that is present, with detailed quantification of the number of plants for each species;
– establishment of a database using the Office Excel Suite tool, aimed at systematically cataloguing each species while reporting the estimates referring to the plants' growth phases (during the first 5 years, the next 5 years, 20 years) and to the average overall value;
– preparation of a spreadsheet for the estimate relating to the vegetation's CO_2 absorption and storage in the current state;
– selection of the tree/shrub species endowed with the greatest capacity for CO_2 storage and removal of atmospheric pollutants derived from vehicular traffic, and fine dust (Fig. 1);
– preparation of the 'green infrastructure' project, with particular attention to autochthonous species, which guarantee a greater likelihood for success, and estimate of CO_2 absorbed and stored;
– verification of the ecosystemic benefits contributed by the proposed planning solution, considering the existing greenery and the new plants introduced, through comparison with the ex-ante status;
– rendering of the general situation of CO_2eq emissions derived from the energy system (heating, cooling, and lighting of the district) and the water, waste, and mobility system, to emphasize the role that vegetation and materials can play in the abatement of pollutants in the urban setting.

The adopted calculation method is founded upon assessment of the overall con-

Fig. 2 | Aerial photo of the San Basilio PdZ (credit: Cartoteca PDTA, 'Sapienza' Università di Roma).

Fig. 3 | Elevations of the buildings present in the San Basilio PdZ (credit: F. Tucci, P. Altamura, V. Cecafosso, M. Giampaoletti, 2022).

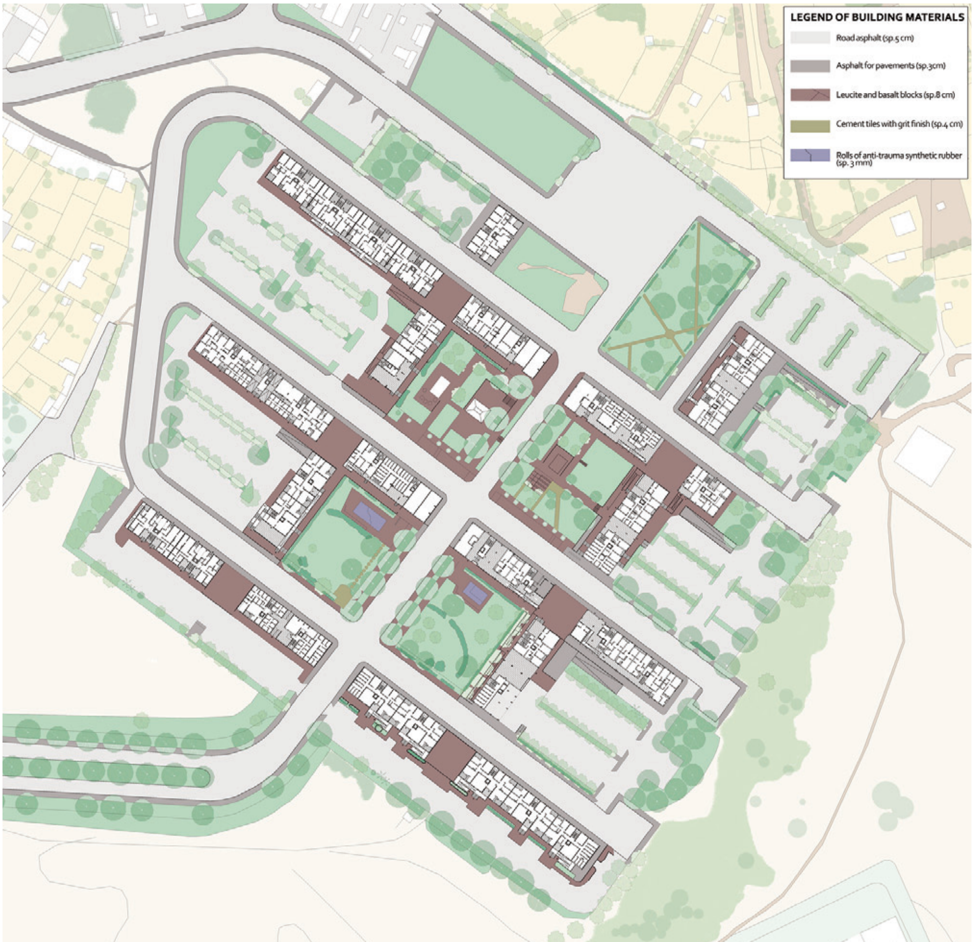

Fig. 4 | Census of building materials present in the current state (credit: F. Tucci, P. Altamura, V. Cecafosso, M. Giampaoletti, 2022).

sumption in the study settings in terms of CO_2 and based on benchmarks, parametric data, and a modelling and simulation process with ENVI-met software, analysing the ante and post-operam situation. As relates to the ‘grey’ solutions, the phases of the methodology adopted in the project for the requalification of existing buildings and of their appurtenant external spaces are as follows: constructive analysis of the existing building for the purpose of characterizing it from the standpoint of performance, technology, and materials (a phase strictly correlated with the activities of evaluating energetic, thermal, and indoor living comfort performance); identification and quantification (in volume and weight) of the main materials present; estimate of the embodied carbon in the materials of the existing construction, based on the pertinent databases[2];

estimate (in volume and weight) of the materials removed from the building and of the corresponding embodied carbon; estimate of the requirement (volume) of materials for the intervention; identification of the materials recoverable in the intervention, including those that are the object of demolition; calculation of the shares (percentages in weight) of the materials that are recyclable/reusable on/off-site; selection of low-embodied-carbon materials and innovative materials with a capacity of storage or direct capture of carbon from the atmosphere; final accounting of the embodied carbon of the requalified buildings, with identification of the portions of emissions avoided through reuse in existing buildings, recycling of materials, adoption of materials with low embodied carbon or with CO_2 storage; calculation of the shares of emissions capturable over time thanks to the use of appropriate materials.

Lastly, the methodology calls for an overall accounting of the intervention scenario's emissions in comparison with the current state, in terms of CO_2 equivalent.

Experimentation on the case of the San Basilio zone plan in Rome | The experimentation involves analysis of the construction and scenic fabric of the zone plan of San Basilio located in district IV of the municipality of Rome (Fig. 2). Located by the city's ring road (GRA), the zone has an area equal to 136,991 sqm, within which are 2,500 public housing units equalling 12% of the total of those available in Rome. Seventy per cent of these units are managed by the local public housing agency (ATER – Azienda Territoriale per l'Edilizia Residenziale Pubblica) and 30% by the Municipality of Rome. The construction types that are present are characterized by terraced blocks of flats, with virtually uniform heights of a maximum of 7 storeys and conformation based mainly on 'closed-cell,' overlapping prefabricated elements, with slabs made with predalles defining the flats' internal partitioning (Fig. 3). Heat insulation is nearly non-existing, a situation aggravated by iron/aluminium single-pane windows and doors and plastic blinds that cause the dwellings to consume a great amount of energy for heating and cooling. The emissions amount to 3,606,178 $KgCO_2eq$/year, while the total embodied carbon of the main constituent materials equals 29,491,298 $KgCO_2eq$.

The district's open spaces, quantified as 86,603 sqm, are characterized by large, mostly degraded green areas (53.473 sqm) and by roads and resident parking. Bituminous asphalt was used for the roads and sidewalks, and blocks of leucite and basalt were used in the buildings' appurtenant areas and the district's four central courtyards, upgraded in 2008 with the introduction of play areas surfaced with anti-trauma pavement, small apparatus for resting, and a small snack bar kiosk. The pedestrian paths are in concrete tiles with grit finish (Fig. 4). The total embodied carbon equals 235,392,400.74 $KgCO_2eq$.

As for the greenery, the tree species that are present are mainly of exotic origin, with a strong prevalence of 'Ailanthus altissima', 'Cedrus atlantica', 'Robinia pseudoacacia', and 'Eucalyptus camaldulensis', often highly invasive with a medium-low quality of environmental mitigation and of the capture of pollutants (Fig. 5). The in-

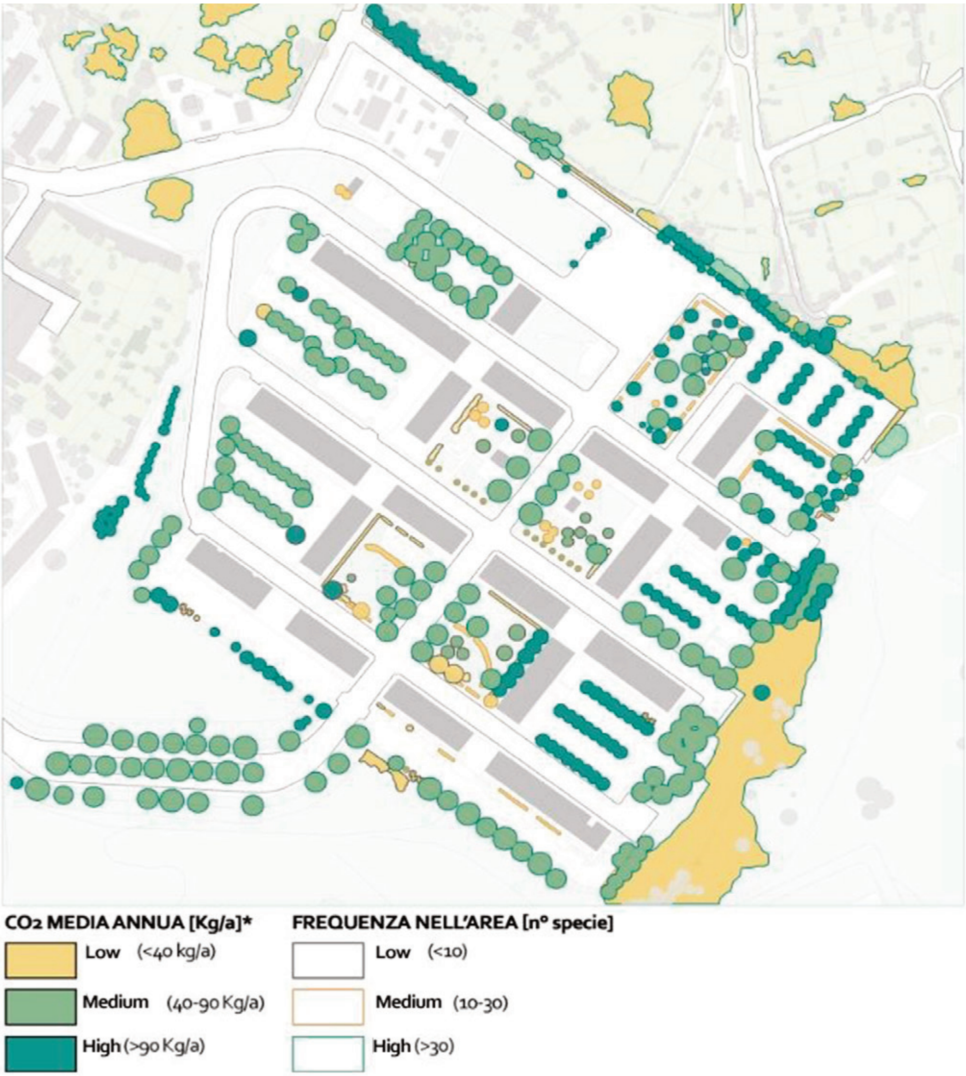

Fig. 5 | Overview of CO_2 by absorption capacity (credit: F. Tucci, P. Altamura, V. Cecafosso, M. Giampaoletti, 2022).

spections that were performed identified 24 types of tree species for a total of 374 medium- and high-trunk trees, with a canopy cover equal to 30% of the open spaces. For each species, a technical data sheet was drawn up, reporting the parameters of environmental mitigation and of capacity for absorbing CO_2 from the atmosphere[3] (Fig. 6). The total absorption potential, including ground-level green spaces, is estimated as 360,577 $KgCO_2eq$/year.

'It is also observed that the neighbourhood lacks systems to manage, save, and

Fig. 6 | Overview of Native and Exotic Flora (credit: F. Tucci, P. Altamura, V. Cecafosso, M. Giampaoletti, 2022).

reuse the water cycle, as well as systems to capture rainwater. In the current state, the energy needed for the water cycle produces emissions equalling 63,485 Kg-CO_2eq/year. The waste collection that is practised is door-to-door, with a separation percentage not exceeding 50%, in keeping with the average for municipal territory, and generates emissions equal to 3,880,351 KgCO_2eq/year. The neighbourhood is poorly served by public transportation (ATAC) lines – daytime, weekdays, and holidays. However, within a 2 km radius is the Rebibbia B-line metro station, and the sta-

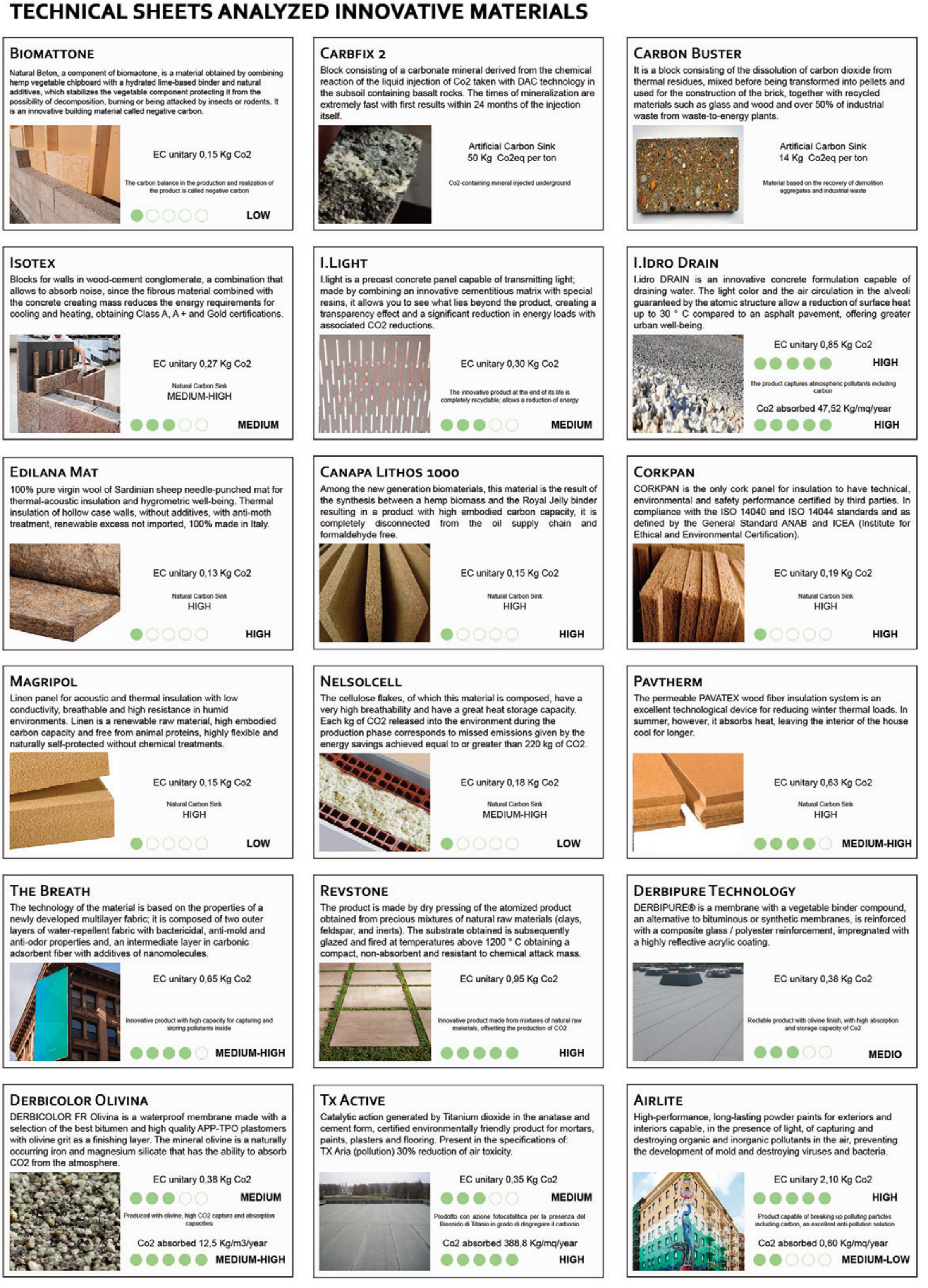

Fig. 7 | Summary data sheets of innovative materials analyzed (credit: F. Tucci, P. Altamura, V. Cecafosso, M. Giampaoletti, 2022).

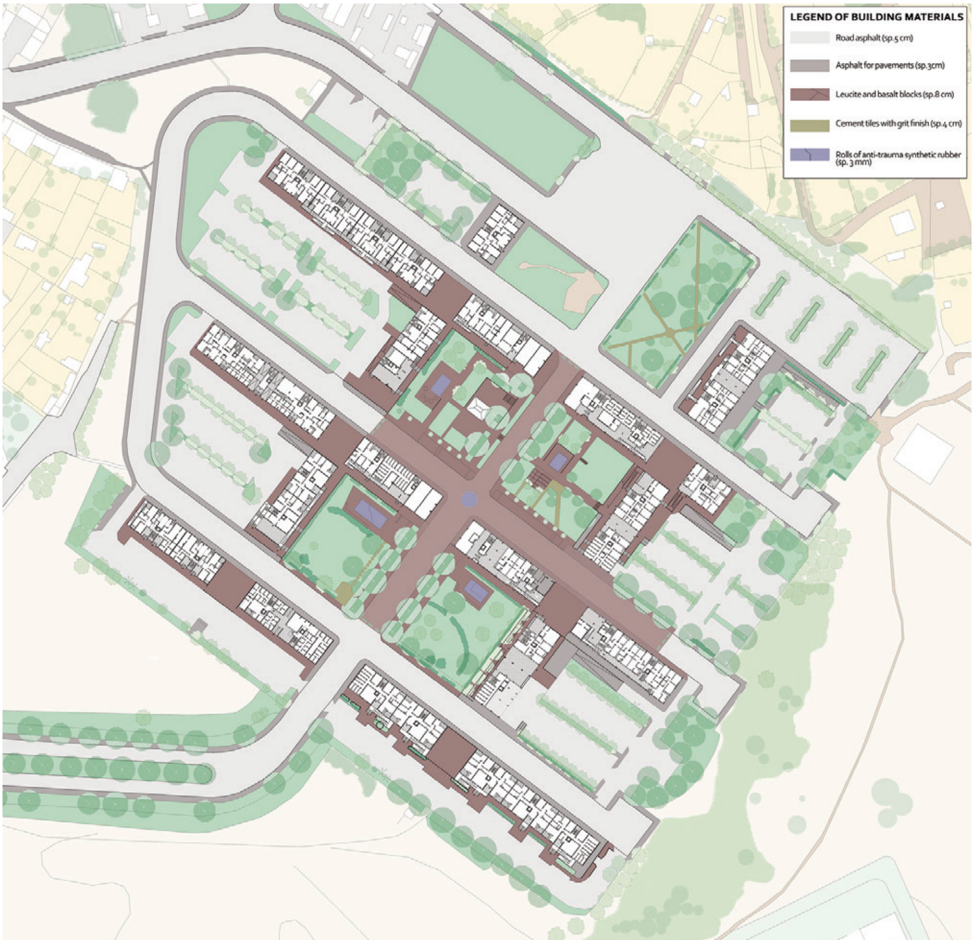

Fig. 8 | Option 1: San Basilio PdZ redevelopment scenario (credit: F. Tucci, P. Altamura, V. Cecafosso, M. Giampaoletti, 2022).

tions of the FL2 Rome-Tivoli railway line are located within a 4 km radius. Pedestrian and bike mobility is also scanty. Given the meagre presence of local public transportation, private mobility by car and motor vehicles is quite widespread. Carbon emissions equal 3,578,130 KgCO_2eq/year.

The requalification, by means of 'grey' strategies, of the building stock and the open areas considered two options: the first with standard materials that are usually used in renovations; the second with materials that are highly innovative, carbon-free, or with emissions extremely reduced in all phases of production and processing, and in certain cases able to make an active contribution towards absorbing carbon from the atmosphere (Fig. 7). The proposed solutions are then compared with one another and

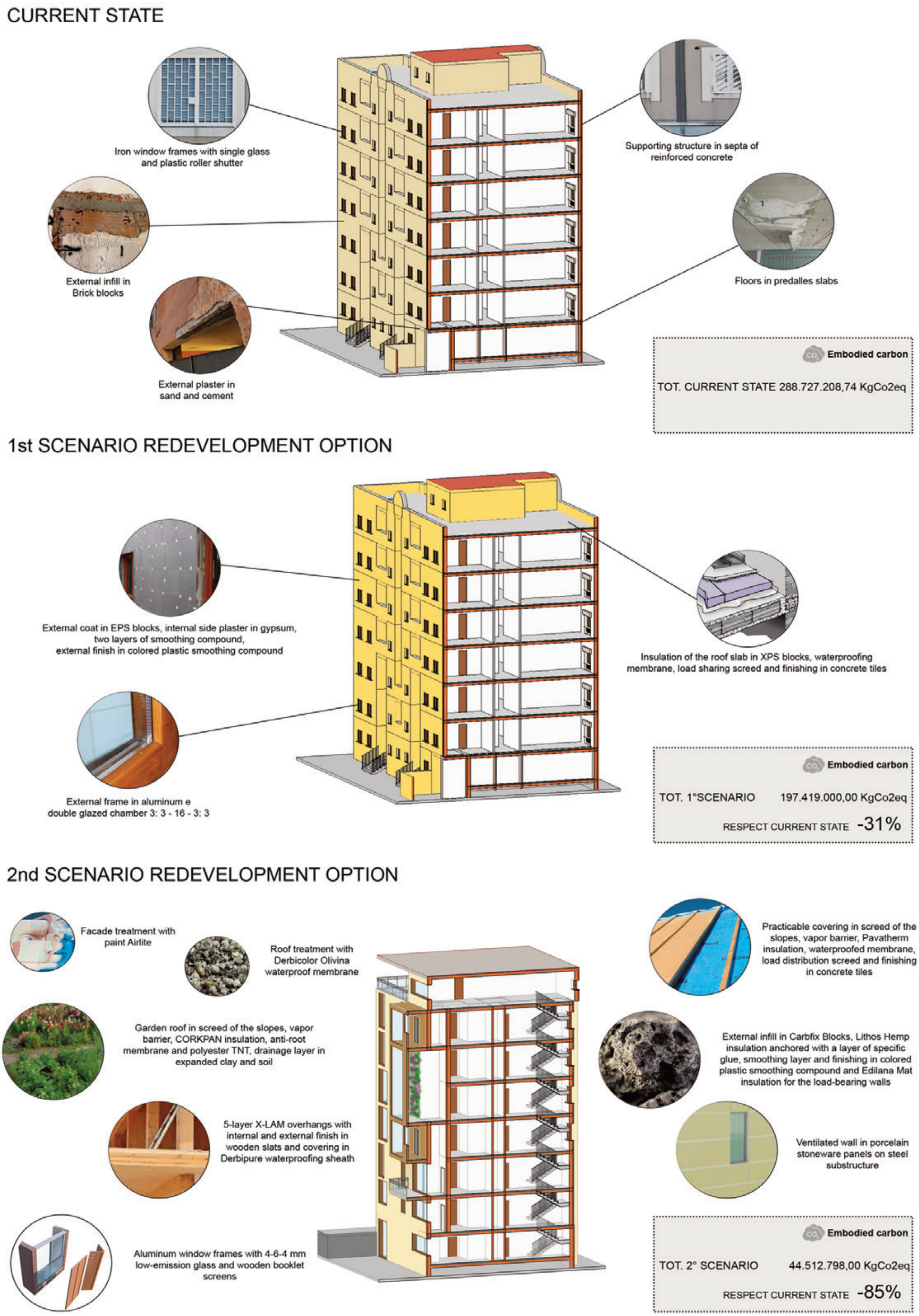

Fig. 9 | Graphical representation of the materials present in the current state and those introduced for the 1st and 2nd Redevelopment Scenarios (credit: F. Tucci, P. Altamura, V. Cecafosso, M. Giampaoletti, 2022).

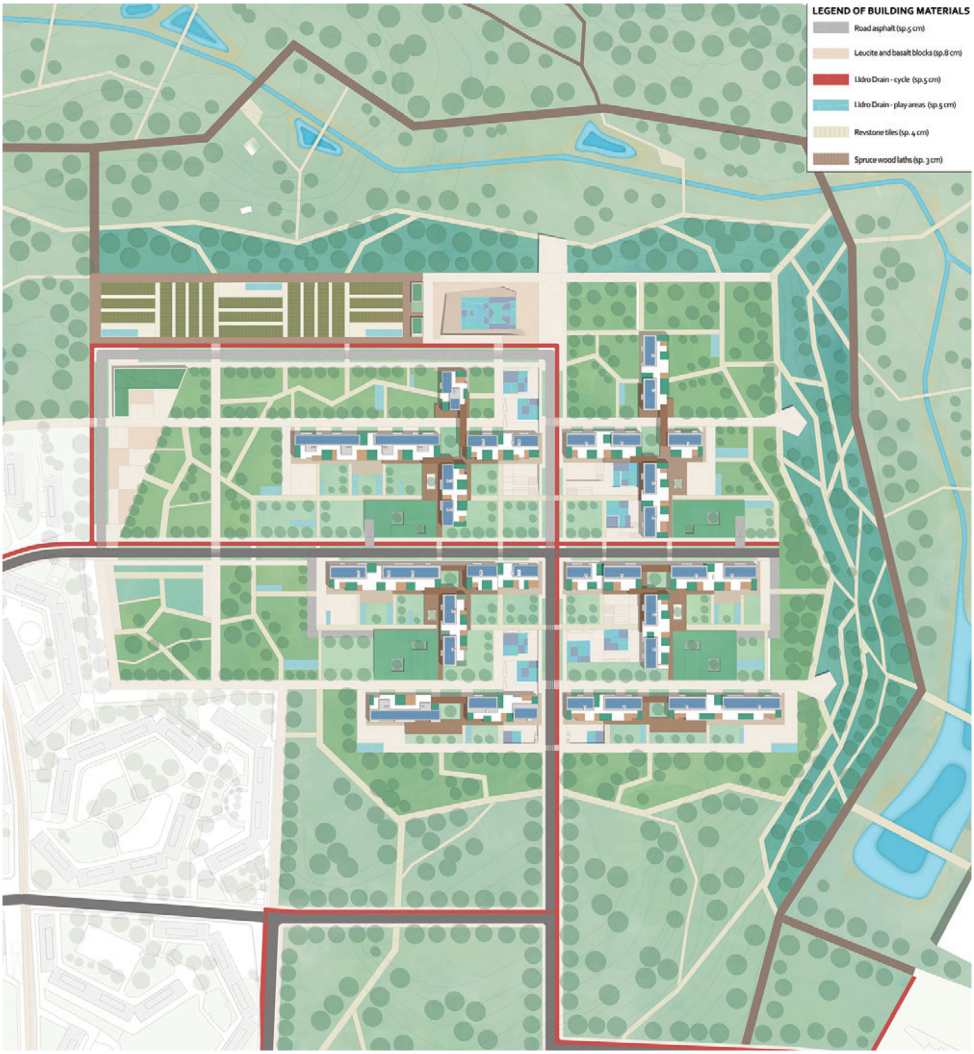

Fig. 10 | Option 2: San Basilio PdZ redevelopment scenario (credit: F. Tucci, P. Altamura, V. Cecafosso, M. Giampaoletti, 2022).

with the actual situation. The first operation for the buildings' energy retrofitting and requalification is therefore based on maintaining the bearing structure in reinforced concrete, and on an application of such building materials as blocks and insulation for horizontal closures for the renovation of exterior envelopes and roofs, and the replacement of doors and windows, capable of increasing and improving thermal and energy performance. Emissions for energy consumption equal 1,013,187 kgCO_2eq/year, with embodied carbon equal to 54,849,066 KgCO_2eq.

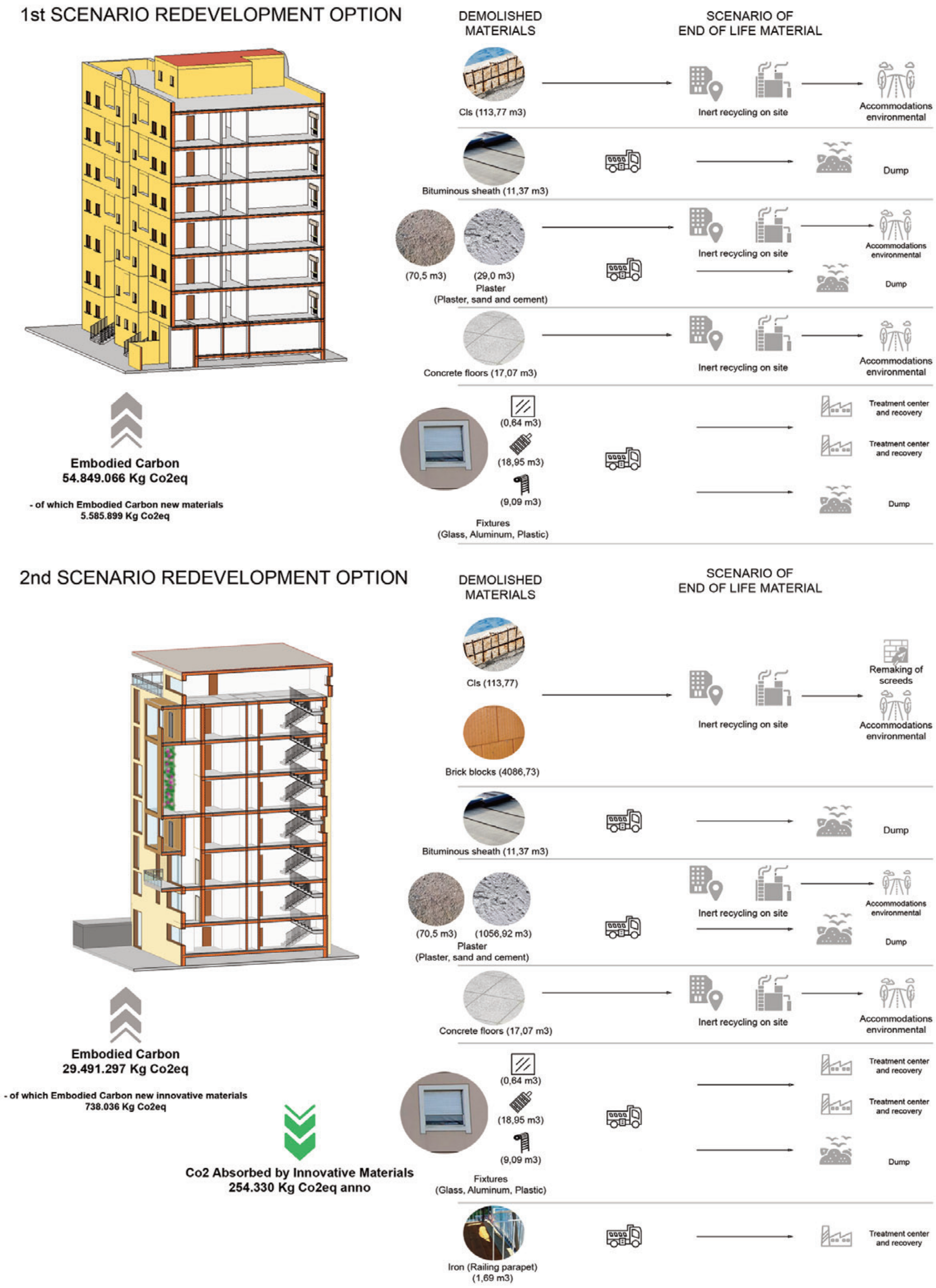

Fig. 11 | End-of-life prospectus of materials subject to demolition for the I and II Redevelopment Scenarios (credit: F. Tucci, P. Altamura, V. Cecafosso, M. Giampaoletti, 2022).

As relates to open spaces, the working hypothesis calls for increasing the pedestrian areas by introducing slabs of basalt and leucite and new play areas (Fig. 8). For the materials subject to demolition like concrete, brick and plaster, onsite recovery is performed through the use of a mobile system for the processing of inert waste and the reuse of recycled aggregate for the renovation of carriageway road beds and environmental and landscape arrangements of the urban district, with a recovery percentage exceeding 90%[4], thus generating a savings of emissions due both to the lack of extraction and procurement of natural inert materials and to the transport of inert waste to the nearest recovery site (5,369 $KgCO_2eq$)[5]. For the materials originating from the replacement of doors and windows, like aluminium and glass, off-site management for additional use after industrial treatment (remanufacturing or recycling) is considered. However, the plaster and waterproofing membranes originating from the renovation of roofs are disposed of in a landfill. This requalification option calls for 142,570,013.88 $KgCO_2eq$ of total embodied carbon post-intervention.

The second requalification option calls for using innovative, experimental construction materials derived from processes of recycling urban and/or industrial solid waste, and completely recyclable natural fibres with extremely low unit embodied carbon. In specific terms, for the building stock, the interventions call for maintaining the existing bearing structure, with a redefinition of the vertical closures through the introduction of large glass surfaces with low-emission windows and doors, passive bioclimatic devices such as courtyards to the south, buffer space to the north, and overhanging bioclimatic greenhouses which result in increased volumes in keeping with the regulations in force, thereby improving the housings' adaptability and flexibility to achieve greater environmental comfort while reducing energy consumption for heating and cooling.

The exterior buffers were coat walls comprising natural insulation anchored onto massive elements in Carbfix blocks[6], derived from the capture of CO_2 in the atmosphere, using DAC (Direct Air Capture) technology, liquid injection into the subsoil consisting mainly of basaltic rocks and subsequent mineralization, and thus generating a building material with carbon storage capacity. The vertical exterior closures oriented to the west call for ventilated walls made with panels in stoneware on a steel substructure. The overhangs consisting of bioclimatic greenhouses are made with X-Lam 5 layers with the internal finish and treated wooded staves on the outside. The design of the horizontal closures, insulated with Corkpan slabs, calls for accessible roofs, garden roofs, and surfaces for introducing integrated photovoltaic panels with finishing in Derbicolor Olivina, with high CO_2 absorption capacity (embodied carbon: 29,491,298 $KgCO_2eq$; Fig. 9). In this regard, a CO_2 absorption equal to 254,330 $KgCO_2eq$/year, due to the use of innovative materials, is reported.

For this option, the project to redefine the open spaces calls for an increase in the permeable surfaces and a major reduction in vehicular traffic within the district, favouring soft mobility with the introduction of bike and pedestrian paths made with concrete, and I.Idro Drain with high absorption and storage capacity within its molecular structure of pollutant cells (Fig. 10). The design of leisure spaces and recreational areas to host open-air events and commercial activities considers the adoption of Rev-stone pavement, blocks of leucite and basalt, and pavement with tiles of photocatalytic cement. For the materials subject to demolition, a recovery percentage exceeding 88% is supposed, with in situ treatment of aggregates originating from concrete, brick, and plaster for the making of screed and exterior pavement, as well as, as relates to the remaining portion, for the urban district's scenic arrangement (embodied carbon: 15.021.500 KgCO_2eq; Fig. 11).

In the case in point, for the entire district, CO_2 emissions for heating, cooling, and lighting are set back to zero thanks to the emission savings equal to 607,058 Kg-CO_2eq/year due to the reduced energy requirement; these emissions are also offset by energy produced by renewable sources, embodied carbon equal to 44,512,798 Kg-CO_2eq. As regards the requalification of the water cycle, waste, and mobility, in this case as well two levels of improvement are considered. The highest-performing one refers to the EU indications at 2050, while the less substantial one is in an intermediate position between this and the current state (Fig. 12). This is discussed in greater detail as follows.

For the water cycle, the steps, in the case of the standard scenario, refer to the actual state, since normally no interventions in this regard are established; on the other hand, the innovative scenario provides for recovering the grey water and the rainwater, and for reducing the drinking water requirement thanks to the use of recovered water appropriately purified for the permitted uses (scenario 1: 63,485 KgCO_2eq/year; scenario 2: 16,262 KgCO_2eq/year).

For waste, the current state considers the waste produced for domestic activities and other activities in relation to the current users, for a separate collection percentage equal to 47% (achieved rate); having taken into account the emissions for the transport of waste in the neighbourhood that in scenario 1 waste production does not vary, the separate collection becomes 55% and the replacement of vehicles from Diesel to methane is planned; in scenario 2, the production of solid urban waste declines by 10% due to the inhabitants' greater awareness, the separate waste collection rate grows to 70%, and collection is optimized through the adoption of a pneumatic system integrated into the buildings and the adjacent exterior areas, with few collection points permitting a reduction of emissions for transport using methane vehicles (scenario 1: 3,244,161 KgCO_2eq/year; scenario 2: 1,946,306 KgCO_2eq/year).

For public mobility, the actual kilometres travelled yearly by the bus lines traversing the neighbourhood are taken into consideration, in accordance with the type of ve-

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Fig. 12 | Summary results for Energy, Water, Waste and Mobility Networks Scenario I and II (credit: F. Tucci, P. Altamura, V. Cecafosso, M. Giampaoletti, 2022).

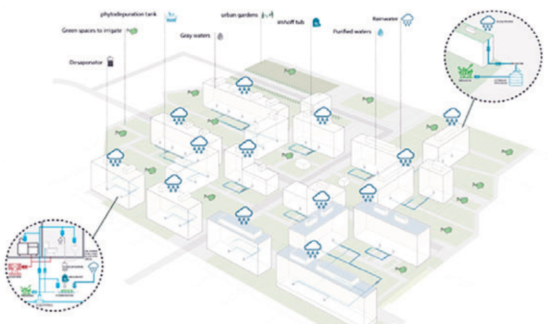
WATER NETWORK

Residential and non-residential water needs
Residential drinking water
169.141 mc/y
Acqu Non-residential drinking water
195 mc/y
Total water requirement
169.336 mc/y
52.426 KgCo2/y

Water requirements for irrigation of green spaces
Pertaining green area (53.473 m2) per year is equal to 35.720 mc/y
11.058 KgCo2/y

Drinking water consumption balance of the res and non-project build-
TOT 205.056 mc/y

TOTAL CO2 CURRENT STATE
63.485 KgCo2/y



2nd PROJECT SCENARIO

Residential and non residential water needs
Residential drinking water thanks to the inclusion of gray and rainwater reuse systems equal to
35.128 mc/y
Non-residential drinking water thanks to the inclusion of gray and rainwater reuse systems equal to
1.384 mc/y
Total water requirement
36.512 mc/y
11.303 KgCo2/y
Emission of CO2 -78%

Water requirements for irrigation of green spaces
Verde di pertinenza (65.378 mq): 57.032 mc/y
tetto verde (1.152 mq): 290 mc/y
orti urbani (8.216 mq): 3.000 mc/y
totale 60.323 mc/y
Final annual requirement with the recovery of rainwater and the surplus of water recovered from constructed wetlands
29.568 mc/y
4.958 KgCo2/y
Emission of CO2 -55%

Water requirements for irrigation of green spaces
Total residential and non residential gray water recovered 36.512 mc/y*
WC 18.025 mc/y
External uses 9.367 mc/y
Surplus 21.414 mc/y

Rainwater recovery
Total rainwater captured by flat roofs (10.393 mq), green roof (1.152 mq) and water square (1.772 mq)
9.341 mc/y

Drinking water consumption balance of the res and non-project build-
TOT 66.079 mc/y

	Emission of CO2
TOT CURRENT STATE	63.485 KgCo2/y
1° SCENARIO	63.485 KgCo2/y
2° SCENARIO	16.262 KgCo2/y

WASTE NETWORK

HOME USERS = 2317
NON-DOMESTIC USERS = 25

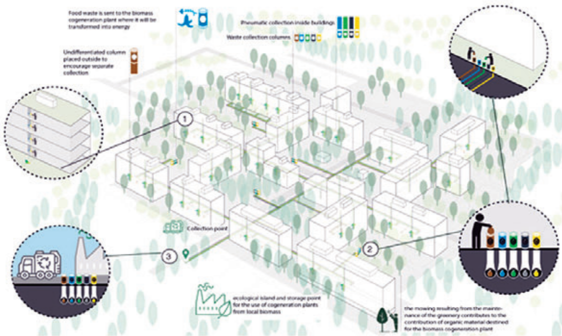
CURRENT STATE → 47% Raccolta differenziata

Municipal solid waste production
1.141.501 Kg/y
Separate collection rate in Rome
47%
Total urban waste collection in the district
677.505 Kg/y
Total undifferentiated RSU district
763.996 Kg/y

TOTAL CO2 EMISSIONS CURRENT STATE OF UNDIFFERENTIATED MUNICIPAL SOLID WASTE

No. of harvest passages per week 7
Type of Vehicle: DIESEL
Current collection system on the road
Co2 emissions for the transport of waste in the neighborhood

TOTAL CO2 EMISSIONS STATE OF THE ART FOR MSW AND TRANSPORT TOT 4.941.547 KgCo2/y*



1st PROJECT SCENARIO	2nd PROJECT SCENARIO
HOME USERS = 2317	HOME USERS = 1604
NON-DOMESTIC USERS = 25	NON-DOMESTIC USERS = 738

2° SCENARIO DI PROGETTO → -10% / 70% Collection differentiated

Municipal solid waste production
1441501 Kg/y — 1.297.351 Kg/y
Total urban waste collection in the district
792.826 Kg/y — 908.146 Kg/a
Total undifferentiated RSU district
648.675 Kg/y — 389.205 Kg/y
TOTAL CO2 EMISSIONS FOR UNDIFFERENTIATED RSU KgCo2/y
3.243.377 Emission of CO2 -12% — 1.946.026* Emission of CO2 -36%

*The share of staff not considered because it is calculated in the context of biomass energy production

No. of harvest passages per week 5
Type of Vehicle: METHANE
Decrease in km traveled in the neighborhood through to an optimization of the collection

Co2 emissions for waste transport in the district KgCo2/y
784 Emission of CO2 - 91% — 280 Emission of CO2 -97%

	Emission of CO2
TOT CURRENT STATE	3.880.351 KgCo2/y
1° SCENARIO	3.244.161 KgCo2/y
2° SCENARIO	16.262 KgCo2/y

NETWORK OF ENERGY AND BIOCLIMATICS (active and

CURRENT STATE	SCENARIO 1	SCENARIO2
Residential useful area 48.971 mq		Residential useful area 36.286 mq
Usable non-residential area 396 mq	48.971 mq	Usable non-residential area 13.081 mq

Residential Current state*	Kwh/y	Emission of CO2	SCENARIO 2 Kwh/y	Emission of CO2
Common consumption and uses	349.112		144.467	
Consumption elect. + illum.	2.133.000		413.239	
Heating	10.969.504		165.165	
Cooling	308.517		7.460	
Domestic hot water	887.064		0	
TOT	14.647.197	3.577.843	730.327	268.246

*Assume standard basic situations based on the type of building

Non Residential Current state	Kwh/y		SCENARIO 2 Kwh/y	
Consumption elect. + illum.	22.964		744.051	
Heating	67.320		204.214	
Cooling	10.996		17.916	
Domestic hot water	2.346		34.291	
TOT	102.960	28.335	1.000.472	338.812
TOT residential and non	14.750.157	3.606.178	1.730.799	607.058

Co2 emissions have been reduced by -83% Emission of CO2

SCENARIO 2

- Efficiency of the envelope and systems

Set of actions to increase the efficiency of the envelope and systems, energy-saving devices and appliances, LED lighting, lifts with energy recovery during braking

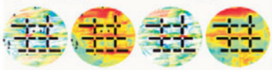
TOT 6.198.113 Kwh/y -58%

- Mitigation and microclimate

Reduction of cooling and heating needs

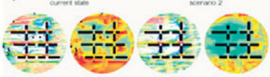
TOT 5.790.787 Kwh/y -61%

Summer



Urban area temperature	Temperature mitigated	Ti	Savings energetic %
30	29	26	20%

Winter



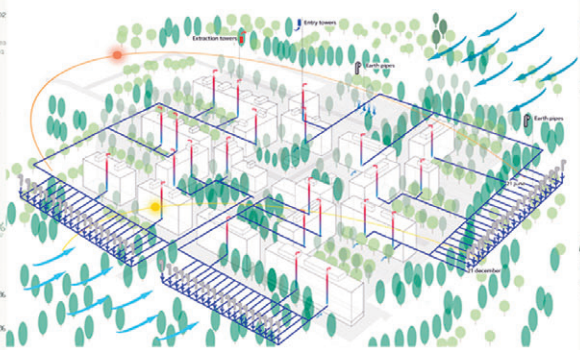
Urban area temperature	Temperature mitigated	Ti	Savings energetic %
10,1	11,9	20	2%

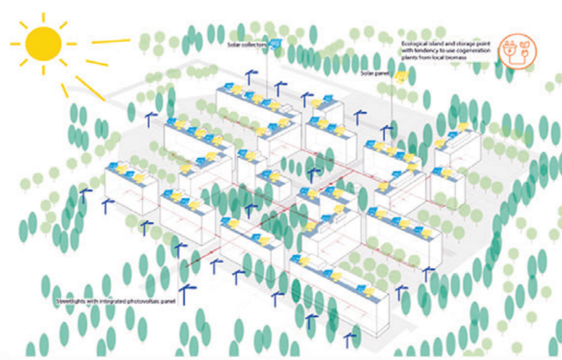
- Passive heating and cooling systems

TOT 2.883.188 Kwh/y -81%

- ICT optimization systems

TOT 1.730.799 Kwh/y -88%





Public lighting

Kwh / a saved for public lighting with LED lamps with integrated photovoltaics: 47.025 Kwh/y
% di riduzione rispetto all'esistente -100%

- Energy from renewable sources

The district's energy demand of 1,730,799 Kwh/y is met by renewable energy sources

Photovoltaic 1.619.547 Kwh/y
% of the TOT energy requirement 94%

Solar Thermal 34.291 Kwh/y
% of the TOT energy requirement 2%

Biomass Produced by:	Kg/y	Kwh/y
Green maintenance	244.380	1.153.474
Organic waste	276.308	2.686.323

TOT Biomass 3.839.797 Kwh/y
% of the TOT energy requirement 122%

\+ =

5.493.633 Kwh/y

TOT. 1° SCENARIO (efficiency of casings and systems) 1.013.187 KgCo2/y
TOT. 2° SCENARIO (energy coverage from renewable sources equal to 217%)
0,00 KgCo2/y

In summary

The final energy needs of the district (lighting and energy consumption of the buildings) are met thanks to renewable energy sources.

Total energy needs of the neighborhood	1.730.799 Kwh/y
Energy from renewable sources	5.493.633 Kwh/y
Surplus	3.762.834 Kwh/y

	Emission of CO2
TOT CURRENT STATE	3.606.168 KgCo2/y
1° SCENARIO (Intervention on passive bioclimatic envelopes and systems and ICT)	1.013.187 KgCo2/y
2° SCENARIO (Integration of renewable energy sources)	0 KgCo2/y

MOBILITY NETWORK

CURRENT STATE
Public transport

N ° lines	8
Average number of passes	56
Number of km traveled per year within the district	113.543 Km
Total CO2 emissions per year for public transport	136.991 KgCo2/y

(the type of power supply was considered on the basis of% of the bus fleet of the municipality of Rome)

Emission of CO2
CO2 emissions due to public transport 136.991 KgCO2/y

Trasporto privato

NB. The average car ownership per inhabitant in the current state is equal to 0.62

Car number	1.452
Average number of km traveled per year	9.805.396 Km

Emission of CO2
CO2 emissions due to cars 3.427.095 KgCO2/y

TOT CURRENT STATE : 3.578.130 KgCo2/y

TOTAL 1° SCENARIO:
- Public mobility (upgrading of bus lines) 2.635.032,58 KgCo2/y
- Private mobility (car ownership rate reduction) 51.154,61KgCo2/y

TOTAL 2° SCENARIO:
Public mobility increases by 20%
CO2 emissions due to public transport carried out with electric buses
51.194 KgCO2/y
- Private mobility
Soft mobility incentive:
Cycle paths with a length of 2000 m
595 bike parking spaces
-76% reduction in level parking spaces compared to the project status
152 charging stations for electric cars (50% of the total)

In the 2nd Project Scenario, the use of private vehicles decreases by 19% according to the European average car ownership threshold per inhabitant (0.5) compared to the current 0.62 in Rome

CO2 emissions due to electric and hybrid mobility of the private vehicle of the project
1.320.696 KgCO2/y

	Emission of CO2
TOT CURRENT STATE	3.578.130 KgCo2/y
1° SCENARIO	2.686.187 KgCo2/y
2° SCENARIO	1.019.574 KgCo2/y

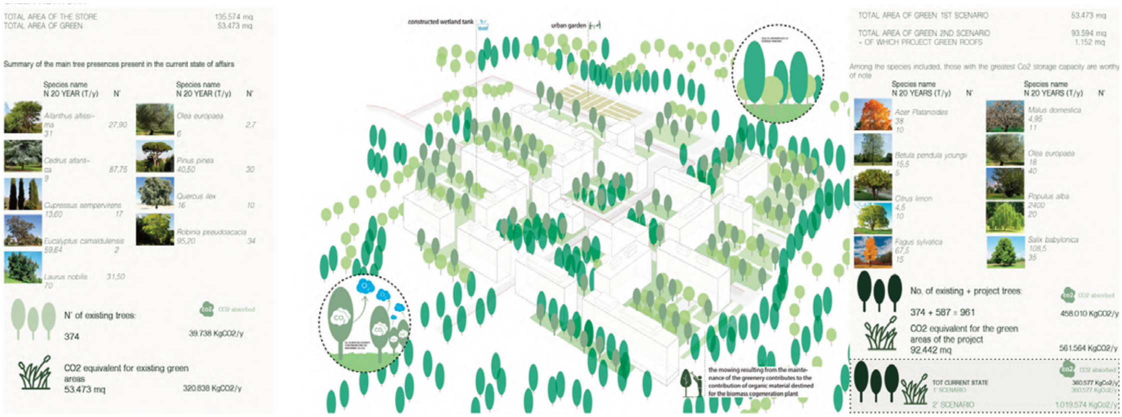
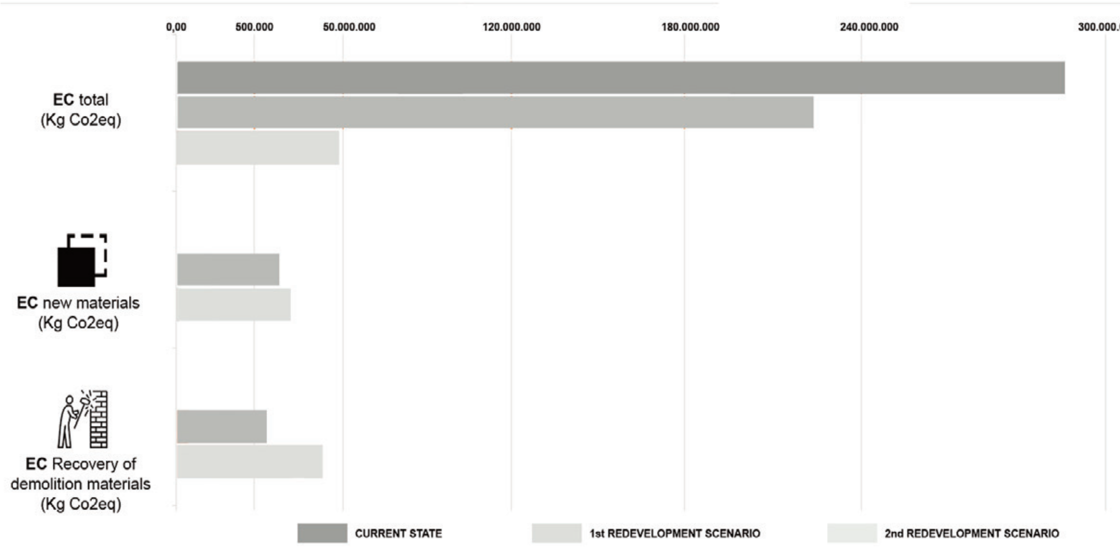


Fig. 13 | Summary results for Scenario I and II of the Green Network (credit: F. Tucci, P. Altamura, V. Cecafosso, M. Giampaoletti, 2022).

hicles provided, and for private transport, consideration is made of the average motor vehicle ownership rate (62%) with the types of fuel that are present, and average yearly distance travelled. As the first hypothesis, the project supposes a 20% increase in public transport becoming entirely electric, against a reduction in the ownership index, as in the European average (50%) which alone brings a benefit in terms of emissions, a 30% increase in electric cars in circulation, 30% of hybrids, the elimination of Diesel, the containment of petrol-fuelled vehicles to 33% (from 54%), and the confirmation of cars fuelled by LPG (7%) and methane (1%). In the second scenario, only private mobility varies, with electric going on to 50%, hybrid to 43%, LPG (7%), and methane (1%) and, having eliminated petrol-fuelled cars, soft mobility is incentivized, with bike paths and more extensive pedestrian area, and the 76% reduction of street-level parking (scenario 1: 1,810,899 $KgCO_2eq$/year; scenario 2: 1,326,126 $KgCO_2eq$/year).

The experimentation considers, in the first hypothesis, the invariance of plant cover, amounting to 374 trees, and in the second one the introduction of 587 new trees of such species as ‘Acer campestre’, ‘Ginkgo biloba’, ‘Populus alba’, ‘Salix babylonica’, and ‘Ulmus minor’, with high capacities for environmental mitigation according to an absorption equal to 146,910 $KgCo_2eq$/year, and the strengthening of existing and autochthonous ones like ‘Fagus sylvatica’, ‘Laurus nobilis’, ‘Malus domestica’, ‘Olea europaea’, and ‘Pinus pinea’, recovering the degraded areas. The green area also increases, from 39% to 68%, and 1,152 sqm of green roofs are installed (scenario 1: -360.577 $KgCO_2eq$/year; scenario 2: -1.019.574 $KgCO_2eq$/year; Fig. 13).

The greenery calculation does not take account of private greenery, which toward this end does not have great weight, but is still an element linked to private behaviours that ought, in any case, to be spurred towards sustainability, because without them the already difficult challenge becomes daunting.



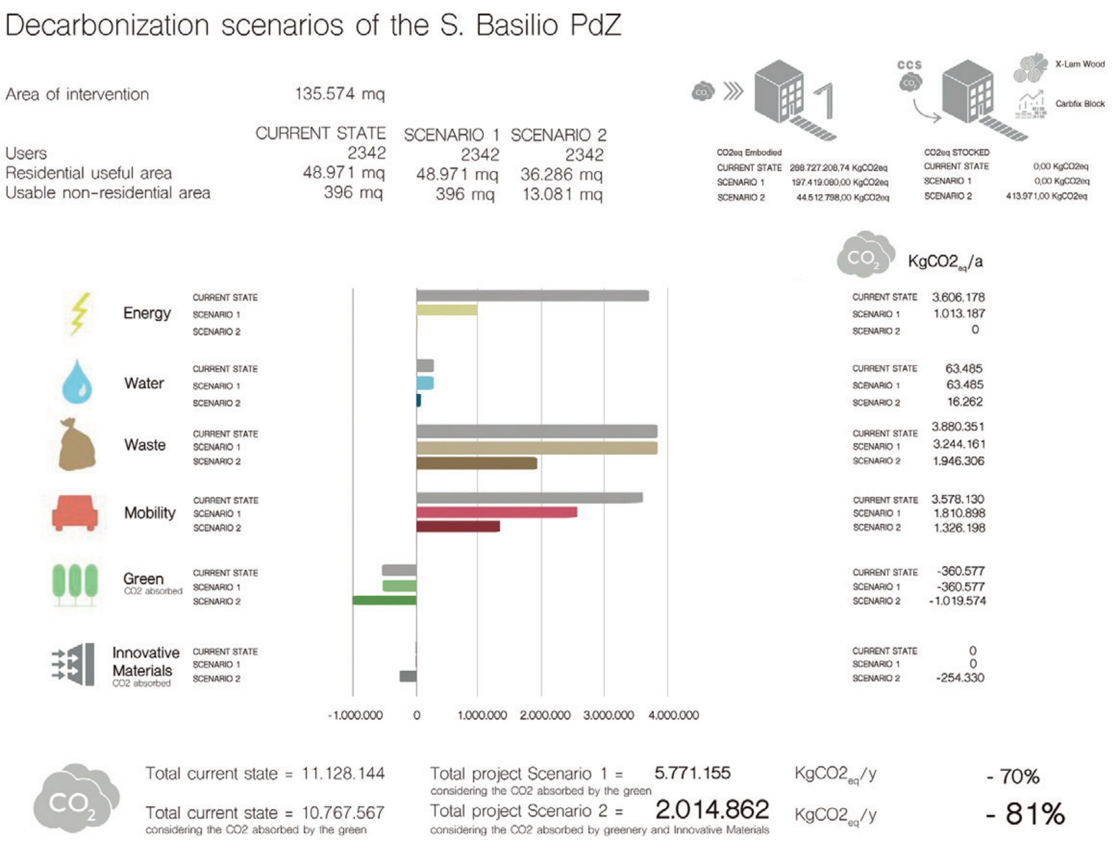


Fig. 14 | Final balance of total embodied carbon, new materials introduced and and recovered from demolition materials, according to the current state, I and II Redevelopment Scenarios (credit: F. Tucci, P. Altamura, V. Cecafosso, M. Giampaoletti, 2022).

Fig. 15 | Final CO_2 emissions budget with district decarbonization scenarios (credit: F. Tucci, P. Altamura, V. Cecafosso, M. Giampaoletti, 2022).

Discussion of the results | The application of the methodological approach and the strategic lines set out during the experimentation allows the impacts and effects of the planning choices to be assessed in terms of performance of unit embodied carbon, and of absorption and storage of carbon from the atmosphere. A useful summary framework for plant selection in urban forestry/reforestation has also been defined. In terms of net emissions, the neighbourhood's general situation in the first hypothesis involves a 46.4% reduction in emissions, and in the second hypothesis an 81.3% reduction in comparison with the current state; their difference marks the advances achieved due to the high-performing materials, the broad use of passive solutions, and increased greenery (Fig. 14). For the individual sectors, the emissions generated by energy consumption are reduced by 72% in the first hypothesis and are reset to zero in the second due to the mentioned interventions and the progressive use of renewable sources; water in the first hypothesis records no variations, and in the second declines by 74%; waste declines in the two scenarios, by 16% and 50% respectively, and mobility by 49% and 63%. The strategy of the increasing tree and shrub stocks with the introduction of new tree species, autochthonous and with a capacity for environmental mitigation, led to a 183% increase in carbon absorption, and as for residual emissions absorbs 31%, while 8% is what is absorbed by the use of 'grey' materials (Fig. 15).

The CO_2 storage capacity relates only to the second hypothesis that was made, and amounts to 413,971 $KgCO_2eq$, a quantity linked to the use of biologically-based material for requalification (wood) and the use of technologically emerging technological DAC solutions derived from the mineralization of CO_2 through industrial processes. In terms of embodied carbon, compared to the construction in the de facto situation, the examined scenarios lead to a 32% reduction in the first case and a 77% one in the second. The application of 'green' and 'grey' solutions for decarbonization in the area in question, therefore, combines the active capacity to absorb CO_2 from the atmosphere during its use phase on the one hand, with the passive CO_2 storage capacity in the built environment, understood as a Carbon Sink, on the other. These choices, combined with the improvement of environmental parameters and microclimate well-being through the strengthening of tree and shrub stocks, increase the capacity for environmental mitigation, guaranteeing more liveable, functional, and healthy spaces for residents.

Research conclusions and future outlooks | The research emphasized how the struggle against climate change and the challenge of remaining within the temperature increase limit set by scientists under penalty of imperilling System Earth, are difficult and complicated, having considered that the time to intervene has shortened, and the commitments taken on by several countries are currently only partially maintained, and not everyone feels involved. Moreover, from the methodological standpoint, it emphasized the complexity of the methods for estimating emissions, linked both the variability of the parameters to be considered, and to the dearth of reliable and relevant databases, especially on a national level. However, important confirmation emerges with reference to the potential contribution that can come from intervention on the built environment and from the effectiveness of the passive technologies that can be applied to bring buildings, districts, and cities to grapple with this problem. In any event, the criticality remains of having to extend the requalification intervention, which should affect a considerable part of the building stock and existing construction.

The establishment of a ‘district grid’ for the management of the various investigation settings (mobility, waste, water, energy) might offer a considerable reduction of CO_2 emissions derived from an improvement of man-made processes, combined with careful design choices aimed at the scenic requalification of open spaces, by increasing permeable surfaces, with the planting of tree and shrub species with a high capacity for environmental mitigation. These urban greening strategies, defined as best practices in the context of infrastructure, are highly incentivized at present thanks also to the sustaining of economic plans and programmes diversified in form and content in each Member State, therefore defining potential positive impacts in cultural and socioeconomic terms in the areas subject to regeneration.

Currently, however, the adoption and use of innovative materials, with the storage capacity, absorption of carbon in the atmosphere, and reduced unit embodied carbon, is limited due to the still experimental nature of some of the materials analysed in this paper. Although the use of materials and insulation derived from natural, recycled, and recyclable resources, is acquiring greater strength in the choices by the actors in the supply chain, aimed at planning that is adaptive and with low energy consumption, product costs – in relation to the capacity to absorb carbon from the atmosphere, especially for solutions like painting and photocatalytic treatments – are currently high. Moreover, doubts remain as to the effect that titanium dioxide, a catalyst in the photocatalysis process, might have on human health, given the recent proposal by European Law and by ISPRA to classify TiO_2 as ‘suspected of causing cancer through the inhalation route’.[7]

The research prospects, then, on the one hand, relate to experimentation on the materials and their gradual improvement in terms of both ecology and bio-toxicity, as well as the optimization of performance in capturing climate-change emissions, and on the other to perfecting verification and calculation methodologies through the construction of databases specific to the national context.

Notes

1) This paper is the product of two research efforts carried out in continuity at ‘Sapienza’ University of Rome, Department of Planning, Design, Technology of Architecture. The first was the PRIN (Progetto di Rilevante Interesse Nazionale – project of overriding national interest) Research titled ‘TECH-START – Key Enabling Technologies and Smart Environment in the Age of Green Economy – Convergent Innovations in the Open Space/Building System for Climate Mitigation’ (2019-2021), with specific reference to the work by the ‘Sapienza’ University of Rome operating unit, Principal

Investigator Prof. F. Tucci. The second is the Research financed by 'Sapienza University' titled 'Climate-Pandemic-Proof Design: strategie, misure, sistemi tecnologici per la mitigazione climatica e la neutralità carbonica post-Covid' (2021), Principal Investigator Prof. Fabrizio Tucci. The working group that worked specifically on the aspects present in this paper, again under the scientific responsibility of F. Tucci, is composed of the following: Arch. PhD P. Altamura, Arch. PhD V. Cecafosso, Arch. PhD G. Turchetti, Arch. PhD M. Giampaoletti; Collaborators: Arch. F. Nava, Arch. M. M. Pani, Arch. G. Romano, Arch. V. Tulelli, Arch. C. Dalsasso, Arch. L. Giannini, Arch. I. Fabiani, Arch. G. Trifoglio, and Arch. M. Vadalà. The images were conceived and developed by the article's authors with contributions by: L. Giannini for Figures 1, 2, 3, 5, 6, and 10; L. Giannini with processing by V. Cecafosso and M. Giampaoletti for Figures 4, 7, 8, 9, 11, 12, 13, 14, and 15.

2) The following were used: Inventory of Carbon and Energy (ICE database), available at circularecology.com/embodied-carbon-footprint-database.html [Accessed 27 August 2021], LCA technical data sheets and studies on specific products.

3) CO_2 absorption capacity of tree and shrub species, done in accordance with consultation and subsequent processing of results of research carried out by CNR's Istituto di Biometeorologia under the Regional Plan for Environmental Air Quality of the Region of Tuscany (2018).

4) Minimum recycled content according to the Italian Ministerial Decree of 11 October 17 (Minimum mandatory environmental criteria of the National Action Plan for Green Public Procurement for construction) is equal to 70%. For more information, see: anit.it/wp-content/uploads/2017/11/DM-11-ottobre-2017.pdf [Accessed 14 August 2022].

5) Estimate calculated taking account of the waste aggregate recovery installation closest to the intervention area (25 Km), analysing CO_2 emissions/Km and the standard load of a truck for the transport of construction-related aggregate waste.

6) For more information on The Carbfix Project (2020), see: carbfix.com/ [Accessed 27 July 2022].

7) For more information, see: isprambiente.gov.it/it/attivita/crisi-emergenze-dann-old/rischio-sostanze-chimiche-reach-prodotti-fitosanitari/news-in-evidenza/proposta-di-classificazione-per-il-biossido-di-titanio-tio2-come-sospetto-cancerogeno [Accessed 27 July 2022].

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