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CASE STUDY

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From the "*Green Station*" to the "*Blue Station*": the role of the renovation of railway stations in the ecological transition of cities. Calculation model and possible measures for mitigation and compensation of impacts.

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Abstract

Nowadays, mobility represents the main productive process: this means that territorial sustainability must necessarily include sustainable movements as a key component. The increase in transport entity and transport routes, economic convenience, and, last but not least, a higher environmental awareness, are leading to higher consideration of the use of railways. In this framework, railway stations represent complex objects requiring significant material flows, which make up their ecological footprint. In this sense, a railway station is the last industrial plant to be accepted in contemporary cities. The last 2 years of pandemics have amplified both the need for tangible sustainability and the demand for active mobility-friendly cities. Discussing the sustainability of a station involves examining and measuring its ecological footprint, to provide active support to the targeted planning and design of mitigation measures. Their impact and effectiveness are certainly amplified by the natural central role of the railway stations. And what if the pursuit of sustainability for the railway stations could be intertwined with the search for quality collective spaces? The answer is positive. The proposed algorithm allows shifting from a qualitative view (so to say, measured on a flat-rate basis), to a quantitative view of the possible improvement actions on the operation and maintenance processes of railway stations. Moreover, through minor adaptations, it could also be applied to industrial or residential processes.

Keywords Railway station, Footprint, Climate-neutral, Nature-based solutions, Urban forest

Introduction

Railway stations are acquiring a more and more significant identity, rather than being *only* nodes of the railway network. A railway station is a complex and ambivalent element: it is a starting/ending point of an infrastructure dedicated to a specific means of transport, and of the journey that people make on that means of transport. Its role as a node of a linear infrastructure is also projected on mobility tout-court, becoming a nodal element for the entire transport system, road mobility, and soft or, better, active mobility. The latter has been strongly boosted by Cov-Sars-2 social distancing policies. In general, infrastructure can be seen as—and indeed, it is—the expression of the self-fulfillment of the needs of a (urban) community. The causal link between form and function, between daily operations and consumption of materials, is also expressed at a higher level. This level is also dichotomous because it is consolidated on the civitas/urbs complementarity, and emerges by:

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- Investigating the mobility infrastructure—as a multi-carrier network—that is upstream from the station.
- Measuring the grade of multimodality of the city where the station is located and, in a broader sense, the geometry of the networks converging on that station.

On this holistic basis, the objectives are:

- The typological and quantitative analysis of the material flows needed for the operation of a railway station and the investigation of the relationships with daily traffic flows.
- The development of a standardized methodology to calculate the ecological footprint of a station based on the environmental loads associated with the production, consumption, and disposal (from cradle to grave) of the flow of energy and materials.
- Framing the ecological footprint of the operation of a station in a logic of urban regeneration by developing design guidelines for nature-based interventions.

Literature review

The energy analysis of railway stations, apart from the movement of the trains, is recent and scarcely investigated research field. This study is articulated in several fields: architecture, technology, and plantations. Hence, it was deemed opportune to outline the bibliography for each sector separately, converging on the last objective, which is the compensation and mitigation of climate-altering emissions.

Life cycle sustainability assessment

The literature on life cycle sustainability analysis (LCSA) is focusing with increasing attention on the upstream processes of infrastructures. On this matter, the position adopted by the International Transport Forum (Good to Go Assessing the Environmental Performance of New Mobility | ITF 2021) is significant, as the 2020 report downsizes the potentially decisive role of the re-sourcing and sharing economy in the future of cities. Rather, it focuses on the intrinsic difficulties of the energy supply chain in finding effective and competitive alternatives to fossil energy. Regarding the emission contributions of transport infrastructures, see Chester et al. (2013).

Valdivia et al. (2013), in support of the United Nations Conference on Sustainable Development in 2012, theorized LCSA: it is an enhancement of the LCA analysis concerning the potential environmental impact along the entire life cycle of the product. He points out that the assessment of the impact should not be a mere sum of LCA, LCC, and S-LCA, but rather a complex interaction of all three investigation tools. The (multiplicative) interaction is treated in a particularly effective way by Zamagni et al. (2013) and Halog et al. (2011).

Onat et al. (2014) provided a bottom-up approach for the LCSA of a building organization: this model can be easily exported from the residential to the commercial and productive sector in general.

The frontier of the application of LCSA assessments to the field of mobility is constituted by the works of Khare et al. (2020) and Hoehne et al. (2020). The two researchers investigate, respectively, the role of asphalt roofs and large car parks in worsening air quality (with the release of particulate matter over time), and positive feedback effects on the heat islands of urban areas.

Social life cycle assessment

The work of Jørgensen et al. (2010) is fundamental, as they reviewed SLCA assessment methodologies, often published in sector journals and not always in an accessible form, using the conceptual breakdown of the LCA (ELCA methodology) contained in the ISO 14044 standard. Jørgensen (2009) also produced guidelines on the quantification of expected social impacts, based on theories and empirical results from different research fields. The definition of a parametric approach to social sciences was also investigated by Benoît et al. (2011) with reference to the mathematical translation of empirical methods from social sciences.

Hosseinijou et al. (2014) integrated the UNEP/SETAC Guidelines for social life-cycle assessment of product procedures for the analysis of building materials. Mathe (2014) introduced the participation factor in SLCA, a static cognitive factor, yet dynamic in terms of direct user/user interaction during the product's life cycle.

Physiology of railway stations

In contemporary cities, railway stations are the last production plant allowed inside urban areas. Since the second half of the twentieth century, industrial plants have been gradually brought outside cities, to the point that they are perceived as external elements (that, is, elements the city has ceased to deal with) in urban planning. Stations are a place of production and exchange of goods and services, with the transformation of large quantities of energy and raw materials. It is indeed a stable production place where, every day, thousands of people go (suffice to say that Rome Termini station, on the weekdays of 2019, was visited by an average of 765,490 people and the Gare du Nord in Paris by 1,134,016 people).

Dewilde et al. (2013) analyzed the relationships between the various elements of the station as a complex organism, studying mutual relationships to provide valid support to the designers of new plants.

Bertolini (2008) analyzed the territorial interactions of new urban station renovation projects in Europe. Mohajeri and Amin (2010) built an analytical model to determine the best location of a new station in an urban area. Zacharias et al. (2011) applied a similar model for the analysis of Tokyo Central Station, undoubtedly one of the most complex and articulated ones in the world.

From the standpoint of the relationships between the station and the territory, Givoni and Rietveld (2007) analyzed the value of the access journey to the station as a lever on the modal impedance of the train journey and as a contribution to the overall satisfaction of the user in choosing the train for their movements.

A key element in the study of the physiology of stations is the identification of a multi-leveled behavior of passengers and users: in fact, contemporary stations are central venues, gradually serving as (Italian model of "*Grandi Stazioni*") meeting places and suppliers of goods and services. Prassler et al. (Tracking People in a Railway Station During Rush | Proceedings of the First International Conference on Computer Vision Systems 2021) created one of the first simulation models of the movement behavior of a user within a station during rush hour. The work by Tie-Qiao et al. (2017) represents the current frontier of user modeling in a station (meant for High-Speed services, but the conclusions can be generalized), using agent modeling: every single element no longer moves from a certain origin to a destination, but it interacts along the way in response to a series of stimuli. This approach can find wide applications in the planning of commercial spaces, which are now necessary in the redevelopment and upgrading process of stations (suffice to say that 600 million euros of investments have been allocated to triple the commercial area of the "*Nouvelle Gare du Nord*" in Paris).

Energy management of railway stations

As an industrial building, a station needs energy—a lot of energy. Longo et al. (2018) have pioneered the analysis of a station as a complex organism. Other research activities have been carried out with a more sectorial approach: Ma et al. (2009) analyzed the energy demand of vertical communication elements (2015) the ceiling heating/air conditioning systems.

Generally, concerning energy analysis, stations are perceived by researchers only as one of the components of the railway infrastructure: both as a source of consumption (González et al. 2014) and as an opportunity for possible efficiency actions (reuse of energy from regenerative braking of incoming trains, in Şengör et al. (2018)).

Concerning energy efficiency actions, the work by Shin et al. (2015) covers the employment of multilevel converters for the effective use of energy from renewable plants (i.e., with discontinuous supply or with mains electricity).

Accessibility of railway stations

As complex objects, one parameter is crucial for railway stations, that is their ability to be effectively integrated within the mobility networks of an urban area: in simple terms, their accessibility. Strong horizontal or vertical asymmetries of accessibility undermine the policies of equity, hospitality, solidarity, and social inclusion.

For a station, the main challenge is physical-ergonomic accessibility, conceived as overcoming the logic of the "architectural barrier". The dichotomous bipartition according to the standard / "disabled" (formerly "handicapped") pattern has been abandoned, in favor of the modulation between permitted and "reduced" mobility (WHO 2001, EU 2001, 2009), which substitutes the concept of disability with the recognition of each individual's different abilities. This passage is both semantic and paradigmatic: it means to restore the value of permeability, porosity, pervasiveness, and continuity of pedestrian paths in the domain of public space, which are intended as a set of collective "rooms". For Monardo (La città liquida. Nuove dimensioni di densità urbanistica - Bruno Monardo - Google Libri 2021), it means paying great attention to the fluidity and functionality of the intermodal connection nodes.

Dovey et al. (2017), in updating the work of Debrezion et al. (2009) propose a heuristic between the modal choice of private transport and isochronous network mapping. This interesting analysis can be transposed to railway stations to link the choice of train to the quality of accessibility with public transport. This is an extension of what Zhang et al. (Pierer and Creutzig 2019) write in relation to the stations of the Chinese high-speed rail network.

Keijer and Rietveld (2000) also authored a study—particularly relevant at the time of Cthe ov-Sars-2 pandemic—on the relationship between cycle accessibility and train usage.

Urban dynamics and railway stations

Another field is represented by the analysis of the expected reaction of a territory to the presence of a station and of the effects—and their speed—, following the construction of a new plant or the redevelopment of an existing one.

For Lin et al. (2014), the analysis is based on the needs of the most sensitive segments of the population, specifically the over-65 s. According to Caset et al. (2018) the reverse path is also possible, by mapping—in a nutshell—the potential of the territory for the design of a new metropolitan rail transport network.

The growing complexity in understanding the phenomenology of contemporary settlements entails a growing difficulty in prefiguring convincing and shared planning scenarios in terms of quality, integration between subjects, times, and resources.

The interpretation of mobility and accessibility as a "synecdoche" of the contemporary urban condition represents an intriguing interpretative key to understanding the forms of contemporary urbanity. For Brons et al. (2009), the main point is to recognize the need to recover a holistic approach, by:

- overcoming reductionist and hyper-specialized logics;
- giving concrete meaning to the rhetoric of sustainability.

A railway station is a door (exit, entrance). For the area it serves, this translates into the most classic transposition of accessibility into everyday life: Vandenbulcke et al. (2009) discretized the Belgian territory by type of land use, relating certain uses to the presence or absence of a railway station. At an urban level, poor (or no) accessibility, in its various forms, implies the limitation or impossibility of implementing the principles of social, economic, territorial, and symbolic cohesion for polis, civitas, urbs. In Dupuy's urban planning (Dupuy 2008), space is at the same time:

- topological: identification of nodes-poles-places and areas with privileged connectivity, selectivity of nodes, hierarchical definition of priority accessibility systems;
- kinetic: speed regulation and modulation for vectors, locations, "space–time network", instantaneous voltage (privileged accessibility);
- adaptive: ability to conform to pre-existing conditions, ability to evolve in the growth stages of the network (centrality of accessibility).

Bruinsma et al. (2008)'s currently ongoing work is aimed at defining reading grids for the effects on the shape (and physiology) of the city induced by the presence of a railway station.

Analysis models for the environmental impact of railway stations

The analysis of the environmental footprint of railway stations has never been an independent object of study. More often, it has been a minor integral part of the studies of the impact of the operation of railway stations (see Guidelines UIC (Tuchschmid et al. 2011)). A station is an architectural object, and as such its management follows the indications from the various environmental certification protocols. However, the prescriptions from these protocols do not consider the specific nature[1] of the "railway station building". As a consequence, the contemporary standards of environmental sustainability can only be achieved through "architectural" actions of energy efficiency improvement, which are unrelated to the context and to the physical dimension of the railway station itself. This vision is the same in the academic field: for example, when Kortazar et al. (2021) evaluate the ecological footprint of the operation of new high-speed railway lines, the station—which is however discussed as a complex building—is not considered differently from other complex buildings such as schools, hospitals, or shopping malls.

Research directions

A railway station is a complex and ambivalent element: it is the starting/ending point of an infrastructure dedicated to a specific means of transport—the railway line—and of people's journey on that means of transport. As a node of a linear infrastructure, this value tends to branch out to mobility tout-court, with the station turning into a nodal element for the rest of the local public transport networks, for road mobility and for soft or, better, active mobility—an element that has received a very strong boost from Sars-Cov-2 social distancing policies.

It represents the product of a need for mobility or the expression of the self-fulfillment of the needs of a (urban) community, but the causal link between form and function, between daily operations and consumption of materials, is expressed at a higher level. This level is also dichotomous because it is consolidated on the civitas/urbs complementarity, and it corresponds to:

- investigating mobility infrastructure—as a multi-carrier network—that is upstream from the station;
- investigating the multimodality of the city where the station under examination is located and, in a broader sense, the geometry of the networks of which that station is a node.

Therefore, the key element is geometry: network geometry but also city geometry, as an underlying matrix that generates the networks. Hence, four research "questions" and the respective researchers are here synthetized.

[1] For example, see Deutsche Bahn Strategy, "Grünen Bahnhof", https://gruen.deutschebahn.com/de/massnahmen/gruener-bahnhof.

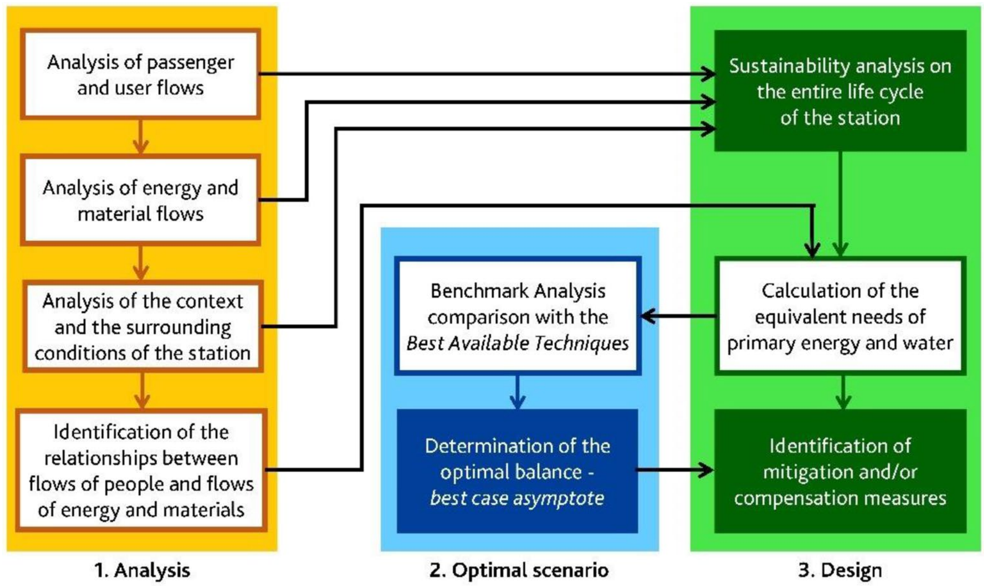

Fig. 1 Conceptual scheme of the model. Source: Author's processing

1. *Can stations have a virtuous influence on the shape of the city?* Pierer and Creutzig (2019), Baiocchi et al. (2015), Creutzig et al. (2020a), (2020b) investigated the star city, organized along priority axes with empty spaces to be re-naturalized with intensive planting of real urban forests. These latter create an ecological continuity with suburban green spaces, not only as a mitigating effect of energy consumption but also in a contingent way (think of resilience to the increasingly frequent heat waves).
2. *How much does network accessibility affect the functionality of a station?* Bruun and Vuhcic (Time-Area concept: development, meaning, and applications https://trid.trb.org/view/452722) investigate "geometric" pollution (of the forma urbis) that underlies the infrastructures and their nodes, through time / area diagrams.
3. *Is it possible to rethink completely the external spaces of a station starting from its main function, that is the parking lot?* Shoup (The High Cost of Free Parking: Updated Edition - 1st Edition - Donald 2021) and Brown (2019) realized an updated critical review of Lewis Mumford's thinking regarding private mobility, and in particular cars. The work focuses on the social costs of unregulated parking, questioning the role of the law in ensuring mobility for all by fulfilling parking demand.
4. *What lever can stations represent, in reducing the impact of road mobility?* Chester et al. (2010, 2013) developed a guideline in recent years, favoring the active role of the measurement of these items in the design and rethinking of infrastructures.

Analysis model of the energy consumption of a station for the evaluation of compensations

The proposed methodology (Fig. 1) is focused on the functional discretization of the operation of a railway station. The methodological steps are discussed below, for more detail on the calculations refer to the Appendix, on the case study of Tiburtina, the second station of the city of Rome.

Overview

The overall energy demand for the operation of railway stations is a significant share of the consumption of railway operations. In Italy (Fig. 2), it is the third-highest share; the first 23 stations of the Italian railway network (including 2264 stations overall) produce 79.6% of the total consumption of all railway stations, representing almost 15% of the 29,880 TJ consumed in 2019.

The energy demand of a railway station is related, rather than to the number of its users, to the size of the building body (in terms of usable floor area) and to the share of commercial floor area. Graphs in Figs. 3, 4 show a strong relationship between specific unit energy demand (kWh year/sqm of the total usable floor area of the station) and commercial floor area ratio for the main stations in the French (78 stations analyzed) and Italian (23 stations analyzed) railway network.

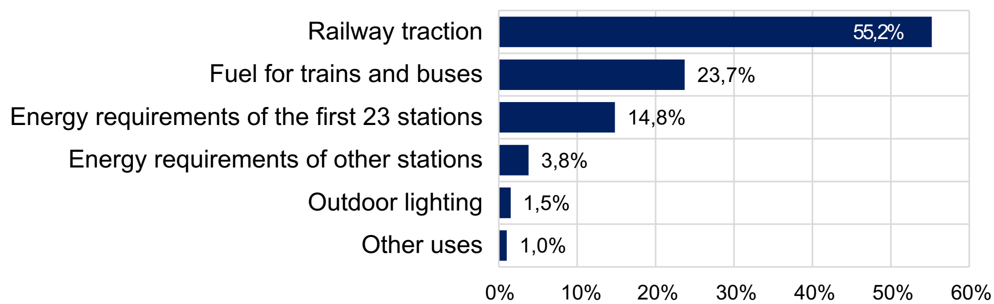

Fig. 2 Distribution of energy consumption for FS, Italian railways (source: Author's processing based on the data of 2019 Environmental Report)

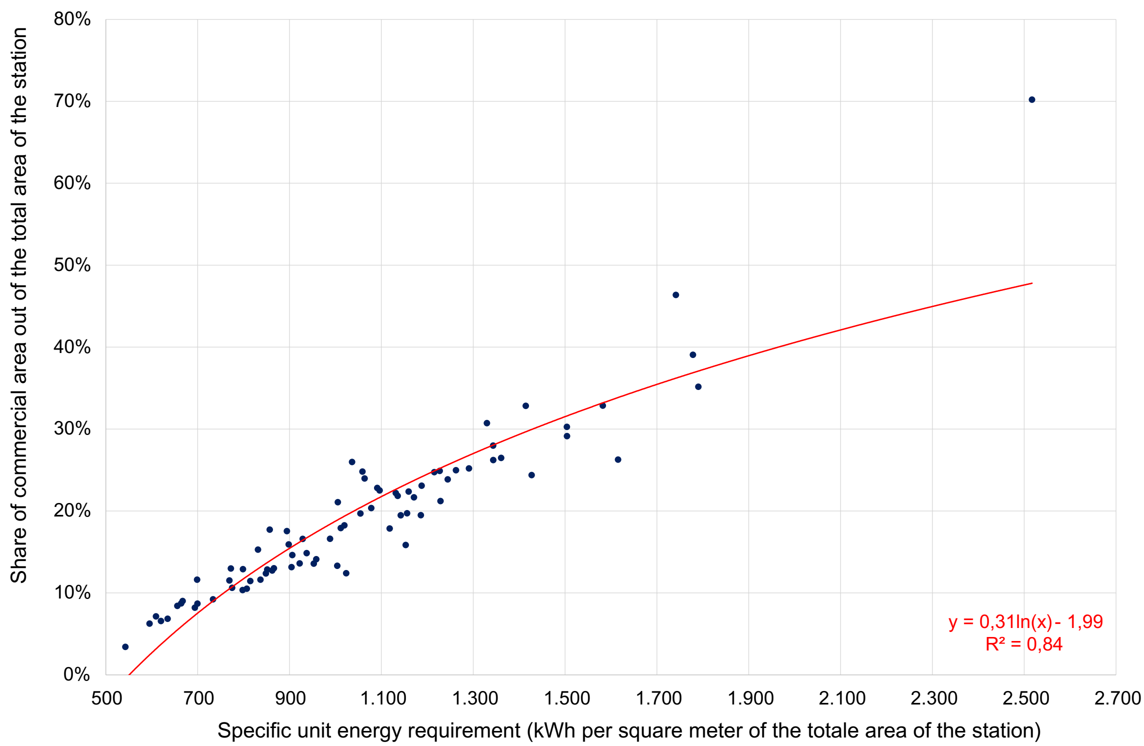

Fig. 3 Relationship between yearly energy demand and commercial floor area ratio for French stations. Analysis of the data provided by SNCF for 2019, related to the 78 main stations of the French railway network. Source: Author's processing

Assumptions

The analysis only considers the impact daily operations of the station, not railway traffic. All energy and water needs induced by lighting, by vertical translation systems (escalators and elevators), by the operation of sanitary systems, by the preparation of food and drinks for sale are then measured. The energy requirements for winter heating and summer cooling are calculated in degree-days required for the reference climatic zone. The degree-day is the measurement unit that estimates the energy demand to maintain a comfortable indoor environment in standard conditions. It represents the sum of the average daily temperature increases needed to reach the threshold of an optimum temperature of 20 °C, extended to all days of a conventional annual heating period. Daily consumption is calculated for the whole year by considering the following coefficients: daily opening hours of the station: 5:00–00:00 (19), annual opening days: 365.

Regarding the HVAC system, the efficiency of a heat pump is measured by the COP—*Coefficient of Performance*, which is the ratio between the produced thermal energy and the consumed electrical energy; the higher the COP, the more efficient the machine is (low consumption). A COP value of 3 means, for example, that for each kW of electricity, the heat pump returns 3 kW of thermal energy to the heated room; one of these is supplied

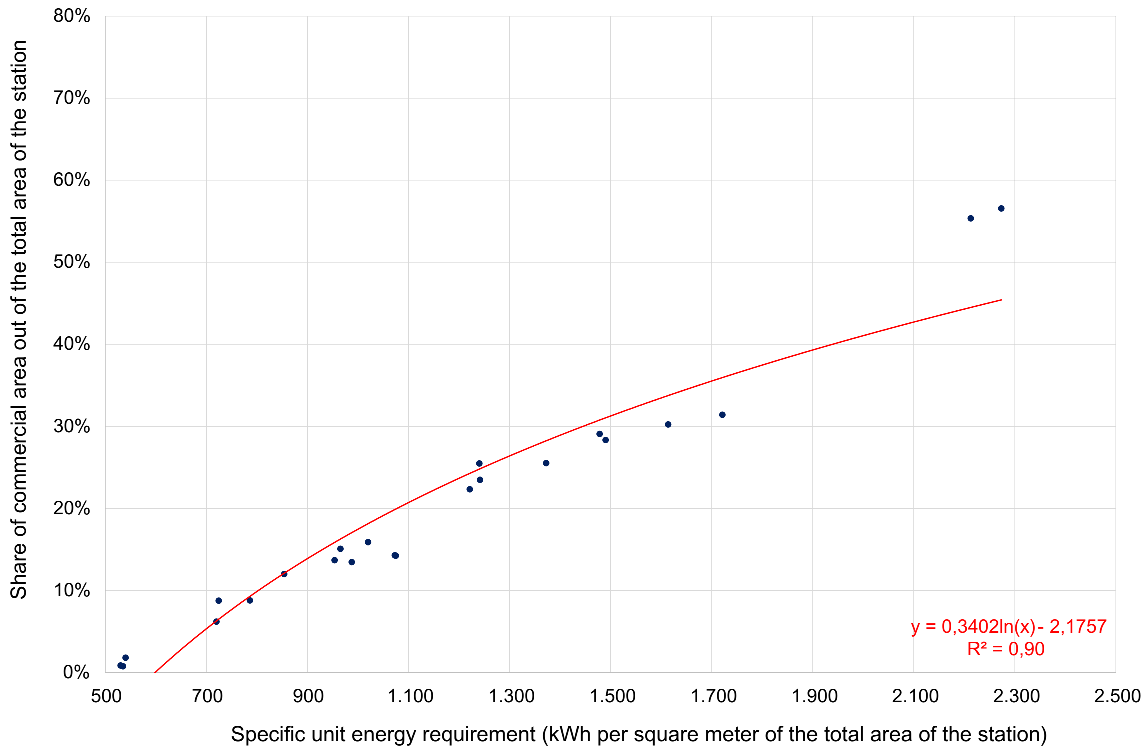

Fig. 4 Relationship between yearly energy demand and commercial floor area ratio for Italian stations. Analysis of the data provided by FS for 2019, related to the 23 main stations of the Italian railway network. Source: Author's processing

by the consumed electricity and the other two kW are drawn from the external environment. For the case study of the stations of the city of Rome, the following values are assumed: a COP = 3.00 for heating; COP = 2.50 for cooling.

Regarding water consumption, the following needs are considered: toilet/Sanitary use, food & beverage, cleaning, and disinfection.

The water impact has a double weight as, in addition to the water resources consumed, the remote energy impact on the adduction system and on the waste disposal and purification system is considered as well. The picture is completed by the need for detergents and disinfectants for sanitary use and for cleaning. In this case, too, both resource consumption and remote energy impact have been considered.

Evaluation model for the compensatory measures

The study is carried out in two phases:

- Functional and performance analysis (pre-pandemic, year 2019) and evaluation of the impact of the ordinary operation of the station;
- Definition of mitigation/compensation scenarios.

The possible compensatory actions are assessed based on the following assumptions:

- the management and maintenance operations follow the *Best Available Techniques*;
- the waste and scrap materials produced in the daily operation of the station are properly collected and placed in the recycling chain by at least 95%. The use of plastic is reduced to the minimum, and only when alternatives with highly recyclable materials (glass, paper, compostable derivatives) are not available.

The starting assumption is that the mitigation of the emissions produced by the station is possible through the combined action of specific compensatory wedges, that is, measures with a proper construction and operational impact. These impacts—in a context of overall economic sustainability—are absorbed by the induced benefits, with an overall positive balance. Each wedge is linked to one of the following actions:

1. energy production for the partial fulfillment of daily energy demand;

2. rainwater collection for the partial fulfillment of daily water needs, and/or reduction of the volume of wastewater through partial recovery and reuse;
3. in situ combined heat (and possibly energy) production to reduce the overall energy demand for heating and cooling;
4. indirect compensatory absorption of the total CO2 released into the atmosphere through an intensive urban planting.

Two scenarios have been defined: the medium and the optimal one, differing in terms of investments and active benefits on final climate-altering emissions. Intensive urban planting is a passive measure, chosen to absorb the residual impact that cannot be reduced by the other measures. The proposed actions are evaluated in terms of technical feasibility and economic sustainability in relation to the peculiarities and the specific needs of a railway station.

The scenarios and related action wedges are the following:

- Medium scenario:

  Wedge 1.1: regenerative braking of incoming trains, for local-use energy recovery and storage
  Wedge 1.2: installation of a solar field for energy production
  Wedge 2.1: rainwater collection
  Wedge 2.2: partial gray water recovery
  Wedge 4: urban planting

- Optimal scenario:

  Wedge 1.1: regenerative braking of incoming trains, for local-use energy recovery and storage
  Wedge 1.2: installation of a solar field for energy production
  Wedge 2.1: rainwater collection
  Wedge 2.2: partial gray water recovery
  Wedge 3: heat extraction subsoil with a low enthalpy geothermal plant
  Wedge 4: urban planting

The calculation parameters assumed for each part (wedge) are described below.

Table 1 Wedge 1.1—recovery of braking energy from trains entering the station: assumptions. Source: Author's processing of data from experimental projects by SNCF (France), DB (Germany) and FS (Italy)

Battery sizing		
Construction	4.18E−03	kWh/kWh
	2.31E−01	m^3/kWh
Use	4.00E−04	kWh/kWh
	1.43E−04	m^3/kWh
Incoming cruise energy	392.01	kWh/train
Recovery capacity	58.80	kWh/train
Gross cost of the system	200.00 × 1.25	Euro/kWh
Average service life	10	Years

At the current state, the technology for regenerative braking on trains with alternating is currently ready for the market, while regenerative braking on trains with direct current is still under experimentation

First wedge: regenerative braking of trains entering the station

The recovery system consists of the train on-board equipment and the trackside system, which allows collecting, directing, and accumulating part of the energy generated by the on-board traction system. In fact, during braking, the latter behaves like a generator of current. The ground system is divided into the following components:

- The interface with the railway power supply network;
- Current limiter, which protects both the contact line and the storage system from overcurrent phenomena;
- Accumulation system for storage and gradual release of electrical voltage for on-site use.

The parameters of the storage system are those assumed to size the investment cost and the ecological footprint of the plant. Unit references are derived from the following sources:

- Concerning the ecological footprint, from the biennial report[2] "*PEFCR—Product Environmental Footprint Category Rules for High Specific Energy Rechargeable*" published by Re-Charge, The Advanced Rechargeable & Lithium Battery Association;
- Concerning installation and maintenance costs, from the report[3] "*World Bank. 2020. Economic Analysis of Battery Energy Storage Systems*" of the World Bank.

[2] https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_Batteries.pdf.

[3] https://openknowledge.worldbank.org/handle/10986/33971.

Table 1 summarizes the calculation parameters assumed in the analysis.

First wedge: on-site electricity production via photovoltaic field

The action involves the installation of a photovoltaic system. Generally, this is placed on the roof or in an adjacent area that is not affected by shading during the day in any season.

Unit references are derived from the following sources:

- For the productivity of the plant:

  Italian atlas of solar radiation,[4] Enea *Area Fonti Rinnovabili*;

  World Bank technical documents.[5]

- For the ecological footprint, installation, and maintenance costs, from the technical reports[6] of the World Bank.

The following symbols are used in the tables: Π is the total power of the systems in kW (o kW peak for solar systems); Σ is the total annual production of the system in kWh.

Table 2 summarizes the calculation parameters assumed in the analysis.

Second wedge: rainwater collection and partial gray water reuse

The system for rainwater collection and partial gray water recovery requires the installation of a collection basin and related sanitation, and a connection to the sanitary network. The geometric parameters of the basin correspond to the ones assumed for the dimensional scheduling of the investment cost and the evaluation of the ecological footprint of the system.

Benchmarks are derived from the following sources:

- For the ecological footprint, from the research "*EFIResources: Resource Efficient Construction towards Sustainable Design*"—Model for Life Cycle Assessment (LCA) of buildings, published[7] by the European Commission;
- For installation and maintenance costs, from the FAO "*TECA—Technologies and Practices for Small Agricultural Producers*" reports.[8]

Table 3 summarizes the calculations of the parameters assumed in the analysis.

Table 2 Wedge 1.2—on-site electricity production with photovoltaic field: assumptions. Source: Author's processing of parameters from IEA

Wedge 1.2. Footprint		
Panels		
Construction	1250.0	kWh/m^2
	12.012	m^3/kWp
Use	0.8	kWh/m^2
	0.472	m^3/kWp
Battery sizing		
Construction	4.18E–03	kWh/kWh
	2.31E–01	m^3/kWh
Use	4.00E–04	kWh/kWh
	1.43E–02	m^3/kWh
Annual production per kW peak	Local value	kWh/kWp
Solar radiation	Local value	kWh/m^2
Plant power Π	Available area/5.5	kWp
Annual production Σ	3,217,909.09	kWh
Gross cost of the plant		
Materials	1500 Π	
Supports	220 Π	
Inverter	350 Π	
Battery	200 Σ/365	
Design	7.50%	Net cost
Works supervision, testing assistance	5.00%	Net cost
Testing	2.20%	Net cost
Safety charges not included in unit costs	3.50%	Net cost
Surveys, assessments, and investigations	2.00%	Net cost
Connection to the grid	5.00%	Net cost
Unforeseen costs	5.00%	Net cost
Average service life	25	Years

IEA, Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications: Third Edition, https://iea-pvps.org/key-topics/best-practices-handbook-for-the-collection-and-use-of-solar-resource-data-for-solar-energy-applications-third-edition/

[4] Data source: http://www.solaritaly.enea.it/.

[5] Global Photovoltaic Power Potential by Country, http://documents1.worldbank.org/curated/en/466331592817725242/pdf/Global-Photovoltaic-Power-Potential-by-Country.pdf.

[6] E.g., Environmental and Social Impact Assessment Report Under Feasibility Study for Development of Utility Scale Solar PV & Wind Projects in Bangladesh, http://documents1.worldbank.org/curated/en/449091539166909882/pdf/07102018-Final-ESIA-Report-of-Utility-Scale-PV-Wind-Project-cleared.pdf.

[7] https://ec.europa.eu/jrc/en/publication/model-life-cycle-assessment-lca-buildings.

[8] http://www.fao.org/teca/about-teca/en/; http://www.fao.org/3/a-br326e.pdf.

Table 3 Wedge 2—rainwater collection and partial gray water reuse: assumptions. Source: Author's processing of data from the aforementioned sources

Water collection sizing		
Construction	337.50	kWh/m^3
	4.20E–01	m^3/m^3
Use	2.78	kWh/m^3
	1.18E–04	m^3/m^3
Gross cost of the system	80.00	Euro/m^3
Average service life	15	Years

Third wedge: heat extraction from the subsoil with a low-enthalpy geothermal system

A low-enthalpy geothermal plant uses deep geothermal probes to exchange energy with the ground in a continuous and natural way. From a theoretical perspective, the heat of the earth increases with depth and is always constant throughout the year: for example, at about 500 m underground, the temperature reaches about 25° in both summer and winter. Generally, the vertical probes are positioned at a depth of about 100 m in the subsoil, and it is connected to a heat pump, and then to a hydraulic system to exchange heat with the final user. The low enthalpy geothermal system consists of the following basic elements:

- ground heat exchange probes: they consist of a set of high-density polyethylene (HDPE) pipes, connected in parallel, in which the heat transfer fluid circulates; the pipes represent the heat exchange batteries. This geothermal exchanger enhances the thermal energy in the subsoil and in any intersecting aquifers;
- heat supply terminals: the heat transfer fluid can be used to supply energy for both cooling and heating and for the production of domestic hot water;
- thermal unit, equipped with a heat pump: the heat pump is a thermal machine that transfers thermal energy from a lower temperature source to a higher temperature source and vice versa. A reversible geothermal (water-water) heat pump can produce hot water and chilled water for winter and summer air conditioning in the structure, as well as domestic hot water throughout the year (at about 50°).

The calculation parameters were obtained from the following sources:

- For the ecological footprint, from the research "*EFIResources: Resource Efficient Construction towards Sustainable Design*"—Model for Life Cycle Assessment (LCA) of buildings, published by the European Commission;
- For installation and maintenance costs, derived and updated from the "*2015 JRC Geothermal Energy Status Report*" of the JRC Research Center of the European Council and IEA[9];
- For the geothermal potential, the JRC Geothermal Power Plant Dataset.

Table 4 summarizes the calculation parameters assumed in the analysis.

Table 4 Wedge 3—subsoil heat extraction with a low-enthalpy geothermal system: assumptions. Source: Author's processing of data from the aforementioned sources

Wedge 3. Footprint		
Probes sizing		
Construction	2,320	kWh/m
	24.378	m^3/m
Use	1.747	kWh/m
	0.472	m^3/m
Storage tank/boiler		
Construction	4.18E–03	kWh/m^3
	1.27E–01	m^3/m^3
Use	4.00E–04	kWh/m^3
	7.87E–03	m^3/m^3
Thermal needs	10.00	kW/m^2
Geothermal power	0.05	kW/m^2
Drilling depth	120.00	m
Number of 4-pipe probes	1	Probe/250 m^2
Storage tank/boiler	2.50	l/m^2
Gross cost of the system		
Drilling	90.00	Eur/m probes
Installation and cementation of the probes	30.00	Eur/m probes
Heat pump	45.00	Eur/ m^2
Storage tank/boiler	0.35	Eur/l
Design	7.50%	Net cost
Works supervision, testing assistance	5.00%	Net cost
Testing	2.20%	Net cost
Safety charges not included in unit costs	3.50%	Net cost
Surveys, assessments, and investigations	2.00%	Net cost
Connection to the grid	5.00%	Net cost
Unforeseen costs	5.00%	Net cost
Average service life	25	Years

[9] IEA, Handbook of Best Practices for Geothermal Drilling 2010, https://iea-gia.org/publications-2/working-group-publications/drillinghandbooksjbpubver-bauer-20jan11-2/.

Table 5 Unit compensation of urban forests for each species, considering a maximum 5 × 5 sqm intensive planting layout

Tree species	Absorbed CO_2 kg/pc.
Acer campestre	2720
Fraxinus ornus	2392
Gingko biloba	4056
Morus alba	2392
Quercus cerris	4000
Tilia platyphyllos	4056
Ulmus minor	4056
Mean	3382

Table 6 Variability range of average life data for the seven species considered in the case study. Source: Loehle (1988)'s processing

Species	$R_{(min)}$	$R_{(a)}$	$M_{(a)}$	$M_{(max)}$
Acer campestre	10	20	150	300
Fraxinus ornus	20	40	150	250
Gingko biloba	25	50	250	500
Morus alba	10	15	50	125
Quercus cerris	25	50	200	400
Tilia platyphyllos	15	50	100	250
Ulmus minor	20	40	250	300

R(min), minimum age of the first reproduction; R(a), average age of the first reproduction; M(a), average typical age of mortality; M(max), maximum longevity

Fourth wedge: intensive urban forestation

This intensive planting activity is aimed at producing a protected urban forest, requiring as little human intervention as possible during its life. The approach, albeit on a limited scale, was proposed[10] in 2016 by biologist Edward Osborne Wilson: to allocate half of the earth's surface to a "wilderness" nature reserve to preserve biodiversity.

The compensation is based on the absorption coefficients of some native species over a period of 30 years (Figures 6, 7, 8, 9). These values were calculated by Ibimet-CNR in the GAIA-urban forestation project (Table 5).[11]

The compensation is based on the absorption coefficients of some native species over a period of 30 years according to Ibimet-CNR parameters, evaluated within GAIA-urban forestation project. Many factors influence the process of absorption and sequestration of atmospheric carbon in organic molecules (Piovesan and Biondi 2020): species, size, place of implantation and sixth, climate, intensity of the surrounding stress. These factors affect the growth of the trees, and therefore the CO_2 absorption process. For this reason, data based on a time unit (monthly or annual absorption) make little sense: instead, it is preferrable to consider the total content of CO_2 absorbed by a tree during its entire life cycle, considering average values for the duration of its life. In the present case, seven medium-tall trees were analyzed. Out of these, six are natives to the Roman countryside: *Acer campestre*, *Fraxinus ornus*, *Morus alba*, *Quercus cerris*, *Tilia platyphyllos*, *Ulmus minor*; one, *Gingko biloba*, is a naturalized allochthonous species. The average life parameters for these species are summarized in Table 6.

Figures 5, 6, 7 and 8 show the absorption curves for the plant species considered for compensatory forestation. Like other technological interventions, the urban forestation system is not limited to being a compensatory measure. It has an extremely varied and articulated ecological (Manoli et al. Sep. 2019) and social (Grimm, et al. 2008; Bowyer et al. 2021) value.

Application of the model to the Rome railway network

The analysis is aimed at identifying a multi-action strategy for to the full compensation of the climate-altering emissions produced directly and indirectly—calculated without considering train movement—by the stations of Roma. Two scenarios have been defined—a medium and an optimal one—differing by budget and achievable results (Table 7).

Each scenario is constituted by the combined action of specific compensatory wedges:

1. energy production for the partial fulfillment of daily energy demand;
2. rainwater collection for the partial fulfillment of daily water needs, and/or reduction of the volume of wastewater through partial recovery and reuse;
3. in situ combined heat (and possibly energy) production to reduce the overall energy demand for heating and cooling;

[10] Half-Earth: Our Planet's Fight for Life, Liveright 2016; https://www.half-earthproject.org/.

[11] The project defined knowledge, tools, and innovative ways of using urban forests. Through a public–private partnership, GAIA has managed to create a collaboration between different stakeholders in the area (24 companies, trade associations, institutions) and has allowed a wide and diversified audience to talk about environmental sustainability (CO2 and carbon management). Thanks to the results achieved with the initiative, in 2013 the Municipality of Bologna decided to make it one of the administrative tools to reduce CO2 emissions, with a council resolution (PG.147297 / 2013). More information at: https://www.vivam.it/green-areas-inner-city-agreement-gaia-how-local-enterprises-can-contribute-to-local-adaptation-to-climate-change/.

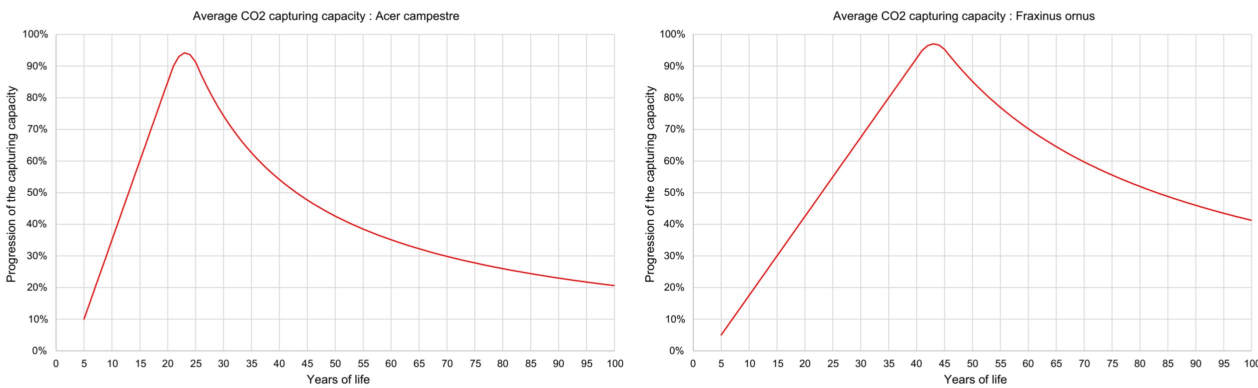

Fig. 5 Progression of CO_2 absorption capacity for native species of the Roman countryside—Field maple (left) and South European flowering ash (right)

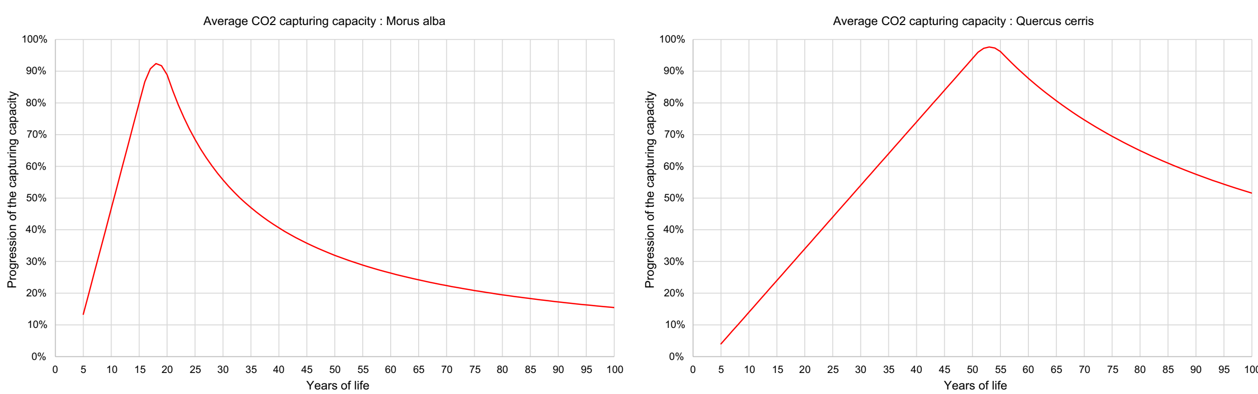

Fig. 6 Progression of CO_2 absorption capacity for native species of the Roman countryside—White mulberry (left) and Turkey oak (right)

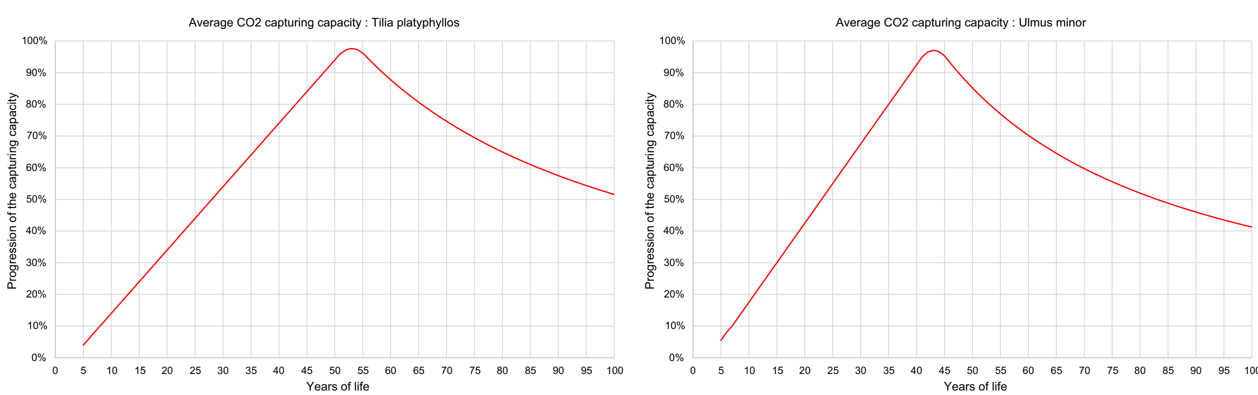

Fig. 7 Progression of CO_2 absorption capacity for native species of the Roman countryside—Large-leaved lime (left) and Field elm (right)

4. compensatory absorption of the CO_2 released into the atmosphere through intensive urban planting.

The actions can be grouped into three sets: by mediating between the minimum and maximum effectiveness values, it has been found out that the optimization in terms of efficiency of the station systems can offset about 13% of the emissions. The centralized production of thermal energy (for both heating and cooling and the production of domestic hot water) can offset up to 31%

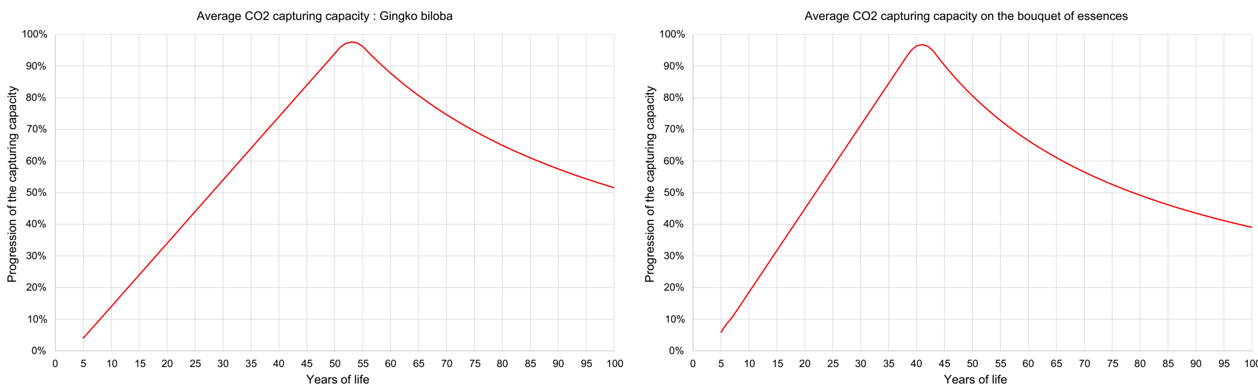

Fig. 8 Progression of CO_2 absorption capacity for Gingko biloba (left) and average absorption curve on the whole set of essences examined (right). Source: Author's processing of data from Loehle (1988)

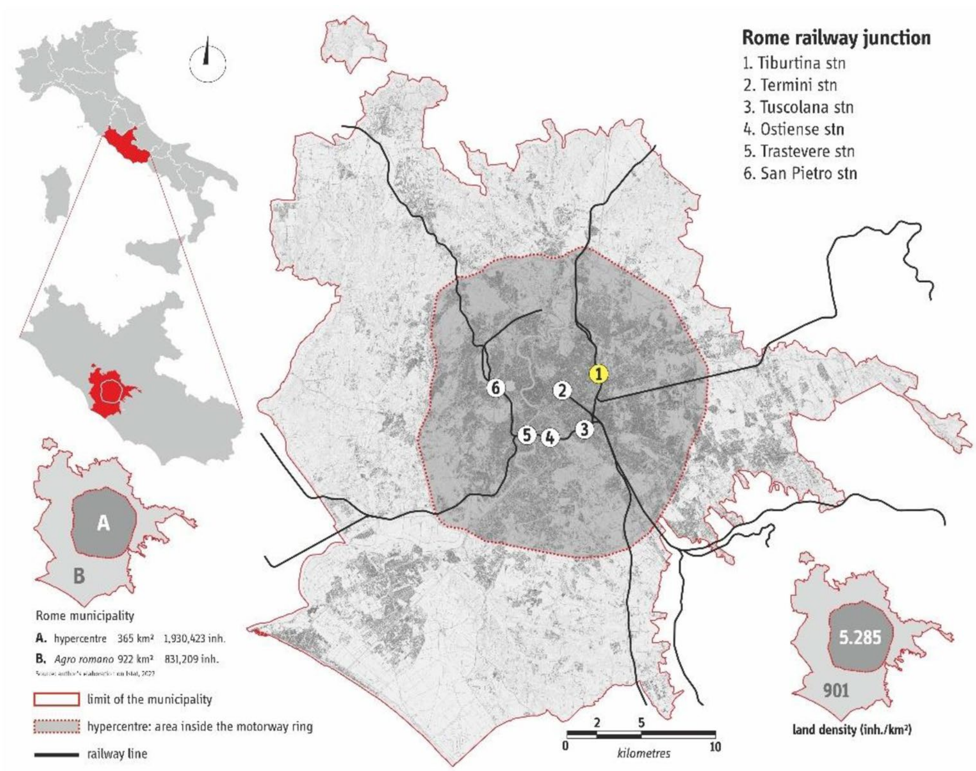

Fig. 9 Administrative boundaries of the Municipality of Rome and subdivision into the hyper-center, located inside the ring road named GRA, and low-density external area (*Agro Romano*). The railway network and its six main stations are also highlighted

of the emissions. In total, active compensatory measures can offset 44% of emissions. The remaining share can be compensated through passive measures, such as intensive urban or suburban planting. The analysis, set in a period of 30 years (2020–2050), has been carried out in a business-as-usual scenario relative to the compensation of primary electricity production. Yet, in 2050 EU's long-term strategy for the achievement of full compensation of primary energy will be underway, so primary energy will already be compensated in railway stations because of the reduction of the impact of transformation cycles.

Both analyses highlight some wider key items in relation to the case study:

Table 7 Stations of the Rome railway network: dimensional figures. Source: RFI

Station	Average daily people 2015–2019	Surface (m^2)			Energy needs (kWh, 2019)
		Passenger	Retail	Total	
Ostiense	12,877,200	12,516	20,472	36,988	81,851,736
San Pietro	5,930,700	2,078	38	2,116	1,143,347
Termini	154,182,900	134,772	61,720	196,492	338,264,717
Tiburtina	15,134,200	14,615	19,022	33,637	76,471,039
Trastevere	10,185,600	6,499	56	6,555	3,477,232
Tuscolana	6,081,600	3,120	24	3,144	1,682,263
Total	204,392,200	177,600	101,332	278,932	502,890,334

1. the relevance of the energy demand for heating/air conditioning (both in the BAU scenario and in the Net-Zero scenario);
2. the relevance of the impact of water consumption and use of detergents: 19% of overall emissions in the BAU scenario, 42% in the Net-Zero scenario.

The first point suggests rethinking the complex water system of the station through the introduction of both storage tanks and rainwater and, above all, the progressive reuse of gray water before final disposal.

The second point shows the need to consider a railway station as a part of the urban body or at least one of its components, rather than as a complex, but isolated object. In this sense, the proposal of introducing district heating (Connolly et al. 2014) using heat pumps and geothermal probes for heat extraction/accumulation—destined for air conditioning and warm water—appears to be an inevitable design direction.

In conclusion, it appears that the most effective strategy to bring the operation of the analyzed stations—but these are generalizable conclusions—toward the goal of zeroing climate-altering emissions should be based on the following design actions:

1. improvement of the performance of the building envelope and the intrinsic efficiency of the systems;
2. partial closure of water cycles with the introduction of the accumulation capacity of both rainwater and gray water for local reuse after sanitization;
3. construction of district heating networks based on geothermal heat pumps for heat extraction and storage;
4. intensive urban planting.

It is fair to ask which effect the improvement of the sustainability of railway stations produces on the city. The EU Commission provided a comprehensive Nature-based Solutions (NBS) impact assessment framework (Evaluating the impact of Nature-based Solutions: a handbook for practitioners 2021), with a robust set of indicators and methodologies to assess the impacts of NBS across 12 societal challenges: Climate Resilience; Water Management; Natural and Climate Hazards; Green Space Management; Biodiversity; Air Quality; Place Regeneration; Knowledge and Social Capacity Building for Sustainable Urban Transformation; Participatory Planning and Governance; Social Justice and Social Cohesion; Health and Well-being; New Economic Opportunities and Green Jobs. Table 8 summarizes the indicators chosen to measure the effects of railway station sustainability wedges on urban key societal challenge areas.

The indicators are measured[12] on the catchment area of each station. The universe of comparison is the central area of the Roman metropolitan area, that is the urban area enclosed within the 68 km motorway ring called GRA, "*Grande Raccordo Anulare*". It is an area of about 365 km^2 (28% of the territory of the Municipality) which hosts 70% of the population of the Municipality (1.93 out of 2.76 million inhabitants) and 45% of the population of the metropolitan area (4.31 million inhabitants).

In the framework of the railway station of Rome, the transformation of the Tiburtina station (Figs. 10, 11, 13)— the second most important station in the city after Termini—according to the *Blue Station* model, would help reducing the impact of the city's externalities by about 6% (Figs. 12, 14, 15). This is possible by looking at the stations as hot-spots for the generation of thermal energy flows for heating and cooling the adjacent neighborhoods.

Conversely (Figs. 14 and 15), by transforming all 6 major stations in the city, the improvement effect on the

[12] Environmental data from Ispra (https://www.isprambiente.gov.it/it/banche-dati) and the Municipality of Rome (https://dati.comune.roma.it/catalog/dataset/10e681a5-82e0-454f-a7fd-ae562a51c151/resource/d824ec4d-78e2-43fe-8a8a-95b0572b2a9f).

Table 8 Set of indicators and measurement units for the evaluation of the operation of railway stations according to methodology (Vogt-Schilba et al. March 2018). Source: Author's processing of data from RFI (railway stations) and the Statistical Bureau of the City of Rome (urban indicators)

Key societal challenge areas	Indicator	Unit
Climate Resilience	Reduction of climate-related emissions	Annual CO_2 tons
Water Management	Treated water	m^3
Natural and Climate Hazards	Total permeable area	ha
Green Space Management	Total monitored green area	ha
Biodiversity Enhancement	Connected green area	ha
Air Quality	Induced atmospheric particulate emissions	kg PM10
Spatial Regeneration	Public spaces area	ha
Knowledge and Social Capacity	People reached by the sharing and dissemination processes	inh
Participatory Planning and Governance	Residents involved in participatory design processes	inh
Social Justice and Social Cohesion	Management transparency and possibility of control by third parties	businesses*jobs
Health and Wellbeing	Residents in the catchment area	inh
New Economic Opportunities and Green Jobs	Green Jobs (satellite activities)	jobs

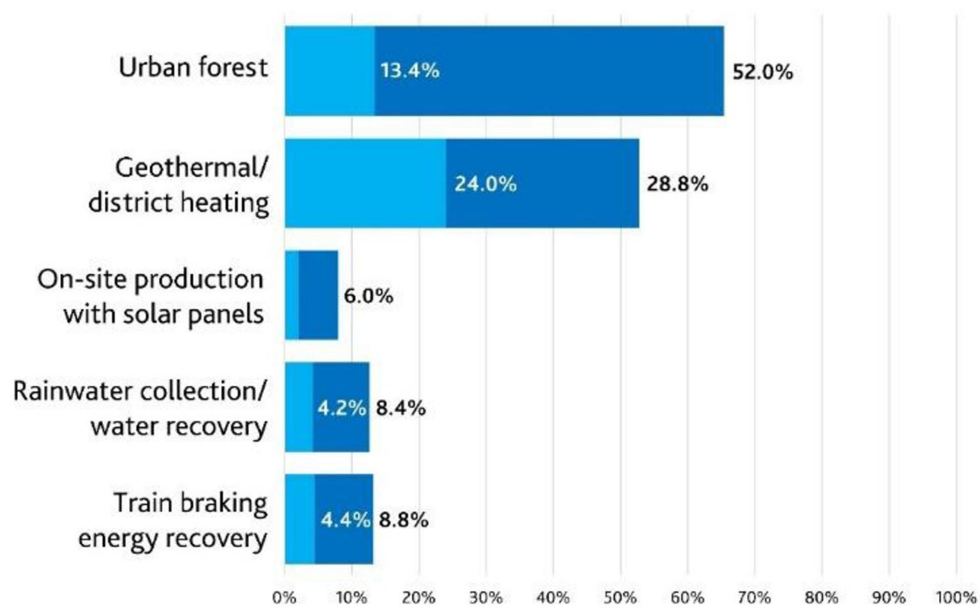

Fig. 10 Rome Termini station: effectiveness domain of mitigation wedges. Results of the medium (light blue) and optimal (blue) scenarios

inner-city environmental performance would be significant: 10% for the medium scenario and 36% of the optimal scenario.

Discussion

The author proposed a compensative model that allows shifting from a qualitative view to a quantitative view of the actions to improve the operation and maintenance processes of a railway station. A model that, with the appropriate modifications, could be generalized and applied for other industrial or residential purposes.

The truly innovative contribution is that of considering a railway station no longer as an infrastructural element for the purpose of railway operation o, at most, as the hub of the transport network (Fig. 16), but rather as a redevelopment driving force for the adjacent urban areas (Fig. 17). This is particularly relevant for those showing unlikeliness to be deeply involved in ecological transformation policies (Fig. 18), at least in the short period and to the extent required by the current situation. One-off measures such as tax reliefs for renovations or building renovation incentives are, at best, limited

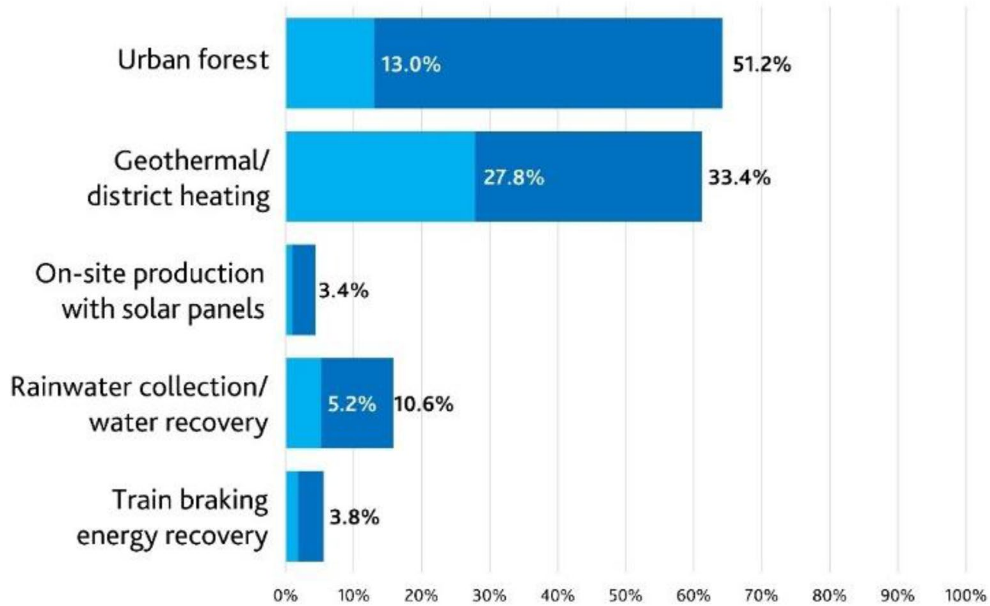

Fig. 11 Rome Tiburtina station: effectiveness domain of mitigation wedges. Results of the medium (light blue) and optimal (blue) scenarios

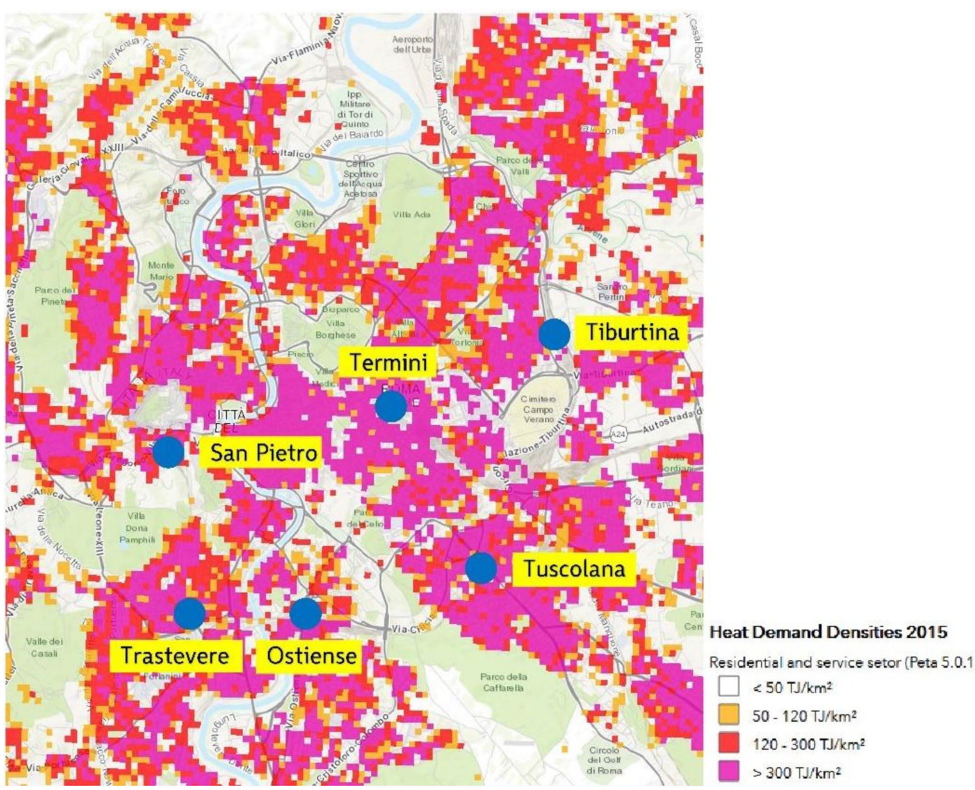

Fig. 12 The examined stations on the map of heat requirements for the city of Rome. Source: PETA (https://www.arcgis.com/apps/webappviewer/index.html?id=8d51f3708ea54fb9b732ba0c94409133)—Pan European Thermal Atlas 5.0.1

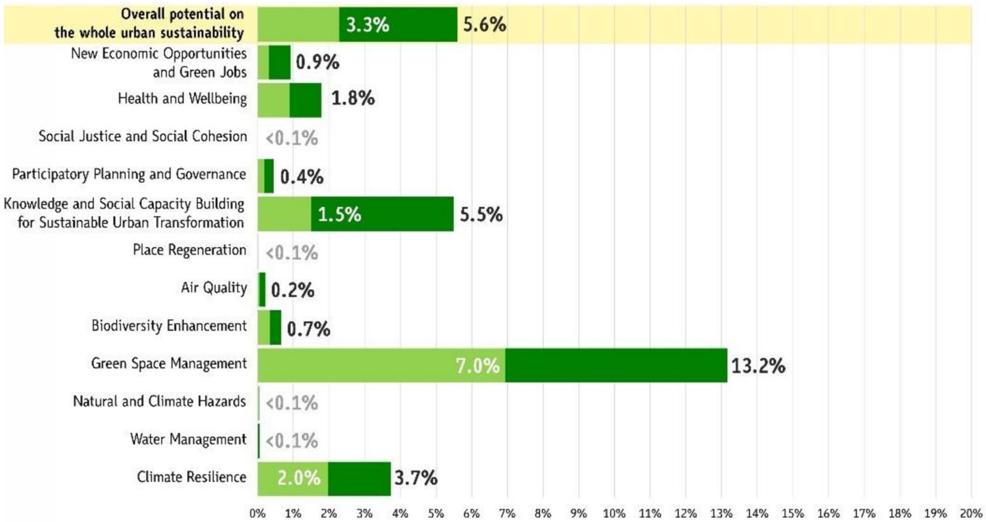

Fig. 13 *Blue Station* transformation of the Tiburtina station in Rome, second in the city by number of passengers: minimum–maximum effect (light and dark green) on the sustainability balance of the core of the metropolitan area

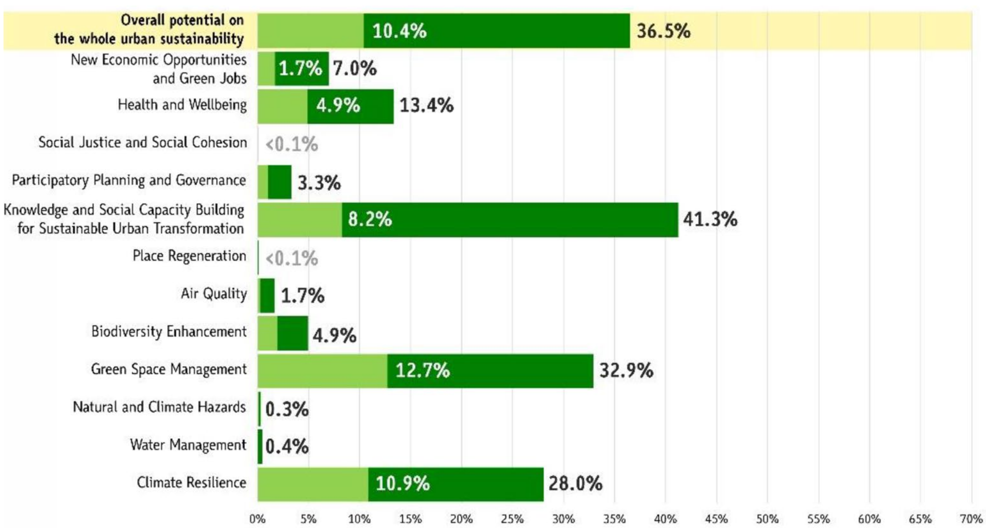

Fig. 14 *Blue Station* transformation of all the 6 main stations of Rome: minimum–maximum effect (light and dark green) on the sustainability balance of the core of the metropolitan area

levers. In fact, their benefit is defused by an excessive fragmentation—or rather, atomization—of the approval and implementation procedures. Such fragmentation stems from the excessive number of actors involved and, from a lack of general planning. The railway stations, on the other hand, are plants built from a unitary planning; and they have a single operator and management subject. Figure 24 shows the action layers of the Blue Station model. Figures 19, 20, 21, 22, 23 exemplify the generalization of the model for the different sizes of a railway station.

In the past two years, issues related to the containment of the Cov-Sars-2 pandemic have also raised awareness on the economic impact of mobility and its infrastructures. In fact, the ecological transition cannot be linked only to decarbonization in order to achieve effective results: there is a broader dimension of the problem, involving system dynamics, which requires overcoming micro-marginalist approaches.

The positive effects of small actions, even when performed at larger scales (the system of incentives or tax reliefs) are nullified by the inertia of climate change;

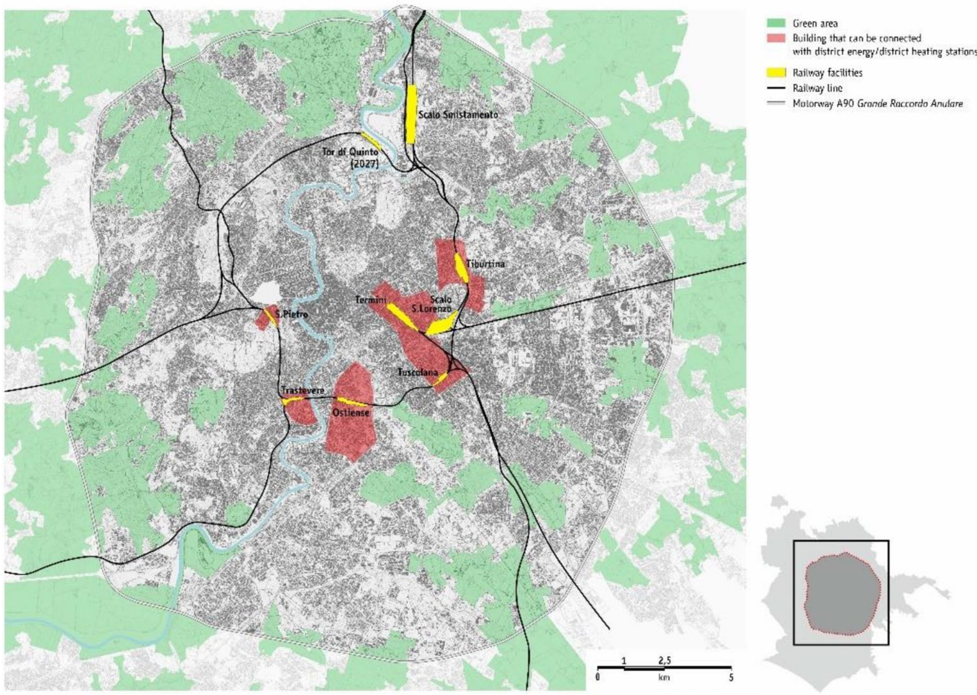

Fig. 15 Areas with a potential for integrated transformation around the six main stations of the inner part of the city of Rome

Table 9 Generalization of the *Blue Station* model: small station

Carbon–neutral station (S)	
Size	Small
Daily Passenger	5000
Annual passenger	1,500,000
Needs	
Energy (kWh/year)	3,000,000
Water (m^3/year)	33,750
Area (m^2)	
Gross Floor Area	1500
Minimum expansion (m^2)	2175
Technical operating area	75
Solar field	600
Geothermal field	1500
Additional volume (m^3)	
Water storage/treatment	51.0
Compensatory green area	
Urban forest (ha)	3.0

Table 10 Generalization of the *Blue Station* model: medium station

Carbon–neutral station (M)	
Size	Medium
Daily Passenger	10,000
Annual passenger	3,000,000
Needs	
Energy (kWh/year)	4,500,000
Water (m^3/year)	60,000
Area (m^2)	
Gross Floor Area	3000
Minimum expansion (m^2)	3300
Technical operating area	150
Solar field	900
Geothermal field	2250
Additional volume (m^3)	
Water storage/treatment	90.0
Compensatory green area	
Urban forest (ha)	4.5

instead, discontinuities must be overcome through complex and onerous actions (Vogt-Schilba et al. 2018). This drastic approach is favorable both to infrastructural investments, and to the acceleration of the ecological transition of cities, starting from large function containers such as railway stations. Their sustainable transformation can—and must—become a lever for the functional redesign of the parts of the city that surround them.

Tables 9, 10, 11, 12 and the Figs. 16, 17, 18, 19 are schematizations realized by the author: they show minimum design indications for 4 dimensional classes of

Table 11 Generalization of the *Blue Station* model: large station

Carbon–neutral station (L)	
Size	Large
Daily Passenger	15,000
Annual passenger	5,000,000
Needs	
Energy (kWh/year)	6,000,000
Water (m^3/year)	87,500
Area (m^2)	
Gross Floor Area	5000
Minimum expansion (m^2)	4450
Technical operating area	250
Solar field	1200
Geothermal field	3000
Additional volume (m^3)	
Water storage/treatment	131.0
Compensatory green area	
Urban forest (ha)	6.0

Table 12 Generalization of the *Blue Station* model: extra-large station

Carbon–neutral station (XL)	
Size	Extra-large
Daily Passenger	30,000
Annual passenger	10,000,000
Needs	
Energy (kWh/year)	10,000,000
Water (m^3/year)	150,000
Area (m^2)	
Gross Floor Area	10,000
Minimum expansion (m^2)	7500
Technical operating area	500
Solar field	2000
Geothermal field	5,000
Additional volume (m^3)	
Water storage/treatment	225.0
Compensatory green area	
Urban forest (ha)	10.0

stations. Compensatory urban forestation areas are not shown in the diagrams (Figs. 20, 21, 22, 23, 24).

Conclusions

The most effective strategy for the zeroing of climate-altering emissions deriving from the operation of the examined railway station is based on the combination of active (technological) and passive (urban forestation) actions: certainly, these conclusions can be extended beyond the context of this research. Both in the business-as-usual and in the *Net Zero 2050*—that is, with fully compensated primary energy consumption—scenarios, urban forestation must not be considered as a one-off compensation measure of the emissions produced by the daily operation of the station. Albeit it has been conceived as compensation measure, its significance for urban areas is much deeper and more articulate:

- the creation of areas with a high thermal and hydraulic inertia is fundamental to increase the compensation of heat waves, in addition to improving the response to heavy rainfall, without overloading rainwater collection systems;
- the partial filtration of airborne pollutants represents a strong ecological benefit; from a social standpoint, it notoriously improves collective well-being.

Concerning active compensatory measures, the use of low-enthalpy geothermal energy for the heating and cooling of the indoor environments of a railway station can be extended to adjacent urban areas. In this case, a merely technological intervention can be turned into a lever of urban efficiency improvement, shifting from single building cogeneration to district heating.

In relation to the literature on to the currently in-progress research lines, the inherent innovation of the paper consists in providing an interpretation of the railway station as a driving force for the requalification of the surrounding building and social fabric, rather than as a mere infrastructural element of the railway network, or a node of the transport system. Moreover, this fabric would be hardly involved in ecological transformation policies in a short period. One-off measures, such as tax reliefs for building refurbishments, or incentives for building envelope renovations, can be at most limited levers, as long as their benefit is not defused by excessive fragmentation—or rather, atomization—in terms of procedures and implementation.

In the last 20 months, the issues related to the containment of the Cov-Sars-2 pandemic have also sensitized the debate on the economic impact of mobility and infrastructures. An effective ecological transition cannot be merely linked to decarbonization: the problem has a wider dimension in terms of system dynamics (Connolly et al. 2014), which requires surpassing micro-marginalist approaches. The positive effects of small actions, even when performed at larger scales (the system of incentives or tax reliefs) are nullified by the inertia of climate change; instead, discontinuities must be overcome through complex and onerous actions.

This is an important course of action, which benefits infrastructural investments and favors urban ecological

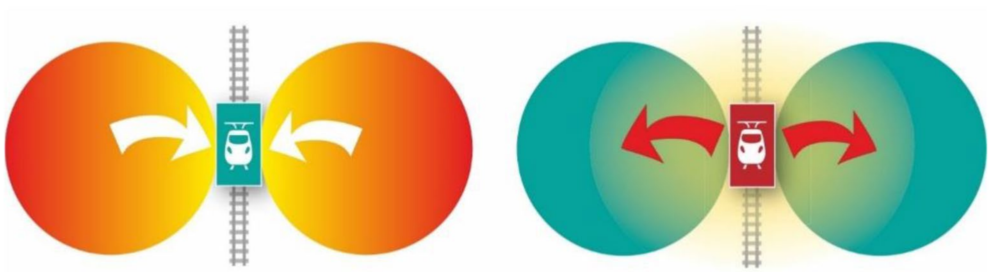

Fig. 16 According to the traditional approach, the stations adapt to the urban context; the Blue Station is an active element for the improvement of the surrounding urban environment

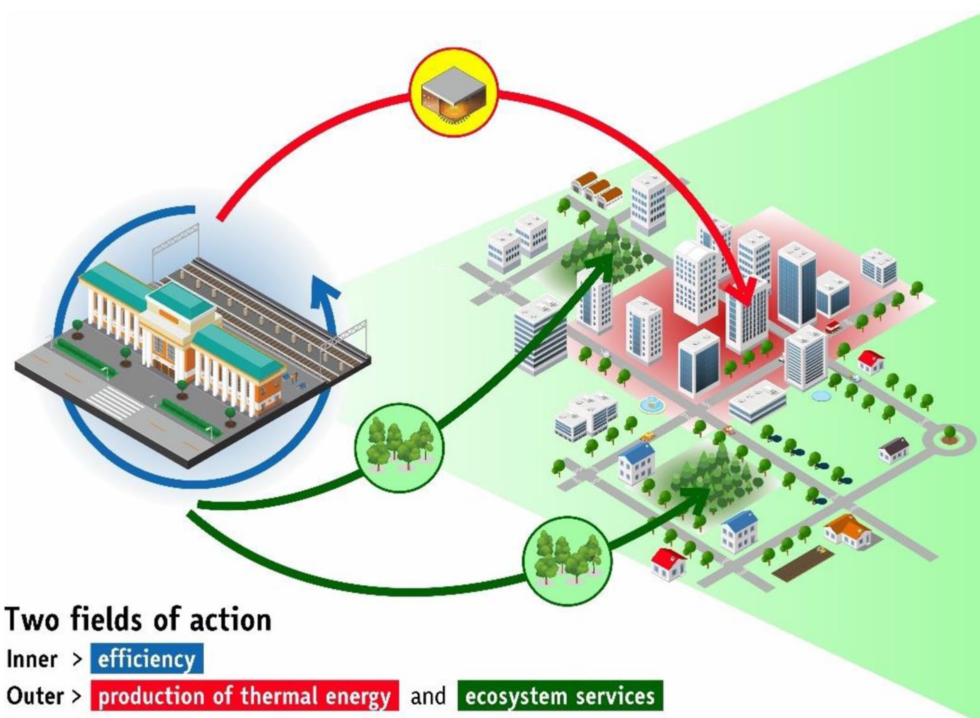

Fig. 17 Schematization of the city-station interaction in the *Blue Station* model

transition by starting from large function containers such as railway stations.

Working on the case study, an opportunity emerged to discuss the proposed method with RFI, the owner company of the Italian railway network and stations, and SNCF, its French homologous. The method resulted particularly interesting, despite the abundance of operational difficulties in developing the "Blue Station" for the railway context. Due to their complexity, these issues will be focused on in a future publication; only a brief outline will be provided here. Concerning procedures, a lack of application tools to allow railway organizations to deal directly with territorial planning has emerged. Unavoidably, this requires national coordination between the railway company and local authorities, establishing local partnership tools for the development of territorial-scale projects.

From a technical standpoint, the railway company is not even acknowledged with the additional role of energy supplier beyond the fulfillment of its needs. However, by their own nature, railways are network services; for this reason, they are "naturally" responsible for moving energy flows in addition to people.

The challenge for the next years is to transpose the ambitious European and national goals to every person's daily needs. Concerning single housing units,

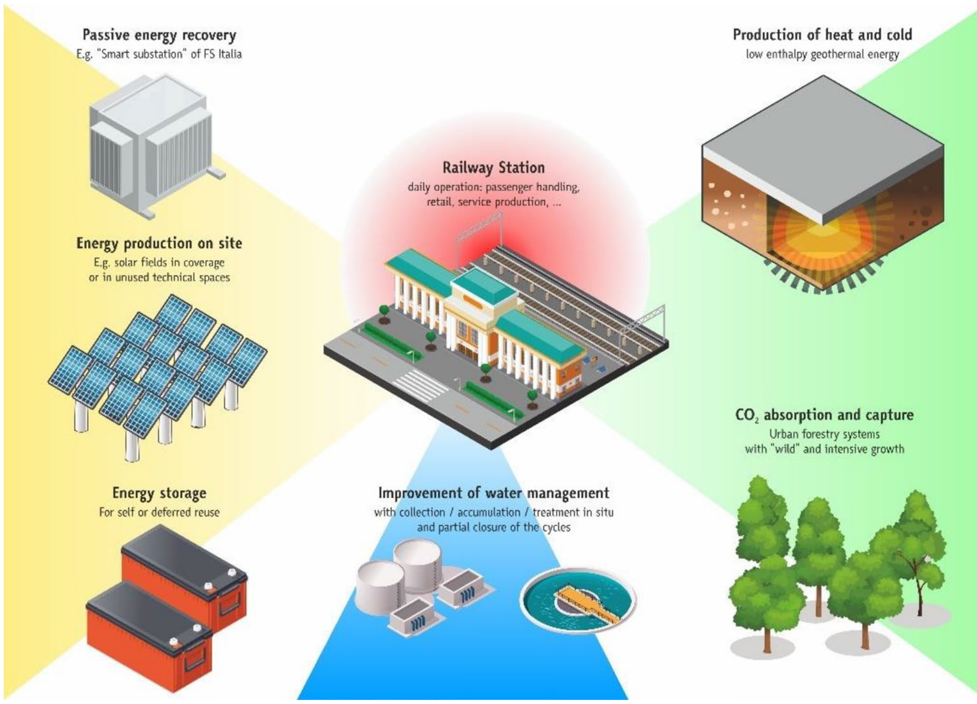

Fig. 18 *Blue Station* model: sustainability action wedges

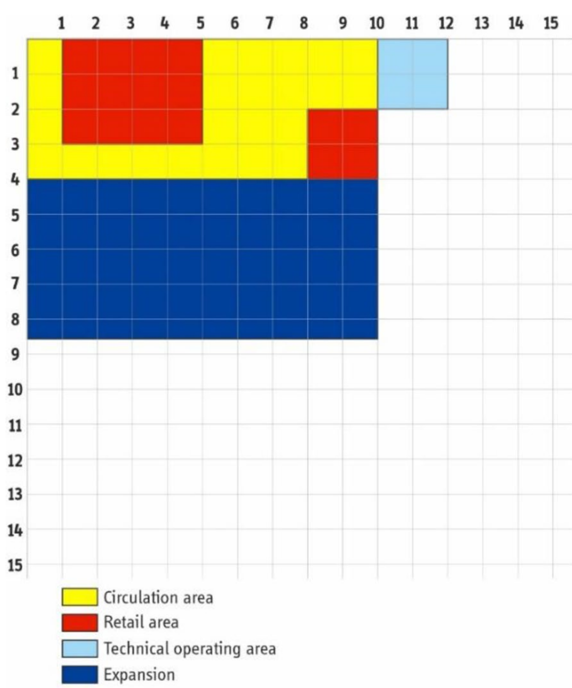

Fig. 19 Usable area requirement for a small *Blue Station*

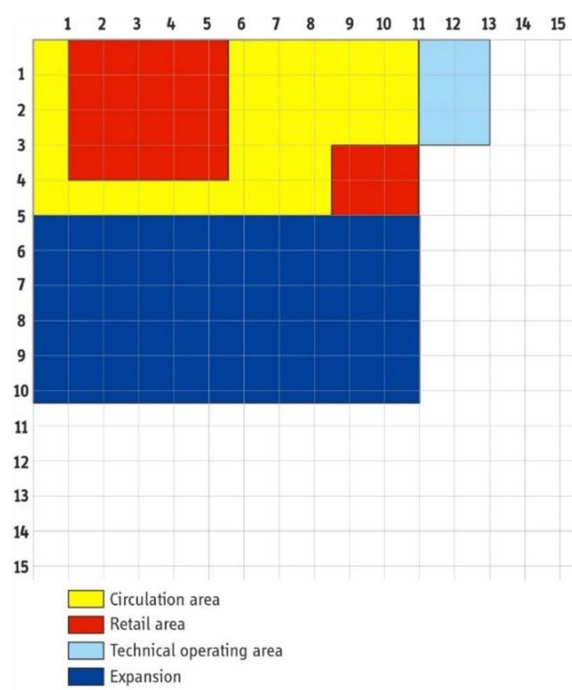

Fig. 20 Usable area requirement for a medium *Blue Station*

ecological transition—hence, intended as more than the simple reduction/compensation of direct and indirect climate-altering emissions—requires spaces that are not compatible with those available in urban apartment blocks and large condominiums. A classic solar panel for balconies, whose commercial value is around 700 euros,

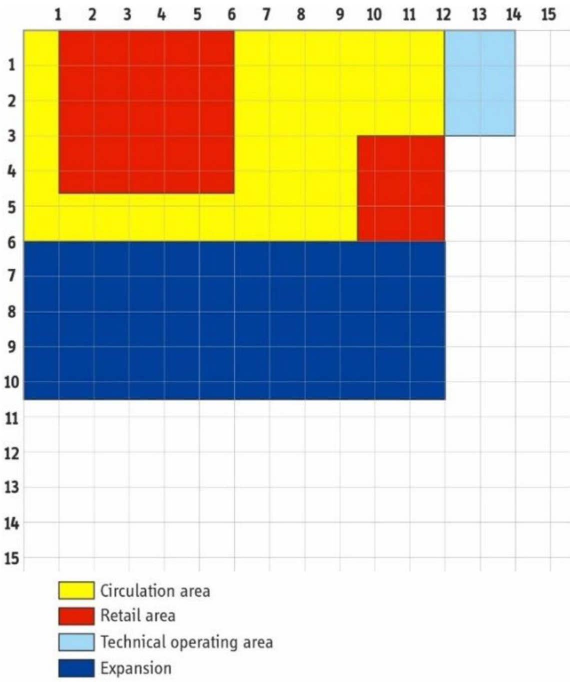

Fig. 21 Usable area requirement for a large *Blue Station*

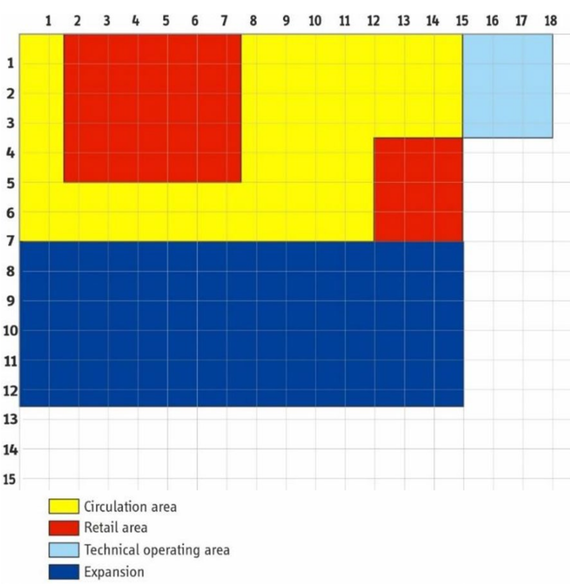

Fig. 22 Usable area requirement for an extra-large *Blue Station*

Fig. 23 Compensatory urban forest size as a function of station size according to the *Blue-Station* paradigm

is 150 cm wide and 100 cm high, and produces a useful power output of 300 W; to achieve a total of 3 kW, a surface of 19 m^2 per residential unit would be required. To maximize the use of available spaces (roof; washhouses; underground rooms used for dismissed systems, such as the centralized kerosene furnace, when not reused for other purposes), it would be possible to recur to technologies with higher efficiency, if they can be scaled and articulated in an urban residential context. Hence, while neglecting micro-wind systems, concentrated solar plants and geothermal systems could be considered.

Higher system efficiency entails higher technological complexity; this type of solution cannot be presumed compatible with the available spaces and the regulatory requirements for health safety and protection of housing units and shared spaces.

On the one hand, for these technological solutions, feasibility for each housing unit, and, above all, standardized repeatability for each building are not obvious; on the other hand, a more impactive issue must be considered. Each technological intervention is subjected to increasing performance decay over time, which is tentatively cured by performing maintenance interventions and substituting damaged components when necessary and feasible. Obsolescence is compounded by a multitude of actions progressively reducing the performance effectiveness that led to adopting a specific technological intervention.

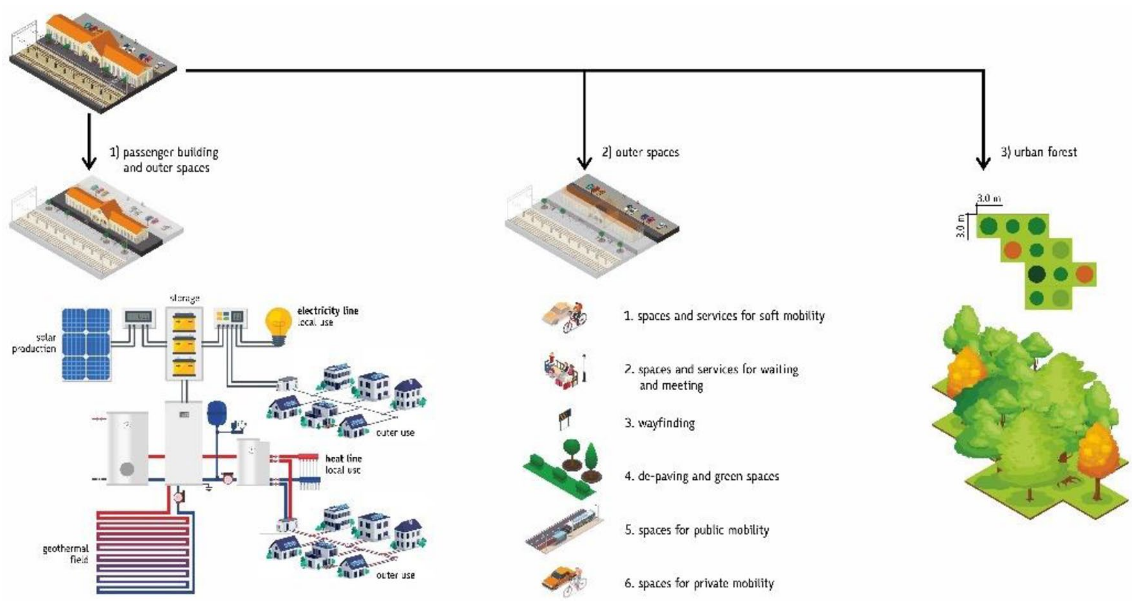

Fig. 24 *Blue Station* plant diagram

This occurs in a non-stationary context, which cannot be considered background noise, but instead induces a progression that mutates environmental targets: just think of the growth[13] of the concentration of climate-altering gas in the atmosphere or the progression of climate change.

Let Γ be the nominal cost of a meliorative technological intervention, let η_0 be its efficiency, equal to 100, and let χ be the nominal value of energy consumption reduction associated with it. When expanding this analysis to the whole life cycle of the products involved in the designed intervention, the gray energy to compensate is equal to χ_0; moreover, it is necessary to consider the effect on the real performances induced by the natural obsolescence curve of the design systems, which affects performance in a logarithmic trend. For a technological system whose average service life of Θ years, at the i-th year, its effective efficiency $\eta_{\psi,\iota}$ is:

$$\eta_{\psi,i} = \eta_0 - \ln(i+1)\left(\frac{\Theta}{2}\right)^{-1}$$

This performance decay can be compensated through extraordinary maintenance and substitution interventions, whose execution can be hypothetically set at the year $\frac{\Theta}{2}$, with an associated cost of $\frac{\Gamma}{\rho}$. ρ is between 5 (for minor interventions) and 2 (for major interventions). Also the technological components introduced through R substitutions with a χ_R value will be subjected to a progression of obsolescence, which will involve a minor time length (in this example, half of the service life of the systems, as we hypothesized concentrating interventions at the year $\frac{\Theta}{2}$) and will generate a share of gray energy to be compensated in the general economic balance.

Hence, the overall energy efficiency of the intervention at the i-th year is:

$$\eta_i = \eta_{A,i} + \eta_{R,i}$$

where $\eta_{A,i}$ is the general efficiency of the systems and $\eta_{R,i}$ is the efficiency of replaced components.

Considering obsolescence, global net efficiency is:

$$\eta'_i = \eta'_{A,i} + \eta'_{R,i} = \left(\eta_{A,i} - \eta_{\psi,i}\right) + \left(\eta_{R,i} - \eta_{\psi R,i}\right)$$

Instead, the gray energy to amortize at the i-th year is:

$$\varepsilon_i = \varepsilon_{A,i} + \varepsilon_{R,i}$$

where $\varepsilon_{A,i}$ is the gray energy of initial systems and $\varepsilon_{R,i}$ is the gray energy of the replaced components.

The net economic effect of the intervention is:

$$\chi'_i = \chi \cdot \eta'_{A,i} + \chi_R \cdot \eta'_{R,i}$$

However, this is affected by the natural progression of the environmental damage: concerning the accumulation of climate-altering gas in the atmosphere, the current growth velocity can be estimated as:

$$\Lambda_i = 1 + \ln(\alpha + 1) \cdot \beta$$

[13] See the weekly indicators of the Global Monitoring Laboratory in Mauna Loa (Hawaii): https://gml.noaa.gov/ccgg/trends/weekly.html.

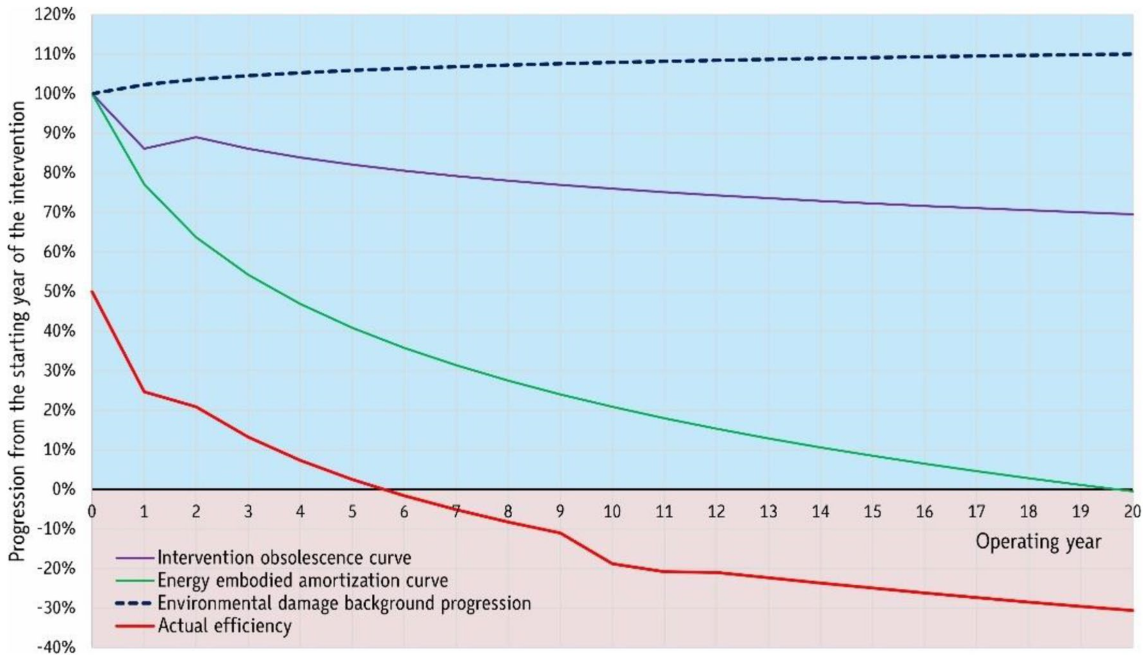

Fig. 25 Case 1: Small-scale energy improvement plant project, nominal and real progression of the benefits in terms of effective reduction of the climate-changing impact

with $\alpha = 1$ e $\beta = \frac{1}{30}$. Hence, the final economic effect of the designed technological intervention at the *i*-th is:

$$\chi'_{\Lambda,i} = \chi'_i - (1 - \Lambda_i)$$

Certainly, $\chi'_{\Lambda,i} < \chi$ applies, where the latter is the target nominal consumption reduction, associated with the circadian impact.

Reflecting on a small-scale intervention, such as the purchase of a heat pump for an apartment, when examining the overall effects on the general impact of the activities of the family living in the apartment, the final reduction of climate-altering emissions can be quantified as 10%. Considering the amortization of the gray energy of the system and its substituted components, performance decay due to obsolescence, and the progression of the accumulation of climate-altering gas in the atmosphere (which should produce a progressive updating of performance targets), the resulting net efficiency is $\chi'_{\Lambda,i} > 0$. In other words, rather than a reduction of externalities with respect to the Zero scenario, the outcome is a slight yet progressive negative impact (Fig. 25).

When considering a large-scale intervention, such as the adoption of a *zoned* district heating system, despite gray energy amortization and performance decay due to obsolescence and the general deterioration of environmental conditions, net efficiency is $\chi'_{\Lambda,i} < 0$; that is, there is a reduction of externalities with respect to the Zero scenario (Fig. 26).

Transposing the ecological transition to the urban scale will unavoidably result in failure (as occurred with heating automation) when operating on single buildings, or, worse, on single housing units. It is not a matter of adding an ETICS or incentivizing the substitution of boilers or air conditioners: despite being necessary, these actions are only a part of a significantly complex problem, which cannot be partitioned at the individual scale. This is because the variables into play, analyzing the contribution that each housing unit produces in its life cycle, are so significant to waste the highest effort, that is, complete substitution (demolition-reconstruction, when feasible) (Fig. 27).

Instead, transposing this approach to railway stations and other urban infrastructure—proceeding from the largest to the local ones, progressively—a complete transition of entire urban sector can be realized, progressively covering the whole urban area. From railway stations to urban sites for energy production (such as solar, wind, geothermal fields), it is possible to create energetically and thermally integrated urban islands. They can be interconnected, on turn, by a main network, to cover the whole urban area through subsequent network expansions (in a perspective of ecological transition), where the following would be considered energy nodes in a broad sense:

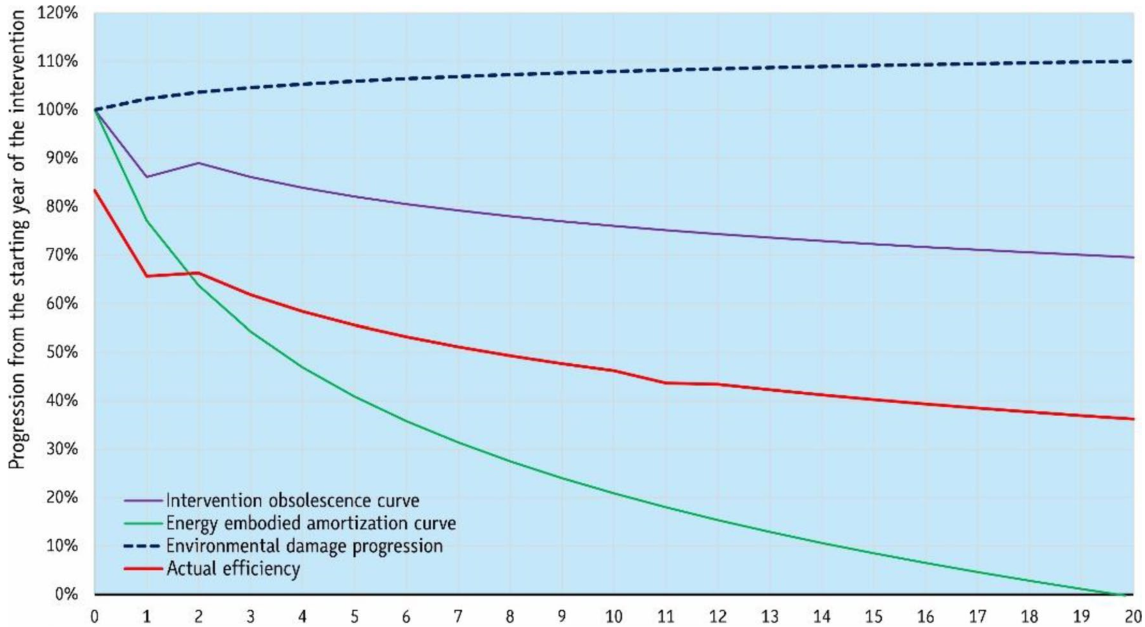

Fig. 26 Case 2: Large-scale energy improvement plant project, nominal and real progression of the benefits in terms of effective reduction of the climate-altering impact

- waste treatment plants;
- territorial health centers, excluding hospitals, whose complexity and cruciality prevents them from being make a network to support local healthcare units;
- school buildings;
- community facilities involved in the policies aimed at the realization of the so-called *15-min city*.

Future research lines, indeed, lie in the technical study of these new *neural* energy lines and their consequences on urban planning, concerning their potential for the transition toward the city of the future (Fig. 28).

Appendix: outline of the evaluation methodology

This section reports the outline of the calculations performed for the case study of the Tiburtina station in Rome. The following Table 13 summarizes the main dimensional and functional parameters (as of 2019) of the Tiburtina station.

In this analysis, only the impact of the daily operation of the station has been evaluated, without considering train movement. Hence, the following sources of energy and water needs are measured: lighting, elevation systems (escalators and elevators), sanitary systems, and preparation of retail food and drinks.

The energy demand for winter heating and summer cooling has been evaluated based on the degree days of the reference climatic zone. Specifically, the city of Rome is in the climatic zone D: the degree day (DD) is a measurement unit for the estimation of the energy demand for the obtainment of a comfortable environment in the reference zone. It is the sum of the mean temperature increases required to reach the threshold of 20 °C for the indoor temperature, for all the days of a conventional heating period (Table 14).

Daily consumption is extended to the whole year by considering the following coefficients:

- Daily opening hours of the station: 5:00–00:00 (19)
- Annual opening days: 365

The following Table 15 shows the calculation parameters of the (direct and indirect) energy needs of Tiburtina station. The Table also reports the adopted unit coefficients for each item of consumption.

Concerning the HVAC system, the efficiency of a heat pump is measured by the COP—*Coefficient of Performance*, that is the ratio between the provided thermal energy and the consumed electric energy; the higher the COP, the more efficient is the machine (low consumption). If the COP value is equal to 3, the heat pump provides 3 kW of thermal energy to the conditioned space for each kW of electric energy; 1 of them is provided by consumed electric energy, and 2 are taken from the external environment. The following values have been assumed for the Tiburtina station:

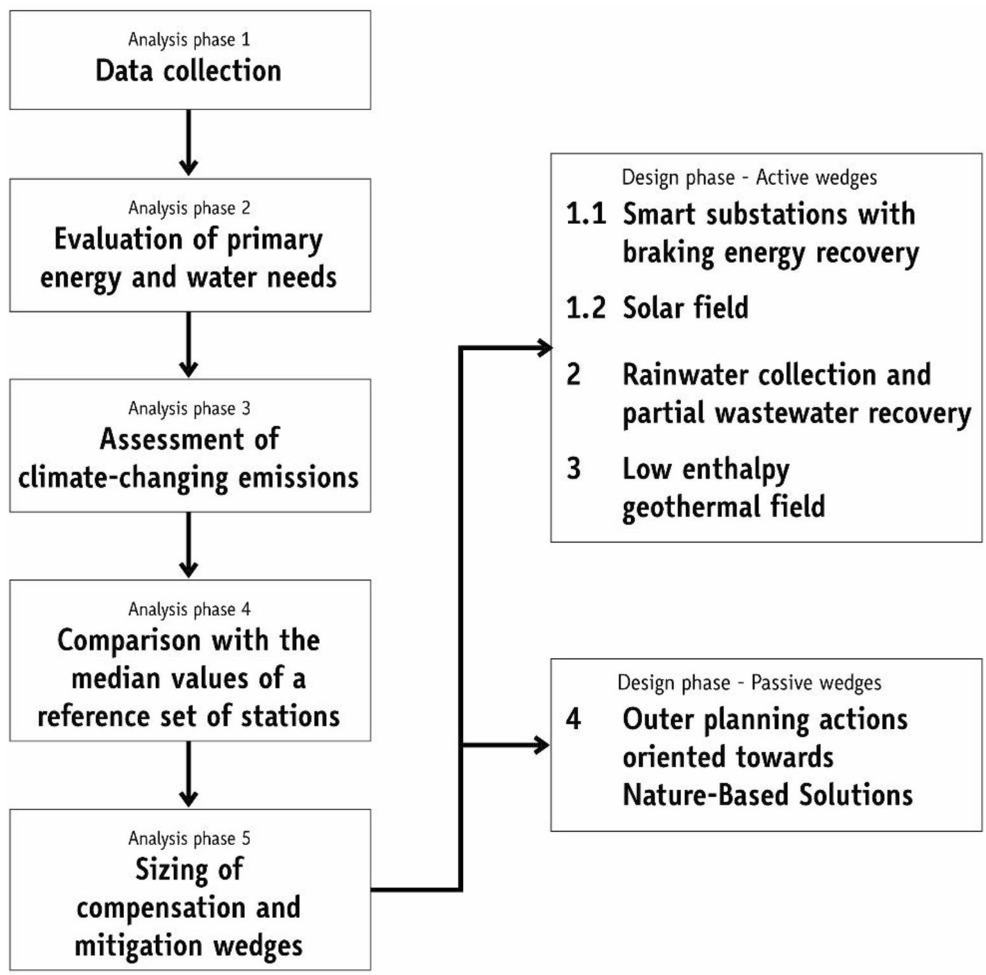

Fig. 27 Flow-chart of the *Blue Station* approach as a transposable analytical method

- COP = 3.00 for heating;
- COP = 2.50 for cooling.

The following hydric needs are considered:

- Sanitary use;
- Food;
- Cleaning and disinfection.

Two different hydric impacts are considered: in addition to the need itself, the remote energy impact on the water adduction system, and on the waste disposal and purification systems. Finally, the need for detergents and disinfectants for sanitary use and cleaning are considered: in this case as well, the accounted impacts are those related to production, use and remote impact related to final water purification (Table 16).

Concerning the electric system,[14] the following table shows the emission factors for electricity production and consumption (Sinanet/Ispra[15]) (Table 17).

The following total needs have been determined for the Tiburtina station (2019):

- Energy: 76,471,039 kWh, corresponding to 5,053 kWh/pax.
- Water: 371,190,471 l (371.190 m^3), equal to 24,52 l/pax.

[14] Si veda anche Enea: http://kilowattene.enea.it/KiloWattene-CO2-energia-primaria.html.

[15] Si veda: http://www.sinanet.isprambiente.it/it/sia-ispra/serie-storiche-emissioni/fattori-di-emissione-per-la-produzione-ed-il-consumo-di-energia-elettrica-in-italia/view.

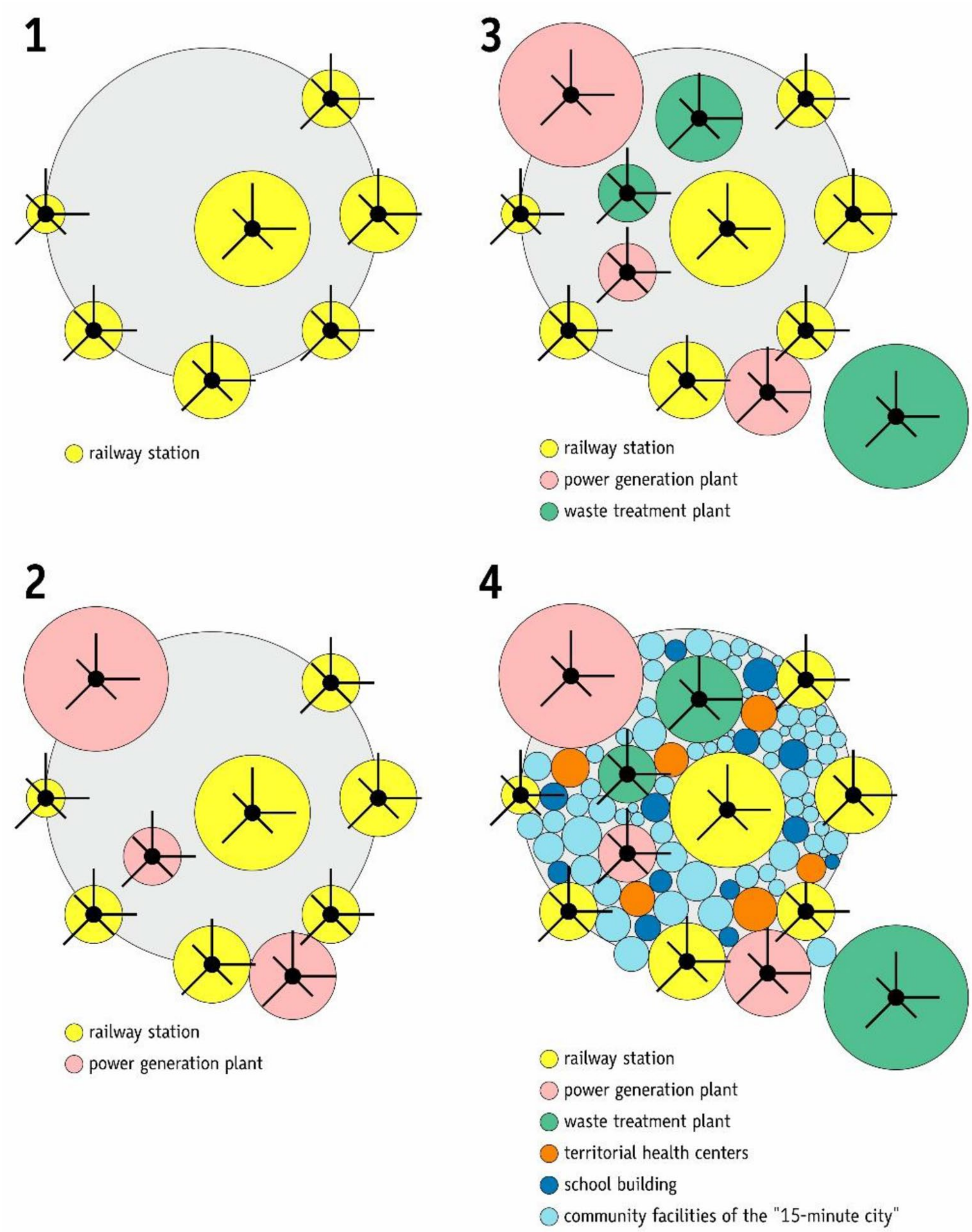

Fig. 28 Generalization of the *Blue Station* model to all city facilities for the creation of an integrated energy and heat network for the complete, measurable, and monitorable ecological transition of the entire building stock as a whole

65% of the energy demand of the station is related to the HVAC, that is heating, ventilation, and air conditioning: most is related to summer cooling (41% of the total), while heating consists in the 24% of the total. 22% is for the lighting, while the motive force of communication/elevation systems corresponds to the 4% (Figs. 29, 30).

Possible compensatory actions have been devised based on the following assumptions:

- operation and maintenance activities follow the *Best Available Techniques*;
- the waste and scrap materials produced in the daily operation of the station and during the activities performed inside it are properly collected and placed in the recycling chain, by at least 95%. The use of plastic

Table 13 Dimensional and functional parameters (as of 2019) of the Tiburtina station

Architecture		
Parameter	**Unit**	**Quantity**
Total area	m^2	157,540.00
Covered platforms and passenger subways (underpasses)	m^2	11,687.50
Connective spaces	m^2	14,614.70
Fully enclosed platforms	m^2	10,961.03
Pedestrian underpasses	m^2	2813.68
Waiting rooms	m^2	840.00
Ticket and luggage offices and counters	m^2	2040.80
Maintenance and repair bays	m^2	3354.70
Signal boxes, technical room	m^2	876.40
Retail area	m^2	14,560.00
Food area	m^2	4462.00
Food refrigeration systems	m^3	16.52
Administrative area, offices and services	m^2	27,173.90
Access tunnels	m^2	1155.00
Parking areas	m^2	6418.00
Net average height	m	4.20
Commercial units	N	49
Food & beverage units	N	17
Number of levels	N	4
Escalator	N	32
Lift	N	18
Employees	N	536
Transport data		
Parameter	**Unit**	**Quantity**
Tracks	N	19
Daily trains	N	485
Annual trains	N	160,050
Annual passengers	N	15,134,200
Environmental data		
Parameter	**Unit**	**Value**
Climatic zone	–	D
Degree day—heating	HDD	1,290.35
Degree day—cooling	CDD	887.15
Daily opening time	hours	19.00

is reduced to the minimum, and only when alternatives with highly recyclable materials (glass, paper, compostable derivatives) are not available.

The mitigation of the emissions produced by the station is only possible through the combined action of specific compensatory wedges. In turn, the implementation of these wedges is associated with a realization impact and an operational impact: in general, these impacts are compensated by the related benefits, with an overall positive balance. Specifically, each wedge is related to one of the following actions:

1. energy production for the partial fulfillment of daily energy needs;
2. rainwater collection for the partial fulfillment of daily water needs, and/or reduction of the volume of wastewater through partial recovery and reuse;

Table 14 Heating degree days (HDD), cooling degree days (CDD) and total degree days for the city of Rome

Month	T_{day}	T_{night}	T_{inner}	Days	D_{day}	D_{night}	DD	HDD	CDD	Total DD
January	11.1	4.0	18.0	31	9.33	14.67	319.9	319.9	0.0	319.9
February	12.5	4.7	18.0	28	10.37	13.63	246.6	246.6	0.0	246.6
March	15.3	6.9	18.0	31	11.58	12.42	176.6	176.6	0.0	176.6
April	18.6	9.4	18.0	30	13.22	10.78	40.0	40.0	0.0	40.0
May	23.2	13.1	20.0	31	14.35	9.65	−53.1	0.0	53.1	53.1
June	27.5	16.7	20.0	30	15.12	8.88	−191.2	0.0	191.2	191.2
July	30.5	19.2	20.0	31	14.45	9.55	−275.9	0.0	275.9	275.9
August	30.1	19.1	20.0	31	13.52	10.48	−247.2	0.0	247.2	247.2
September	26.6	16.6	20.0	30	12.31	11.69	−119.8	0.0	119.8	119.8
October	21.2	12.5	20.0	31	11.07	12.93	51.7	51.7	0.0	51.7
November	15.8	8.4	18.0	30	9.53	14.47	170.5	170.5	0.0	170.5
December	12.2	5.3	18.0	31	9.13	14.87	285.2	285.2	0.0	285.2
Year	20.4	11.3		365				1290.3	887.1	2177.5

The heating requirement, for a winter day, is represented by the difference between the external temperature and the reference average internal temperature (18°); HDD is the sum of these offsets for all days of the year. Similarly, CDD is the sum of the daily summer differences between the external and internal reference temperatures (20°). DD is the sum of the absolute values of HDD and CDD

Table 15 Calculation of (direct and indirect) energy needs of the Tiburtina station

Energy consumption			
Parameter	**Unit value**		**Quantity**
Administrative area, offices and services		m^2	27,173.90
Spaces open to the public—shops, food & beverage		m^2	19,022.00
Spaces open to the public—connective spaces		m^2	14,614.70
Covered platforms and passenger subways (underpasses)	00054	kWh/m^2	547,305.90
Connective spaces	0.0108	kWh/m^2	820,958.85
Ticket and luggage offices and counters	0.0162	kWh/m^2	229,277.76
Maintenance and repair bays	0.0162	kWh/m^2	376,890.48
Signal boxes, technical room	0.0108	kWh/m^2	65,640.61
Retail area	0.0810	kWh/m^2	8,178,861.60
Food area	0.0540	kWh/m^2	1,670,974.38
Administrative area, offices, and services	0.0243	kWh/m^2	4,579,359.21
Access tunnels	0.0027	kWh/m^2	21,626.80
Parking areas	0.0005	kWh/m^2	10,119.90
Escalator	1.75	kWh/pc. /day	388,360.00
Lift	0.23	kWh/trip	516,454.58
Food refrigeration systems	1,500.00	$kWh/m^3/year$	24,786.00
Heating demand	309.68	kWh_H/m^3	55,112,195.81
COP heating	–	–	3.00
Cooling demand	532.29	kWh_C/m^3	78,010,834.19
COP cooling	–	–	2.50
Water collection, transportation, and handling	0.0080	kWh/l	2,969,524
Wastewater treatment	0.0175	kWh/l	6,495,833
Energy consumption		kWh	76,471,039

Table 16 Evaluation of the (direct and indirect) hydric need of the Tiburtina station

Water consumption	Unit value		Quantity
Sanitation—employees	12,100.00	l/pc./year	6,479,550
Sanitation—passengers	21.43	l/pc	324,304,286
Food & beverage	0.24	l/pax	3,632,208
Cleaning—spaces open to the public	0.15	l/m²/day	2,529,226
Cleaning—spaces closed to the public	0.05	l/m²/day	266,718
Water consumption		l	337,211,988
Cleaning—detergents for crockery and cutlery	1.25	l/100 pax	189,178
Cleaning—detergents for people	0.50	l/100 pax	10,810
Cleaning—detergents for surfaces	1.00	l/ 500 m²	139,797
Detergents consumption		l	339,785
Equivalent water consumption		l	371,190,471
CO2 equivalent emissions per kWh	276.3	t/GWh	44,213.3
CO2 equivalent emissions per detergents production	5,000.0	t/Ml	1698.9
CO2 equivalent emissions		t/year	45,912.2

Table 17 Emission factors for electricity production and consumption in Italy (preliminary estimates 2019, source: Sinanet/Ispra)

Year	Gross thermo-electric production (only fossil fuels)	Gross thermo-electric production[1]	Gross electric production[2]	Gross electric production and heating[2,3]	Electric consumptions
2005	582.6	571.4	485.0	447.4	464.7
2010	544.8	522.4	403.0	378.2	388.6
2011	546.6	520.6	394.3	366.5	377.8
2012	560.6	528.4	385.3	359.9	372.9
2013	554.0	504.7	337.0	316.6	326.4
2014	573.3	512.1	323.2	303.4	308.8
2015	542.6	487.7	331.6	311.8	314.2
2016	516.3	465.6	321.3	303.4	313.1
2017	491.0	445.4	316.4	298.8	308.1
2018	493.8	444.4	296.5	281.4	281.4
2019	*473.3*	*426.8*	*284.5*	*273.3*	*276.3*

Values in g CO_2/kWh

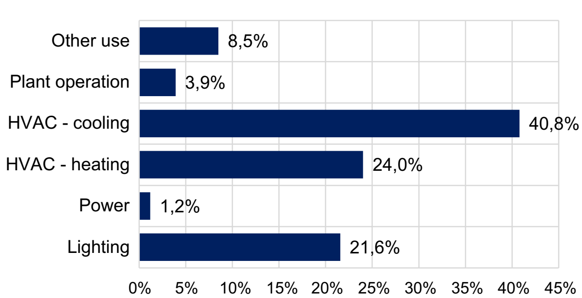

Fig. 29 Roma Tiburtina station, subdivision of the energy demand into macro-items

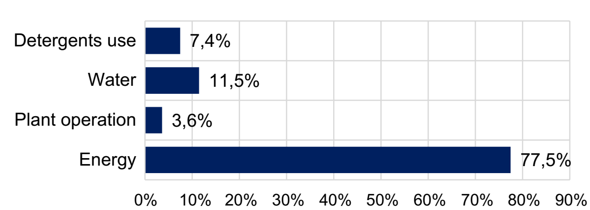

Fig. 30 Roma Tiburtina station, subdivision of climate-altering emissions into functional items

3. in situ combined heat (and possibly energy) production to reduce the overall energy need for heating and cooling;
4. compensatory absorption of the CO_2 released into the atmosphere through intensive urban planting.

Two scenarios have been defined: the medium and the optimal one, differing in terms of investments and active benefits on final climate-altering emissions. The fourth wedge, intensive urban planting, is a passive measure, chosen to absorb the residual impact that cannot be reduced by the other measures. The proposed actions are evaluated in terms of technical feasibility and economic sustainability in relation to the peculiarities and the specific needs of a railway station.

Medium scenario

The scenario is characterized by the following actions:

- Wedge 1.1: Regenerative braking of incoming trains, for energy recovery and storage for local use
- Wedge 1.2: installation of a solar field for energy production
- Wedge 2.1: rainwater collection
- Wedge 2.2: partial gray water recovery
- Wedge 4: urban planting

The creation of an intensive urban forest has been considered a compensatory measure of the ecological footprint related to the operation of the Tiburtina Station,. The impact is weighed over a 30-year period, in which the overall CO2 absorption of the tree growth is assessed. As regards the annual footprint of the station operation:

- The annual passenger volume is considered constant;
- When evaluating the emission coefficient for electricity production, the improvement related to the reduction of the footprint induced by energy consumption has been considered;
- The footprint induced by water consumption is considered constant.

Regarding the evolution of the emission coefficient of the primary electricity supply in the business-as-usual (BAU) scenario, the European Commission's 2016 EU Reference Scenario (Primes[16]) has been referred to. The report tracks the progression of the electricity production mix and the emission coefficients in terms of partial and aggregate climate-altering gases.

[16] https://ec.europa.eu/energy/data-analysis/energy-modelling/eu-reference-scenario-2016_en.

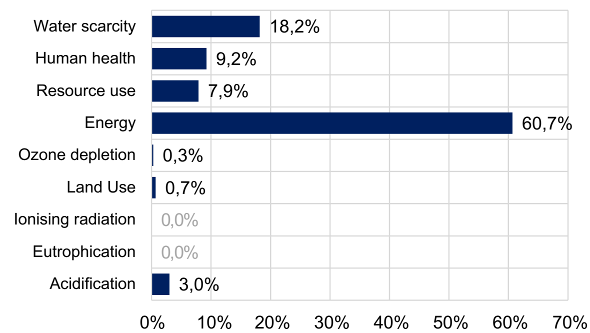

Fig. 31 Roma Tiburtina station, subdivision of the ecological footprint into the main impact categories

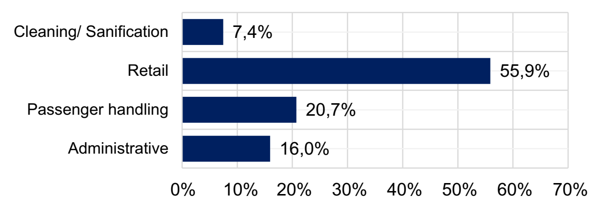

Fig. 32 Roma Tiburtina station, subdivision of the ecological footprint into the main operation categories of the system

Table 18 Medium scenario: Wedge 1.1 detailed calculations

Regenerative braking		
Battery footprint		
Construction	4.18E−03	kWh/kWh
	2.31E−01	m^3/kWh
Use	4.00E−04	kWh/kWh
	1.43E−04	m^3/kWh
Incoming cruise energy	392.01	kWh/train
Recovery capacity	58.80	kWh/train
Daily train	235	
Daily capacity	13,818.27	kWh
Accumulation capacity	13,000.00	kWh
Gross cost of the plant	3,250,000.00	Euro
Average service life	10	years
Footprint/year		
	1905.33	kWh
	978.84	m^3
Net production		
	4,031,344.67	kWh
	− 978.84	m^3
Wedge effect on the balance		
	94.7%	Energy
	100.3%	Water
	96.1%	Total

Table 19 Medium scenario: Wedge 1.2 detailed calculations—1

On-site production with solar panels		
1. Footprint		
Panels		
Construction	1250.0	kWh/m^2
	12.012	m^3/kWp
Use	0.8	kWh/m^2
	0.472	m^3/kWp
Battery		
Construction	4.18E−03	kWh/kWh
	2.31E−01	m^3/kWh
Use	4.00E−04	kWh/kWh
	1.43E−02	m^3/kWh
2. Available area	15,000.00	m^2
3. Annual production per kW peak	1242.00	kWh/kWp
4. Solar radiation	1687.00	kWh/m^2
5. Plant power	2727.27	kWp
6. Annual production	3,217,909.09	kWh
Gross cost of the plant	9,646,118	Eur
Materials	4,090,909	
Supports	600,000	
Inverter	954,545	
Battery	1,763,238	
Design	555,652	7.50%
Works supervision, testing assistance	370,435	5,00%
Testing	162,991	2.20%
Safety charges not included in unit costs	259,304	3.50%
Surveys, assessments and investigations	148,174	2.00%
Connection to the grid	370,435	5.00%
Unforeseen costs	370,435	5.00%
Average service life	25	years
Footprint/year		
	761,911.65	kWh
	2379.00	m^3

Table 20 Medium scenario: Wedge 1.2 detailed calculations—2

On-site production with solar panels. Net production		
	2,455,997.44	kWh
	− 2379.00	m^3
Wedge effect on the balance		
	96.79%	Energy
	100.6%	Water
	97.8%	Total

The total production of CO2 equivalent to be compensated amounts to 522,284 tons: 74% of these are related to direct and indirect electricity needs, 26% to direct or induced water needs.

Table 21 Medium scenario: Wedge 2 detailed calculations

Rainwater collection and partial gray water recovery		
Hydraulic plant sizing		
Construction	337.50	kWh/m^3
	4.20E−01	m^3/m^3
Use	2.78	kWh/m^3
	1.18E−04	m^3/m^3
Accumulation capacity	500.00	m^3
Gross cost of the plant	40,000.00	Eur
Average service life	15	years
Footprint/year		
	87,976.65	kWh
	14.01	m^3
Net production		
	− 87,976.65	kWh
	155,139.01	m^3
Wedge effect on the balance		
	100.12%	Energy
	58.2%	Water
	89.4%	Total

Table 22 Compensation of urban forests for each native species, considering a 4 × 4 m foliage area

Tree species	Captured CO_2 kg/pc	Total trees needed
Acer campestre	2720	84,532
Fraxinus ornus	2392	96,123
Gingko biloba	4056	56,688
Morus alba	2392	96,123
Quercus cerris	4000	57,481
Tilia platyphyllos	4056	56,688
Ulmus minor	4056	56,688
Mean	3382	72,046
Required urban forest area	1,152,737	m^2
	115	ha

	Energy	Water
Total CO2 tons	388,543.39	133,740.27
	74.4%	25.6%
	522,283.66	

Concerning active mitigation actions, the scenario envisages a plant investment of 12.936 million euros, leading to a reduction of approximately 9% of the overall energy requirement and 41% of the water requirement (Figs. 31, 32; Tables 18, 19, 20, 21).

Table 23 Optimal scenario: Wedge 1.1 detailed calculations

Regenerative braking		
Battery footprint		
Construction	4.18E–03	kWh/kWh
	2.31E–01	m^3/kWh
Use	4.00E–04	kWh/kWh
	1.43E–04	m^3/kWh
Incoming cruise energy	392.01	kWh/train
Recovery capacity	58.80	kWh/train
Daily train	235	
Daily capacity	13,818.27	kWh
Accumulation capacity	13,000.00	kWh
Gross cost of the plant	3,250,000.00	Eur
Average service life	10	years
Footprint/year		
	1905.33	kWh
	978.84	m^3
Net production		
	4,031,344.67	kWh
	– 978.84	m^3
Wedge effect on the balance		
	94.7%	Energy
	100.3%	Water
	96.1%	Total

Optimal scenario

As in the previous scenario, the total production of CO2 equivalent to be compensated amounts to 522,284 tons, 74% of which correspond to direct and indirect electricity needs, and 26% to direct or induced water needs.

	Energy	**Water**
Total of CO2 tons	388,543.39	133,740.27
	74.4%	25.6%
	522,283.66	

For active mitigation actions, the scenario envisages a plant investment of 17.570 million euros for a 65% reduction in the total energy needs and 33% in water needs.

Investment cost	17,570,002.56	Eur
Total effect of the wedges on the balance		
	35.91%	Energy
	67.6%	Water
	44.0%	Total

The compensatory burden on the passive absorption measure of urban planting drops to 28%. The compensation is based on the absorption coefficients of some native species over 30 years on the Ibimet-CNR parameters as part of the GAIA-urban forestation project (Table 22).

Table 24 Optimal scenario: Wedge 1.2 detailed calculations—1

On-site production via solar panels		
1. Footprint		
Panels		
Construction	1,250.0	kWh/m^2
	12.012	m^3/kWp
Use	0.8	kWh/m^2
	0.472	m^3/kWp
Battery		
Construction	4.18E–03	kWh/kWh
	2.31E–01	m^3/kWh
Use	4.00E–04	kWh/kWh
	1.43E–02	m^3/kWh
2. Available area	15,000.00	m^2
3. Annual production per kW peak	1,242.00	kWh/kWp
4. Solar radiation	1,687.00	kWh/m^2
5. Plant power	2,727.27	kWp
Annual production	3,217,909.09	kWh
Gross cost of the plant	9,646,118	Eur
Materials	4,090,909	
Supports	600,000	
Inverter	954,545	
Battery	1,763,238	
Design	555,652	7.50%
Works supervision, testing assistance	370,435	5.00%
Testing	162,991	2.20%
Safety charges not included in unit costs	259,304	3.50%
Surveys, assessments, and investigations	148,174	2.00%
Connection to the grid	370,435	5.00%
Unforeseen costs	370,435	5.00%
Average service life	25	years
Footprint/year		
	761,911.65	kWh
	2.37900	m^3

Table 25 Optimal scenario: Wedge 1.2 detailed calculations—2

On-site production via solar panels. Net production		
	2.455.997,44	kWh
	– 2.379,00	m^3
Wedge effect on the balance		
	96.79%	Energy
	100.6%	Water
	97.8%	Total

Table 26 Optimal scenario: Wedge 2 detailed calculations

Rainwater collection and partial grey water recovery		
Hydraulic system footprint		
Construction	337.50	kWh/m^3
	4.20E−01	m^3/m^3
Use	2.78	kWh/m^3
	1.18E−04	m^3/m^3
Accumulation capacity	500.00	m^3
Gross cost of the plant	40,000.00	Eur
Average service life	15	years
Footprint/year		
	87,976.65	kWh
	14.01	m^3
Net production		
	−87,976.65	kWh
	155,139.01	m^3
Wedge effect on the balance		
	100.12%	Energy
	58.2%	Water
	89.4%	Total

The urban planting requirement to reach a break-even of the overall emissions induced by the operation of Tiburtina station over a period of 30 years consists of 72 thousand tree species, corresponding to a total area of 115 hectares. The urban forest must be intended as a partially usable naturalized area: only in this way, it can produce the desired compensatory effect and absorb the estimated quantity of CO2. Any change in the natural physiology would lead to the alteration of the growth kinematics; in the worst case, it could also worsen the health of trees, reducing their size or causing their premature death.

The following Tables 23 show the detailed calculations for each of the active compensation wedges considered in this second (optimal) scenario (Tables 24, 25, 26, 27, 28).

Compensatory urban forest sizing

Two scenarios have been individuated for compensatory urban forestation, depending on whether interventions are performed on system efficiency (especially air conditioning) and building envelope performance. Figure 28 reports the two cases: in the case of system optimization, the required urban forest has an extension of 30 ha, consisting of 35,000 trees. Instead, the full compensation for the station operation without system optimization requires 65 ha and 75,000 trees (Figs. 33, 34).

Table 27 Optimal scenario: Wedge 3 detailed calculations—1

Geothermal probes		
1. Footprint		
Probes		
Construction	2.3200	kWh/m
	24,378	m^3/m
Use	1747	kWh/m
	0472	m^3/m
Storage tank/boiler		
Construction	418E−03	kWh/m^3
	127E−01	m^3/m^3
Use	400E−04	kWh/m^3
	787E−03	m^3/m^3
2. Reference area	33.63670	m^2
3. Thermal needs	3.36367	kW
4. Geothermal power	1.68184	kW
5. Drilling depth	12,000	m
6. Number of 4-pipes probes	140	
7. Storage tank/boiler	84.000	l
Annual production	44.198.62380	kWh
Gross cost of the plant	4.633.885	Eur
Drilling	1.512.000	
Installation and cementation of the probes	504.000	
Heat pump	1.513.652	
Storage tank/boiler	29.400	
Design	266.929	7.50%
Works supervision, testing assistance	177.953	5.00%
Testing	78.299	2.20%
Safety charges not included in unit costs	124.567	3.50%
Surveys, assessments and investigations	71.181	2.00%
Connection to the grid	177.953	5.00%
Unforeseen costs	177.953	5.00%
Average service life	25	years
Footprint/year		
	1.588.390,31	kWh
	31.482,32	m^3

Table 28 Optimal scenario: Wedge 3 detailed calculations—2

Geothermal probes. Net production		
	42.610.23349	kWh
	−31.48232	m^3
Wedge effect on the balance		
	44.28%	Energy
	108.5%	Water
	60.7%	Total

Fig. 33 Roma Tiburtina station, compensatory urban forest sizing

Discussion

The analysis has been aimed at identifying a multi-action strategy intended to the complete compensation of the climate-altering emissions produced, directly and indirectly, net of railway movement, by Tiburtina station in Rome. Two scenarios have been identified—a medium and an optimal one—differing by budget and achievable results.

The action outlined in the last two paragraphs can be grouped into three sets: by mediating between the minimum and maximum effectiveness values, it has been found that the optimization in terms of efficiency of the

Fig. 34 Compensatory urban forest sizing for Tiburtina station in the two individuated scenarios and representation on the Ecological Network Map of the Municipality of Rome. Source: Author's processing on the map of green areas in the Municipality of Rome)

station systems can offset about 13% of the emissions. The centralized production of thermal energy (both for heating and cooling, and for domestic hot water production) can offset up to 31% of emissions. The combination of all active compensatory measures can offset the 44%. The residual share can be compensated with passive measures, such as intensive urban (or suburban) forest planting. The analysis has been performed considering a 30-year period (2030–2050) and a business-as-usual (BAU) scenario, concerning the compensation for the production of primary electric energy.[17] The definition of the European strategy "climate-neutral Europe" is currently ongoing: it envisages the achievement of the full compensation (net-zero) of primary energy by 2050. In other words, primary energy will already be compensated, and consequently, the compensation of the operation of the railway station will be limited to the sole impacts of transformation cycles. Concerning the Tiburtina station, the reduction of emissions to be compensated would then be reduced by 55% (Table 29).

The analysis highlights some items, which could be generalized beyond the boundaries of the present case study:

1. the relevance of energy needs for heating/cooling (both in the BAU and in the Net-Zero scenarios);

[17] In the framework of the EU strategy, (https://ec.europa.eu/clima/policies/strategies/2050_en) the Italian national strategy has been published in February 2021: https://www.minambiente.it/sites/default/files/lts_gennaio_2021.pdf.

Table 29 Distribution of energy needs, and climate-altering emissions related to the operation of the Tiburtina station in the Net-Zero 2050 scenario, compared to the business-as-usual (BAU) scenario

Energy use	Value (kWh/year)	Rate (%)	Δ BAU (%)
Lighting	825.051	3.2	−95
Power	108.578	0.4	−88
HVAC—heating	5.511.220	21.6	−70
HVAC—cooling	12.481.733	48.8	−60
Plant operation	149.715	0.6	−95
Other use	6.495.833	25.4	0
Total	25.572.130		−67
CO_2 source	**Value (kWh/year)**	**Rate (%)**	**Δ BAU (%)**
Energy	5.91436	57.6	−67
Plant operation	41,37	0.4	−95
Water	2.61528	25.5	0
Detergents	1.69892	16.5	0
Total	10.26993		−55

2. the relevance of the impact of hydric consumption and detergents use: 19% of the total emissions in the BAU scenario, 42% in the Net-Zero.

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