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Green strategies for improving urban microclimate and air quality: A case study of an Italian industrial district and facility

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A B S T R A C T

Densely built areas are affected by higher air-pollutant concentrations, representing a significant risk to public health. At the same time, urban settlements have a remarkable environmental impact: cities are responsible for 70% of annual carbon emissions while buildings account for 37% of global energy and process emissions. Moreover, people living in urban areas are frequently exposed to extreme micro-climate conditions caused by the urban heat island effect, related to increased external air temperature and peculiarities of the built environment. Given this framework and considering the Sustainable Development Goals, it is necessary to point out some effective and strategical mitigation measures to ameliorate micro-climate conditions, reduce pollutants concentration and enhance building performance. This paper investigates the potential advantages of green roofs as retrofitting solutions and tree planting on several micro-climate parameters and particulate matter concentration, considering an industrial district located in Italy and using ENVI-met software. The influence of the extensive green roof on energy performance is further investigated at the building level recurring to Design Builder energy models. Results showed that an extensive green roof could reduce external air temperature by up to 1.5 °C, outer surface temperature by up to 15 °C and wind speed by 50% at roof level compared to current state conditions. The application of the green roof let also to achieve energy savings of 15% for both the summer and winter seasons. Focusing on the effect on particulate matter, intensive green roof solutions proved to be more efficient in capturing air pollutants.

1. Introduction

Nowadays, 55% of the world's population is currently living in urban areas and this ratio is set to grow up to 60% by 2050 [1]. At the same time, several criticalities can be detected when considering the urban environment under multiple aspects. According to the World Health Organisation (WHO), air pollution is one of the major environmental risks to public health [2]. Exposure to both indoor and outdoor polluted air causes 7 million deaths per year, including 500 000 only in Europe [3]. The most dangerous pollutants in the atmosphere are the particulate matter characterised by an extremely low aerodynamic diameter equal to or less than 10 μg (PM_{10}) and, even more critical, less than 2.5 μg ($PM_{2.5}$). These kinds of pollutants are largely related to vehicular traffic or conditioning systems [4] and, for this reason, are mainly registered in dense urban districts. Many authors demonstrated that medium to long-term exposure to this kind of atmospheric pollutant can cause several health diseases [5–8]. Given this context, other researchers suggested possible mitigation strategies to improve urban air quality. Green walls [9,10], vegetated roofs [11] and their combined application [12] were proved to be promising technological solutions in densely built urban districts. Following their introduction PM_{10}, $PM_{2.5}$ and N_{Ox} concentrations can be reduced by up to 70% due to dry deposition [13] and by 38% through active filtration mode [14]. By the way, the latter can significantly reduce the concentration of a wider range of pollutants when compared to the deposition mechanism [15] and, for this reason, many authors underline the importance of choosing the proper vegetation type to be used for vertical and horizontal greenery [13,16]. Considering a comparison between the possible technological solutions available at the building scale, some authors [17,18] highlight that green roofs perform better than green walls in improving urban air quality.

Even if to a lesser extent, also the urban layout and the meteorological conditions, have to be considered since they can affect the air-pollutant removal potential of greenery installation [19–21]. In this regard, Kandelan et al. [22] outline an air quality index correlated with both street canyons' orientation and configuration as well as with wind

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direction. With a similar approach, other researchers try to optimize the urban layout design to enhance particulate matter removal in both winter and summer seasons [21]. Tree planting as well is analysed as a green strategy to reduce outdoor air pollution in urban districts, with several studies suggesting considerable potential for air quality improvements. For instance, Motie et al. [23] demonstrate that deciduous trees can reduce air pollution by 67% during the summer season and by 54% in the winter months. He et al. [24] performed a parametrical analysis considering the morphological characteristics of different vegetation species to define the most influential parameter on $PM_{2.5}$ removal; they concluded that plants characterised by wider vegetation crowns result in less appreciable results. By contrast, Abhijith et al. [25] affirm that trees with highly porous crowns and low-stand density can effectively remove pollutants at the pedestrian level. Anyway, tree planting interventions should be carefully examined because under certain climate conditions, mainly related to poor ventilation, the presence of vegetation can represent a detrimental factor leading to a rise in pollutant concentrations [26].

As far as atmospheric pollutants are concerned, also greenhouse gas (GHG) emissions should not be underestimated because they negatively impact microclimate characteristics, contributing to rising external air temperature and detrimentally influencing global overheating. In this regard, it is worth highlighting that global warming could reach 2 °C by 2052 according to the report of the Intergovernmental Panel on Climate Change (IPCC) [27]. Consequently, such a rise in outdoor air temperature is going to significantly affect also building energy demand [28], that at global scale accounts for 34% of total final energy consumption and 37% of global energy and process emissions [29]. Focusing on the Italian context, according to National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) the National total primary energy demand is about 140 Mtep, still satisfied by natural gas for about 40% and related to the civilian use for 30% [30]. Since buildings are concentrated in urban settlements, cities have a dramatic environmental impact being nowadays responsible for 2/3 of global energy consumption and more than 70% of annual carbon emissions [31].

Given this context, it is necessary to point out some effective strategies to tackle the multiple open challenges, particularly urgent in urban settlements as stressed by the United Nations that include these topics in Sustainable Development Goals (SDGs) to be reached by the end of 2030. In particular, Goal 11 expressly refers to the development of sustainable cities and communities, while Goal 3 and Goal 13 are related to good health and wellbeing and climate action respectively.

Actions capable of mitigating climate change effects, enhancing at the same time human health and environmental conditions, in dense urban districts are therefore urgently requested.

A comprehensive study performed by Hou et al. [32] based on a massive analysis of Chinese megaregions over 17 cities, pointed out urban green factor, land surface albedo, urban morphology and level of human activities as environmental factor determinant for Urban Heat Island effect. The same topics are addressed in literature by researchers proposing mitigation strategies at different scales. Cui et al. [33] focus on optimizing urban layouts for residential districts evaluating different street aspect ratios and vegetation coverages for both summer and winter seasons. Other authors deal with albedo-related issues evaluating interventions to be implemented both in urban public spaces and at buildings' surface level. Rahman et al. [34] highlight the effectiveness and the growing diffusion in the last few years of cool pavement technologies, proposing a critical review. The same strategies are implemented by Battista et al. [35] concerning an urban square in Rome combining changes in the albedo of paving surfaces and the adoption of grass pavers. Morales-Inzunza et al. [36] analysed the currently available technologies in the field of cool materials, suggesting their potential in reducing UHI and in contributing to a substantial decarbonisation of the built environment. As a matter of fact, Wang et al. [37] remark on the effectiveness of cool roofs technological solutions in mitigating the impact of heat waves during summer in central Europe, using the Universal Thermal Climate Index (UTCI) as a reference parameter. In the same research green roof potential is also assessed, showing a positive contribution in reducing the duration of heavy heat stress conditions. The impact of summer heat waves can be also reduced by introducing a mix of grasslands, shrublands and mixed forests in the urban environment, as proved by Imran et al. [38] for Melbourne City. According to previous research, Marando et al. [39] pointed out that a tree coverage of at least 16% let to obtain a 1 °C drop in outdoor air temperature in an urban context and that vegetation introduction has to be promoted for cities in arid regions.

Hence, the implementation of Green Infrastructures can be considered one of the most effective mitigation strategies also concerning UHIs and can be adopted at both urban and building levels, recurring to green roofs and vegetated walls [40–43].

Koch et al. [40] pointed out that vertical greenery can be applied to lower the external air temperature at both building and street levels. Susca et al. [44] highlight that an extensive application of building integrated vegetation technologies (BIVT) can decrease urban warming, reducing air temperature by up to 1 °C. The same authors also focus on the effects that acting on external air temperature through the implementation of BIVTs can cause on buildings' heating and cooling energy demand. Afshari [45] concludes that building integrated vegetation can mitigate the UHI effect by about 16% decreasing cooling energy demand by about 25% at the same time. Following the previous research, Mazzeo et al. [46] evaluate green roof solutions' potential in reducing cooling demand as well as Mihalakakou et al. [47]. The latter assessed savings of up to 70% in cooling load because of the considerable reduction of indoor air temperature induced. Similar analyses were carried out by Bruno et al. [48], even if resulting in cooling energy savings of up to 38% following green roof installation.

It is worth highlighting that most of the studies available in the scientific literature are based on analyses of residential urban districts, while a substantial research gap considering industrial and manufacturing areas can be assessed. These districts are particularly critical because of several peculiarities such as the lack of green areas, the significant percentage of paved surfaces, the traffic of heavy load vehicles and the presence of pollutant sources related to production processes [49]. Studies in the literature related to industrial districts are mainly oriented to specific topics such as district heating solutions [50–52] and smart grids [53], pollutants distribution [54,55] and economy [56]. Moreover, considering the Italian context, the industrial building heritage is characterised by energy and structural issues connected to the old age of manufacturing facilities, their inadequate maintenance conditions and the energy systems installed. Sustainable redevelopment strategies to be adopted for the integrated requalification of these facilities show a considerable energy-saving potential and should be promoted within the perspective of the European goal for a climate-neutral economy to be reached within 2050. However, nowadays retrofitting interventions at building levels are evaluated and studied in the literature for different intended uses categories of facilities, but mainly addressing office, residential and educational ones [57–59]. Only a few research dealing with integrated retrofitting of industrial buildings can be found and the operational phase of these facilities, even if highly energy intensive, is usually underrated, usually paying more attention to production needs and activities. Considering the cited background, the paper aims at evaluating the impact of the introduction of green infrastructures in an industrial urban district located in Italy, focusing on the possible advantages at both urban and building levels in terms of microclimate conditions, air quality and energy demand. As already presented, the application of these mitigation strategies has been widely discussed for residential and office buildings in ordinary urban districts, but no studies were retrieved dealing with industrial districts and manufacturing facilities. The adoption of green roofs, both in extensive and intensive configuration, is considered in the paper as well as tree planting (evergreen type) in public external areas.

Green roofs were chosen instead of vegetated walls based on some evidence already available in the literature that let foresee better performance also considering the geometry and layout of typical manufacturing facilities. This kind of building is usually characterised by wide roof surfaces, much more relevant than external walls ones [60]. Moreover, the latter are usually made by heavy precast concrete panels whose behaviour under seismic actions is particularly critical [61,62] and the installation of green walls should be carefully evaluated not to increase dynamic loads. The introduction of tree species was preferred over flowerbeds implementation, which requires wider surface coverages, to preserve adequate manoeuvring areas for heavy vehicles. To evaluate the effects achievable on the energy demand at the building scale, an existing manufacturing building was selected for energy modelling and simulation procedures. The case study facility was selected following the results of a previous statistical review of the Italian existing industrial building stock carried out at the National [63] and regional scale: the building chosen is, therefore, representative of one of the most recurring typological variants in the Italian scenario, being widely adopted in northern Italy regions [64] and in some specific areas of Tuscany [49,65].

The research aims at demonstrating the influence of the cited mitigation strategies on micro-climate parameters, by considering the impact on UHI, air pollutants concentration and buildings' energy performance. As a final remark, the suitability of similar interventions in industrial urban contexts, where they are usually not foreseen, is investigated.

2. Materials and method

An Italian industrial district located in the Lombardy region is chosen as a case study to investigate the impact of some green mitigation strategies on micro-climate parameters, UHI, air pollutants concentration (PM_{10} and $PM_{2.5}$) and building energy performance. To evaluate the influence of green strategies at the urban level, the industrial district was modelled on the ENVI-met [66] environment and different parameters were evaluated: outdoor air temperature [°C] [67], mean radiant temperature [°C] [68], deposed mass of PM_{10} and $PM_{2.5}$ [$\mu g/m^2$], external surface temperature [°C] [69] and incoming and outcoming longwave radiation [W/m^2] at the building level. Aiming at investigating in detail the effects at the building scale due to the possible installation of a green roof, a representative facility was chosen and modelled in Design Builder [70] to evaluate its energy performance during both winter and summer seasons in terms of heat losses and gains, heating and cooling demand and surface temperature. For both district and building models, the results of the simulations obtained considering the existing condition were compared with the ones achievable after applying mitigation strategies. The methodology applied in the research is synthetised in Fig. 1.

2.1. Case study area

The industrial district studied is located in the Municipality of Caravaggio, in the province of Bergamo (Lombardy Region) in Northern Italy (Fig. 2). Caravaggio (111 m above sea level) is located in climate zone C (temperate climate) according to the Köppen classification and Italian climate zone E [71]; the main climate characteristics are illustrated in Table 1.

This manufacturing site was selected as a suitable case study because highly representative of most of the Italian industrial districts considering its urban layout, its dimensional data, and the typologies of industrial buildings here retrievable. Moreover, an accurate air quality monitoring campaign registering pollutants concentration and microclimate characteristics was carried out in this area by Lombardy Region [72]. The results of this on-field survey, easily accessible online, were useful to validate the environmental simulations carried out using ENVI-met in the following stages of the research.

As illustrated in Fig. 2, only the portion of the Caravaggio industrial district closer to the monitoring station was considered and it covers an area of about 86 100 m^2 hosting 23 industrial facilities. Buildings occupy 42% of the total site surface while public roads represent about 20% including a wide paved space for a parking lot in the northern portion. The lack of green areas typical of industrial settlements is particularly appreciable since only 5% of the total surface is hosting flower beds and only a few trees can be retraced. The main features of the case study area are illustrated in Table 2.

The selected sector is characterised by several urban canyons with different widths and lengths and a homogeneous set of manufacturing buildings with uniform shapes and heights. All these aspects are interesting features to be investigated in detail and deeper correlated to the evaluation of the microclimate characteristics [73]. 68% of the buildings are made of a single-story precast concrete structure with portal frames and precast-prestressed gable beams, referrable to a typological variant widely spread in Italy for buildings with production intended use. As usually registered also in other Italian regions, most of the industrial facilities of the district were built between the 80s and the 90s.

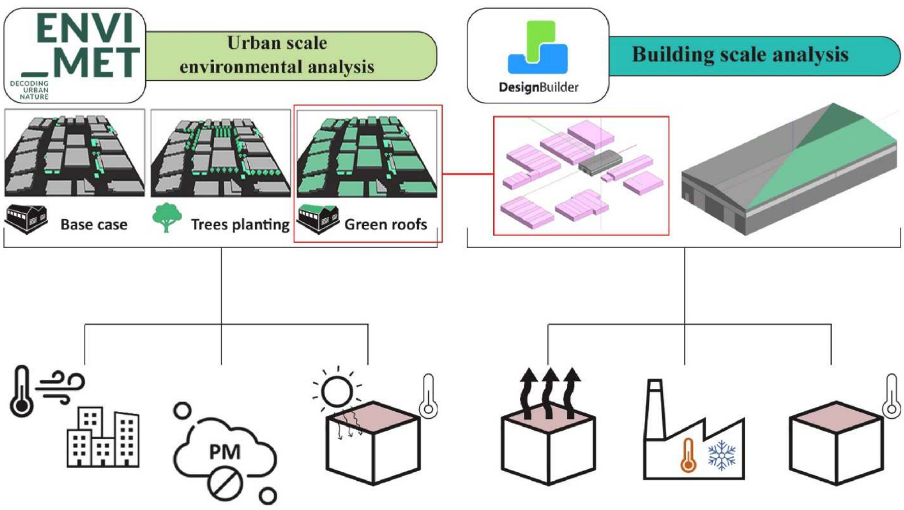

Fig. 1. Schematic overview of the research method.

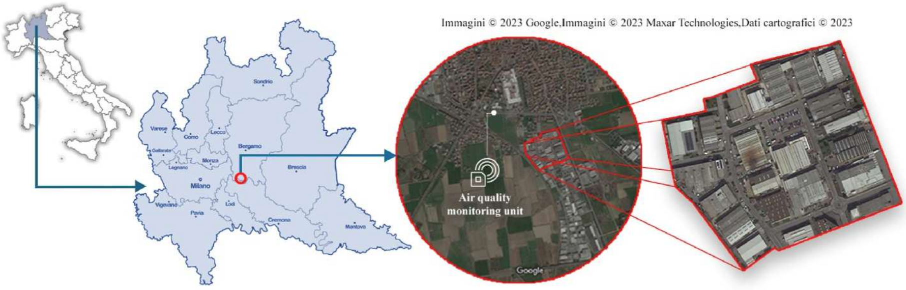

Fig. 2. Case study area overview. Monitoring unit position is highlighted.

Table 1
Climate data for simulations. In the table: HDD means heating degree day, GH stands for global horizontal radiation, Dh means diffuse radiation, Bn means direct normal radiation, Ta stands for air temperature, Td stands for dewpoint temperature and Ws means wind speed. The climate data are the annual means.

Latitude	Longitude	Climate zone	Heating period	HDD [K/d]	GH [kWh/m^{2}a]	Dh [kWh/m^{2}a]	Bn [kWh/m^{2}a]	Ta [°C]	Td [°C]	Ws [m/s]
45.29°N	9.38°E	E	15th/10–15th/04	2383	1123	630	916	14.4	8.8	2.0

Table 2
Main characteristics of the case study industrial district.

Site area [m^2]	Buildings footprint [m^2]	Green area [m^2]	Public roads [m^2]	Parking [m^2]	Private paved surface [m^2]	Number of trees
86 171	36 523	4133	22 902	3250	19 363	15

2.2. Case study building

To produce results of the research also at the building scale, a single facility was selected to be representative of the previously introduced typological variant. The latter, being widely adopted in the reference district chosen, was considered the most promising to be investigated in detail from a requalification perspective. Unfortunately, it was not possible to access the design data of the buildings located within the perimeter of the area selected and none of the companies hosted in the facilities allowed to carry out on-field surveys or to share information about the actual operational conditions. To overcome these limitations, and to guarantee validated results, a building located in the industrial district of Barberino di Mugello (Tuscany) was considered. Despite being in a different administrative region, the facility chosen shares the same constructive peculiarities and geometrical dimensions retrievable in most of the facilities in the Caravaggio industrial site as illustrated in Fig. 3. As highlighted in the same figure, both locations belong to the same climatic zone according to the Italian standard. This consideration was solidly confirmed by an extensive review of publications available in the literature that collect a considerable set of original design drawings for real Italian industrial buildings [63]. For the case study building chosen, detailed information, crucial to producing reliable energy models, was available: monthly energy bills, hourly occupation profiles and information about heating generators and distribution systems were obtained during previous data acquisition campaigns carried out by the authors, while technical details about building components were retrieved in original project documentation and drawings. The case study building, dating back to the 90s, is single-storey and characterised by a regular shape having planimetric dimensions of 23.50 m × 49 m. Nowadays the facility is hosting a company working in the light

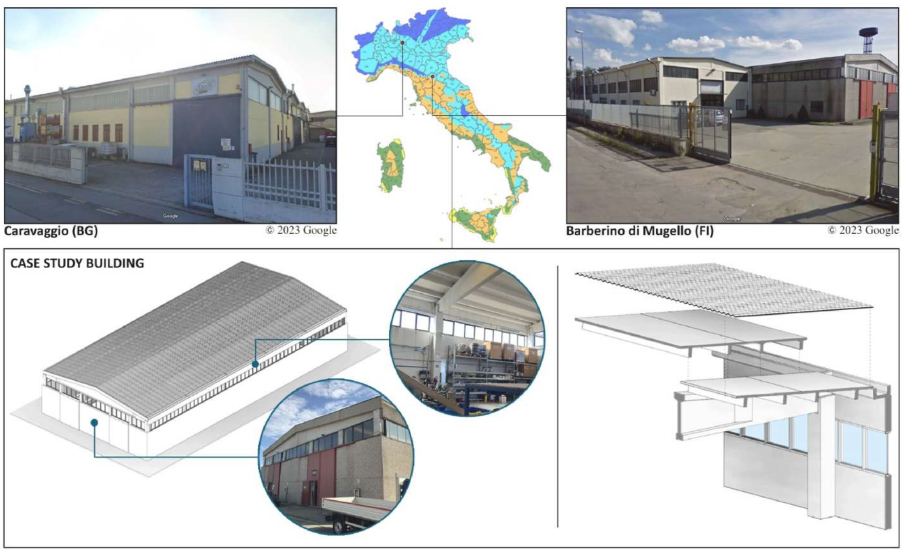

Fig. 3. Model of the case study building along with some photographic evidence and the axonometric details of the constructive solution.

mechanic sector with no specific requirements in terms of internal microclimatic conditions and with neglectable thermal loads related to process activities and machinery. The load-bearing structure is made of precast reinforced concrete columns and prestressed gable beams forming portal frames. The existing external envelope is characterised by lightened precast concrete panels for the external walls (0.20 m thick) and roof stratigraphy is made of π precast concrete slabs. The main distinguishing features and thermodynamic properties of the external envelope components are reported in Table 3. The half thickness of the insulation material included in both roof and external wall stratigraphy is considered during the energy modelling phase to consider the possible decay of the material that occurred over time. Windows are made of a single glazed pane and metallic frame without a thermal break (thermal transmittance = 3 W/m^{2}K, solar factor = 0.6, light transmittance 0.4). A traditional gas boiler with a coefficient of performance (COP) equal to 0.7 is used for heating system with hot air distribution pipes hanging from the ceilings. No air conditioning systems for summer cooling are currently installed in the building.

2.3. ENVI-met set-up

An ENVI-met numerical model was set to analyse the micro-climate parameter and pollutants concentration in the case study area. Recurring to the same software, the impact of the different green and mitigation strategies proposed was evaluated. ENVI-met is a software capable of producing tree-dimensional and grid-based microclimate models to perform complex simulations regarding the interaction between surface, vegetation, and air within the urban environment [73]. In literature, the reliability of the software is widely demonstrated in studies dealing with heat island effect and pollutants concentration in external air [74,75]. Moreover, this software can properly predict meteorological parameters and vegetation interaction with pollutants concentration [12].

Caravaggio industrial district was hence modelled in the ENVI-met environment through its Spaces module. Aerial views by Google Maps source were imported in. bmp format to faithfully reproduce the urban layout. Following the outline of the images, roads, facilities, and greenery were modelled to create the plan configuration of the whole area. The total height of the building was retrieved by Google Maps [76] also considering the design materials collected in ReLuis publication [63]. The general geometrical features of the Spaces-ENVI-met model are listed in Table 4.

It is worth noticing that the Dz grid for the model on ENVI-met spaces was set equal to 2 m and the telescoping factor along the same Z direction was defined equal to 20% starting from 10 m height. Since ENVI-met simulations are carried out by calculating the punctual values in the centroid of each volume of the grid (Dx x Dy x Dz), this approach allowed to avoid detailed calculations at levels where no person would be present and consequently reduce computational time. Moreover,

Table 4
Model geometry settings in the ENVI-met model.

X size [m]	Y size [m]	Z size [m]	Dx [m]	Dy [m]	Dz [m]	Telescoping factor
151	132	11	3	3	2	20% after 10 m height

following the best practice suggestions provided by the software developers, empty cells were added at the border of the model area instead of using nesting grids, to avoid the influence of boundary conditions on simulation results. The climate conditions were set in the ENVI-met by importing the climate data from the. epw file corresponding to the weather station of interest (Table 2). Simulations were performed considering March 2, 2021 and July 14, 2021, within a time interval ranging from 10 a.m. to 4 p.m. while the main results were read at 3 p.m. The first represents the coldest day among the ones monitored by the Lombardy Region campaign, while the second one was selected as representative of summer conditions.

As it regards pollutant concentration simulations, the model was validated concerning the annual medium average of PM_{10} concentrations calculated starting from monitoring data and comparing it with the one obtained after ENVI-met simulations (Fig. 4). It is worth highlighting that according to Italian Law n. 115 of 2010 [77], the daily average limit related to PM_{10} concentration in the atmosphere is equal to 50 μg and it cannot be exceeded more than 35 times per year. Furthermore, the same standard requires a maximum limit for yearly average PM_{10} concentration equal to 40 μg.

To obtain the atmosphere pollution concentrations (PM_{10}) linear pollutants sources were set in the ENVI-met model following main road paths. The average value of PM_{10} concentration achieved is equal to 38.6 μg, comparable with the medium value derived from monitoring data, as reported in Fig. 4. Moreover, these data highlight some peak concentrations over the analysed period exceeding both daily and yearly threshold values, clear symptoms of a generally low-quality air condition in the considered area.

Moving on and introducing mitigation strategies (Fig. 5), two different technological solutions available in the market for horizontal greenery were chosen for the green roof (extensive and intensive). They were set to be applied on the whole roof surface of every industrial facility within the case study area. The installation of the green roof was considered a redevelopment solution of the existing roof stratigraphy (as reported in Table 5) from a technological point of view. In this case, a sandwich panel (double metal layer 0.006 m each and 0.10 m polyurethane insulation) was installed replacing the existing π precast concrete slab, completed with a water drainage layer and substrate topping of different thicknesses based on roof type and vegetation. The detailed characteristics of these technological solutions are reported in Table 5.

Furthermore, the impact of evergreen tree planting was investigated.

Table 3
Stratigraphy and main properties of the external envelope of the existing case study.

	Layer	Thickness [m]	Thermal conductivity [W/mK]	Specific heat [J/kgK]	Thermal transmittance [W/m^{2}K]	Surface Mass [kg/m^2]	Periodic thermal transmittance [W/m^{2}K]
External wall	Precast concrete panel	0.06	2.30	1000	–	–	–
	Insulation material	0.04	0.045	1480	–	–	–
	Precast concrete panel	0.10	2.30	1000	–	–	–
					1.10	385	0.511
Roof	π precast concrete slab	0.05	2.30	1000	–	–	–
	Rockwool insulation panel	0.04	0.036	1030	–	–	–
	Waterproof sheet	0.02	0.23	1300	–	–	–
	Fiber cement panel	0.065	0.50	960	–	–	–
					0.78	135	0.585

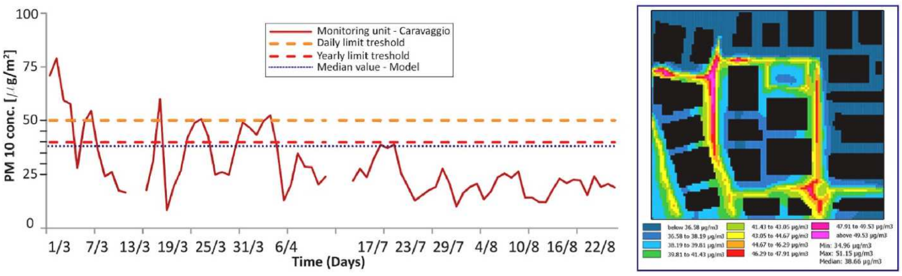

Fig. 4. Validation of the PM10 concentrations modelled in the ENVI-met environment.

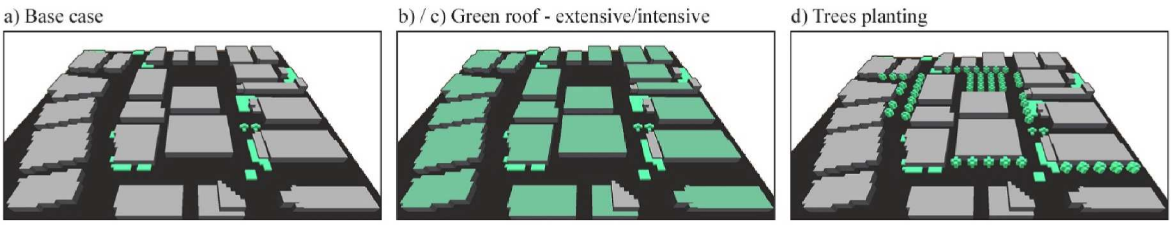

Fig. 5. Green strategies applied to the industrial district. In the figure: a) base case, b) extensive green roof, c) intensive green roof and d) evergreen trees planting. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 5
Green roof technological solutions stratigraphy. In the table e) refers to the extensive type and i) to the intensive one.

Layer	Thickness [m]	Density [kg/m^3]	Conductivity [W/mK]	Specific heat [J/kgK]	Vapour resistance factor
Sandwich panel (polyurethane insulation)	0.10	100	0.022	1450	90 000
Anti-root sheet	–	–	–	–	–
Drainage	0.05	25	0.111	1338.9	70
Filtration (geotextile)	0.00135	–	–	–	–
Substrate	e) 0.08 i) 0.15	980	0.20	836.8	20
Vegetation e) Sisyrinchium angustifolium	e) 0.10	–	–	–	–
Vegetation i) Grass	i) 0.25				

Trees were introduced in both the wider main urban canyons and the parking area, in order not to hinder normal traffic and not to excessively reduce manoeuvring areas for heavy vehicles. The same approach was adopted when choosing the type of trees paying attention to its compatibility with the industrial site in terms of dimensions, vegetated crown and relative spacing. PM_{10} absorption capacity [78] of the vegetation species was also taken into account in this preliminary phase: Quercus Ilex, a medium-sized evergreen tree, was hence selected to be included in the ENVI-met model. The main settings adopted for the greenery considered in the ENVI-met simulations were retrieved in the literature [79] and are illustrated in Table 6 and Table 7 for application at urban and building levels respectively.

Table 7
Settings for the green roof alternatives. The vegetation chosen for the extensive vegetation belongs to the Iridaceae family.

Building level	Mitigation strategy	Greening	Thickness [m]	Leaf Area Density [m^2/m^3]
	Extensive green roof	Sisyrinchium angustifolium	0.10	1.5
	Intensive green roof	Grass	0.25	0.3

2.4. Design builder set-up

The reference case study industrial building and the surrounding facilities were modelled in the Design Builder environment as illustrated in Fig. 6. The latter were reproduced in the model as simple block geometry elements. This choice was made to consider the influence of the built context on the microclimate characteristics of the site (for instance in terms of wind speed and direction) as well as on the energy performance of the case study facility [80]. The geometry of the industrial building faithfully was modelled in the Design Builder environment starting from the original design specifications and on-site survey indications, adequately assigning material properties for each envelope component. All the specific internal conditions were set following the on-site survey: setpoint temperature, activities and metabolic rate, occupancy, air change rates and HVAC specifications were set for the

Table 6
Settings for the tree species.

Urban level	Mitigation strategy	Tree Type	Name	Width [m]	Height [m]	Foliage shortwave albedo	Emissivity of leaves	Foliage shortwave transmittance
	Planting tree	Evergreen	Quercus ilex	6.69 × 8.21	11.32	0.18	0.96	0.30

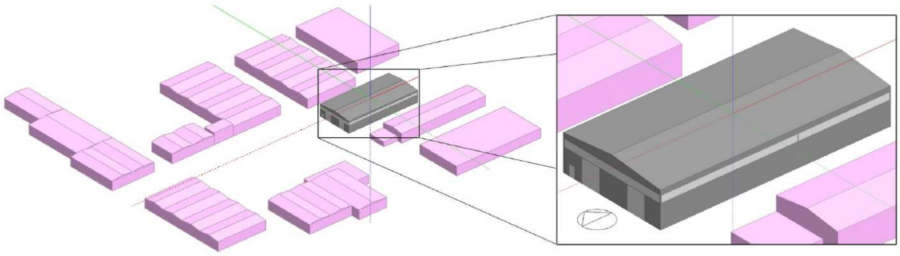

Fig. 6. Design Builder model of the Caravaggio industrial district with the indication of the case study building.

single thermal zone in the facility. Following indications provided by the company itself, heating setpoint temperature was set equal to 18 °C instead of 16 °C, prescribed as the minimum value for industrial and manufacturing facilities classified as E.8 category buildings by the Italian standard [81]. The occupancy time in the energy simulations was set from Monday to Friday, 7:00 a.m. to 6:00 p.m. equal to 0.017 people/m^2. With regards to the activities, the metabolic rate was set equal to 1.6 met (167 W/person) considering the company working sector [82]. Natural ventilation and infiltration rates are calculated based on UNI/TS 11300–1:2014 [83] for workspaces. In the case of workshop spaces, UNI/TS 11300–1:2014 [83] was applied since it provides indications specifically addressing industrial buildings or artisanal workshops. Adopting the formulas proposed by the cited regulation, a natural ventilation flow rate of 0.62 m^3/s was set. The same regulation also contains indications about the value of infiltration to be set in terms of air changes per hour at a fixed air pressure difference of 50 Pa. To overcome the limitations due to the impossibility of an exact estimation of infiltration rates and their daily fluctuations the constant value suggested by the formulation proposed in the cited standard was adopted. Considering the current conditions of envelope components, windows, and external doors a general low airtightness (8 h^{-1}) was observed. Looking at the urban context, a sheltering coefficient equal to 0.07 was chosen. As regard the existing conditioning systems, the simulation was performed considering the simplified method for HVAC proposed by the software.

The validation of the Design Builder model for the existing configuration was obtained considering the real natural gas bills provided by the company hosted in the case study facility: comparing the real energy consumption of the building for one year (114.36 kWh/m^{2}y) and the one modelled on design builder (98.62 kWh/m^{2}y) a difference of about 14% was registered. Anyway, such a discrepancy was acceptable considering the assumption made during the modelling phase, especially regarding envelope thermal insulation, ventilation, and air infiltration rates.

Only the extensive green roof mitigation measure was modelled in this case, following the stratigraphy detailed in Table 5 and assigning all the properties collected in Table 8 [84,85] in the Design Builder construction section (Table 8). This choice was mainly due to the reduced weight of this configuration concerning the intensive one that makes it more suitable for this kind of building and due to the extremely simplified maintenance operation, not even foreseeing irrigation systems to be installed. As regards the choice of the technological solution to be applied for green roof implementation, both intensive and extensive vegetated roofs were considered when performing environmental simulations using ENVI-met. However, it must be specified that intensive green roofs, due to their thicker substratum layer and consequently their higher weight, require a careful evaluation of the structural and non-structural loads acting on the building. In many cases, this solution could hence not be adequate for interventions to be carried out on existing facilities. Also, for this reason, the research at the building level was limited to the extensive green roof solution. It is worth noticing that together with the introduction of the extensive green roof stratigraphy, an air-to-air heat pump (Energy Efficiency Ratio EER = 3) was considered to provide air cooling to ensure comfortable conditions for workers during the summer season as well.

Table 8
Green roof characteristics set in the Design Builder model.

Parameter	Unit	Value
Conductivity of dry soil	W/mK	0.20
Density of dry soil	kg/m^3	980
Specific heat of dry soil	J/kgK	836.80
Thermal absorptance	–	0.90
Solar absorptance	–	0.70
Height of plants	m	0.10
Leaf area Index (LAI)	m^2/m^2	1.50
Leaf reflectivity	–	0.30
Leaf emissivity	–	0.97
Minimum stomata resistance	mmol/m^{2}s	120
Maximum volumetric moisture content	–	0.5
Minimum residual volumetric content	–	0.01
Initial volumetric moisture content	–	0.15

3. Results

To better illustrate the results of the research, at first the main outputs related to both extensive and intensive green roofs are detailed, concerning outdoor air temperature (for both March and July), deposed mass of $PM_{2.5}$, wind speed and longwave radiation balance. Further, some considerations about tree planting dealing with outdoor air temperature, mean radiant temperature, wind speed and PM_{10} concentrations are outlined. Finally, to conclude, the results related to the energy simulations of the representative case study are presented.

As far as the outdoor air temperature is concerned, Fig. 7 shows its variation considering a comparison between the base case and the 2 technological solutions for green roofs. As illustrated, the extensive green roof proves to be the most effective mitigation strategy, decreasing the average value of outdoor air temperature with respect to the base case of about 1 °C for March. Moreover, in Fig. 7 the graph showing the outdoor air temperature trend by number of points is also included comparing the base and the configuration with the extensive green roof. For lower external air temperature values, the number of points in both configurations shares the same trend also because they are representative of boundary grids in the model. By contrast, while base case configuration is characterised by a consistent number of points in correspondence with high temperature, extensive green roof configuration shows completely different behaviour. In this case, points distribution follows a more regular trend with a peak at about 16.65 °C. This evidence is more appreciable if sections BB and AA are analysed. Both green roof configurations have an impact on outdoor air temperature in the urban canyons at the pedestrian level (1.5 m height), but the influence becomes more appreciable approaching the roof level (9 m height). By the way, intensive green roof influences the external air temperature to a lesser extent. Along the Z-axis direction, starting from half the height of the industrial facilities, air temperature decreases from 16.60 °C to values lower than 16.05 °C if an extensive green roof is used. The different behaviour of the technological solutions is mainly related to the characteristics of the vegetation (for instance LAI, LAD, height).

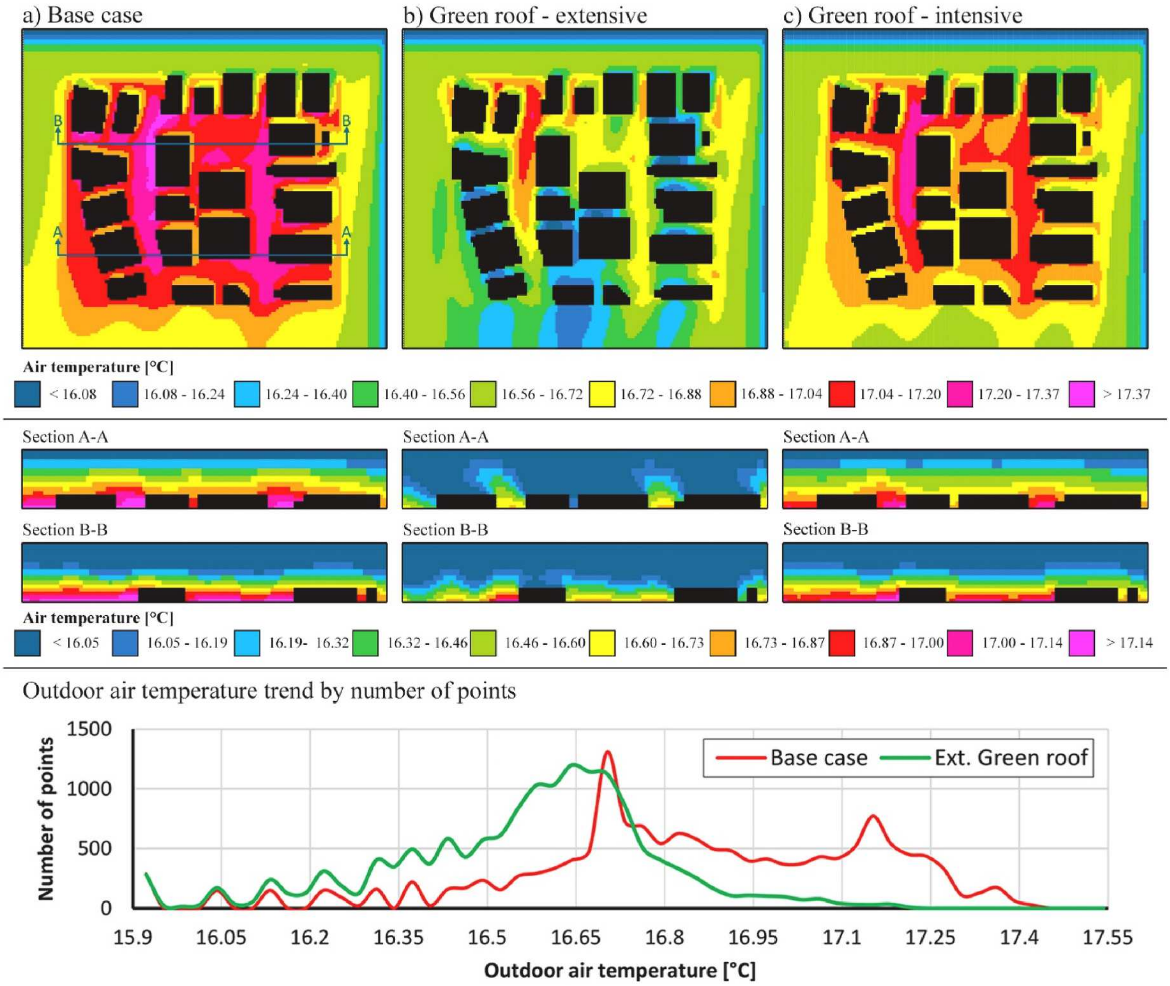

Fig. 7. Variation in the outdoor air temperature [°C]. Month: March.

The previous results are more evident if the outdoor air temperature is analysed during the summer season, as suggested in Fig. 8 where the results of simulations performed in July are illustrated. In this case, the maximum external air temperature is higher than 29.69 °C. Confirming previous results, the extensive green roof solution significantly impacts the outdoor air temperature value, causing a reduction of about 1.5 °C compared to the base case. With the same approach, also for summer conditions, the correlation between outdoor air temperature and the number of points was investigated. Once again, the number of points characterised by high values is reduced and a consistent increase in the number of cells at lower values is registered. Looking at peak point distribution for both configurations, it is worth noticing that, while for the base case it occurs at about 28.63 °C (932 cells), for the green roof layout it happens at about 28.60 °C with 1476 points. It is worth highlighting that the influence is more considerable focusing on narrower urban canyons, as section AA shows. Extensive green roof using Iridaceae species vegetation is the best option to tackle the UHI effect in the industrial district under consideration.

The analyses of microclimate parameters were further deepened considering wind speed and its variation within the industrial district introducing greenery. Fig. 9 illustrates the wind speed variation considering pedestrian and roof levels. It is worth noticing that at 1 m height wind speed is not affected except for a slight decrease detected in the parking area. More interesting outputs can be observed at 9 m height. The difference in the behaviour of the 2 types of horizontal greenery is considerable. The installation of an extensive green roof characterised by a higher LAD (1.5 m^2/m^3) results in a decrease in wind speed at roof level equal to about 50% compared to the base case. In fact, for the former, it ranged between 0.31 m/s and 0.76 m/s while for the latter from 0.76 m/s to values higher than 1.36 m/s. For the intensive solution modelled with grass (LAD 0.3 m^2/m^3) the reduction is less significant and equal to about 0.4 m/s. Moreover, it is possible to highlight that the variation of wind speed is strictly correlated to the position of the greenery layers, both in terms of position within the urban district and distance from ground level and to the main distinguishing vegetation features.

As regards pollutants concentration, Fig. 10 shows the deposed mass of $PM_{2.5}$ [μg/m^2] on roofs in the different configurations analysed. It is possible to observe that in this case the intensive green roof shows more promising results, being characterised by a deposed mass ranging between 35.13 μg/m^2 and 45.10 μg/m^2 with a peak of 50.21 μg/m^2. This configuration can capture particulate matter 3 times more than the base case (ranging between 15.03 μg/m^2 and 20.05 μg/m^2) and this kind of greenery solution presents higher removal capacity for pollutants in the atmosphere compared to Iridaceae species vegetation. Relating these results with the previous one dealing with wind speed, it is worth noticing that the configuration with a higher reduction of the wind speed shows lower values of pollutants deposed mass.

Fig. 11 indicates some results regarding building level, considering the variation in the value of the outer surface temperature at roof level (9 m) and some outputs about longwave radiation for all the configurations considered during summer conditions. The external surface temperature considering the base case is usually higher than 45.12 °C with a maximum peak value of 52.38 °C. Both extensive and intensive

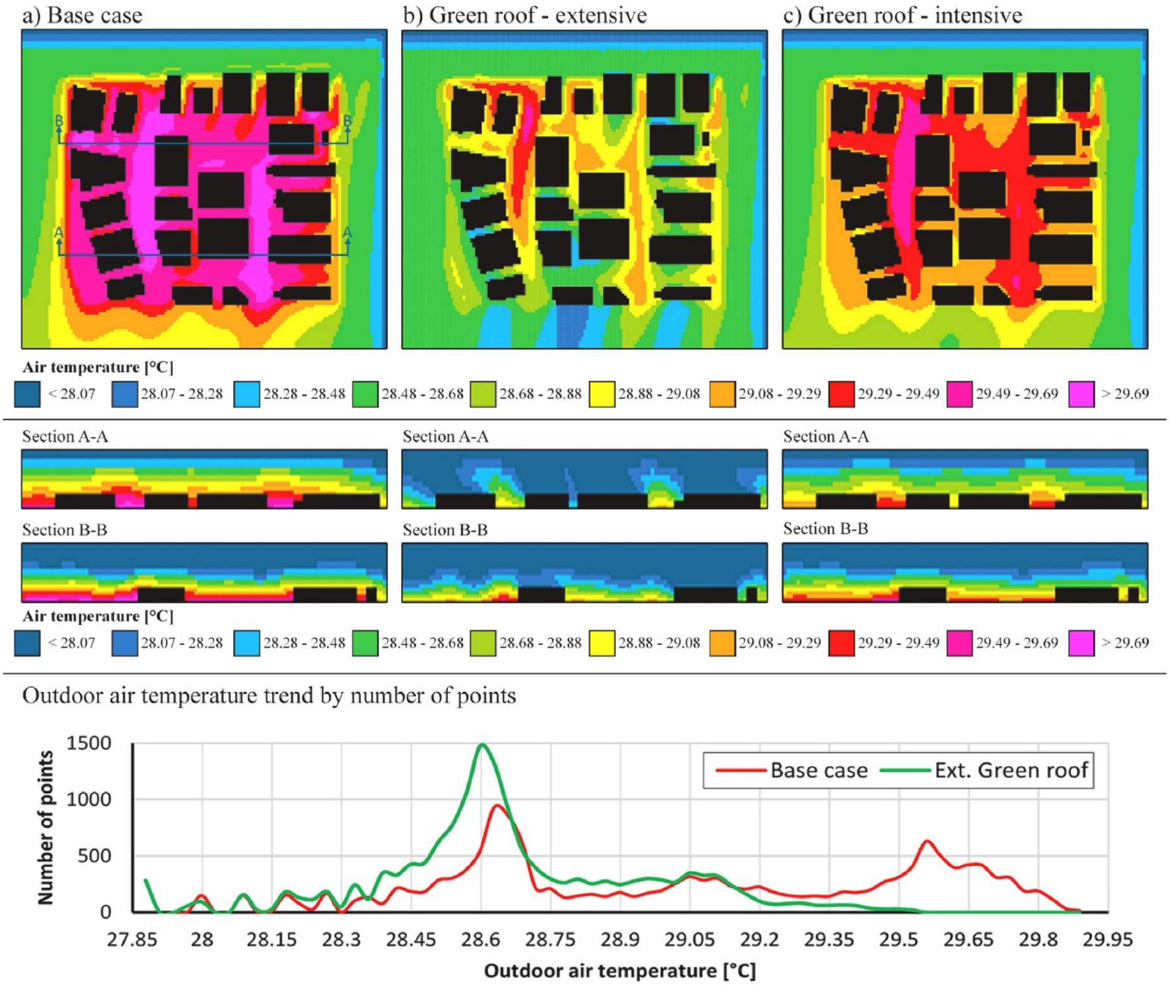

Fig. 8. Variation in the outdoor air temperature [°C]. Month: July.

green roofs positively affect this value, ensuring a decrease in average surface temperature that is equal to about 30 °C and 38 °C respectively. The extensive green roof solution is the most valid and efficient one also considering these parameters at the building level. An evident maximum reduction of the external surface temperature of 15 °C occurs with respect to the base case. Considering industrial buildings, the roof surface is generally wider than the external walls and exposed to the highest rate of solar incident radiation during the hottest hours as illustrated in Fig. 11 for external surface temperature and emitted longwave radiation. By reducing emitted longwave radiation, lower heat flux through the atmosphere is obtained and this allows to tackle the UHI phenomena within the district. The emitted longwave radiation in the case of the extensive horizontal greenery is equal to 440 W/m^2, 17% lower than the base case. About the longwave radiation balance, the lower the value, the more the roof stratigraphy solution is characterised by materials with a better performance in terms of UHI reduction. Once again, also in this case the vegetation properties are a key element. It is worth noticing that in the base case the last analysed parameter ranged from 134 W/m^2 to values higher than 160 W/m^2 while in the case of green roof with Iridaceae species, an average value of about 43 W/m^2 is registered, more than 3 times lower.

In Figs. 12 and 13 results related to tree planting results are collected, showing the main outputs in terms of variation of outdoor air temperature and mean radiant temperature for March and July respectively. As suggested by the results obtained, this mitigation strategy mainly influences micro-climate parameters at the local level, slightly affecting the conditions of the whole district. This evidence is demonstrated for both March and July simulations with a decrease in the outdoor air temperature of about 0.2 °C and 0.3 °C respectively, focusing in the parking area where trees are planted with a dense layout. Changes in temperature values occurring in urban canyons are in this case negligible as well as the reduction in the average value at the district level. Further considerations can be produced considering the mean radiant temperature. Punctual effects can be registered in correspondence with trees crown, where an evident decrease of 10 °C can be traced according to simulations' results. The reduction in mean radiant temperature due to tree planting interventions can be noted considering the Z direction: in section BB, a decrease by 3 °C occurs at the tree's crown level with respect to the base case.

Figs. 14 and 15 show the variation in wind speed and PM_{10} concentration respectively, comparing the base case with tree planting mitigation strategy. As demonstrated in section BB, wind speed is reduced by about 0.4 m/s by trees crown. This mitigation strategy affects the wind speed in urban canyons to a lesser extent and this is mainly due to the trees' characteristics, especially those related to the crown (e.g., width). The correlation between this mitigation strategy and the concentration of the pollutants can be retrieved in the comparison between the 2 sections BB, where the white frame is highlighted. A slight decrease in PM_{10} can be observed behind the trees' barrier: vegetation tends to maintain pollution concentrated in the main roads, avoiding exposure of human pedestrians in the related paths. Similar results were also assessed in the literature in the case of urban road greenbelts [86]. Despite being characterised by a higher rate of trees concentration, parking areas are not affected in terms of PM_{10}. Such a

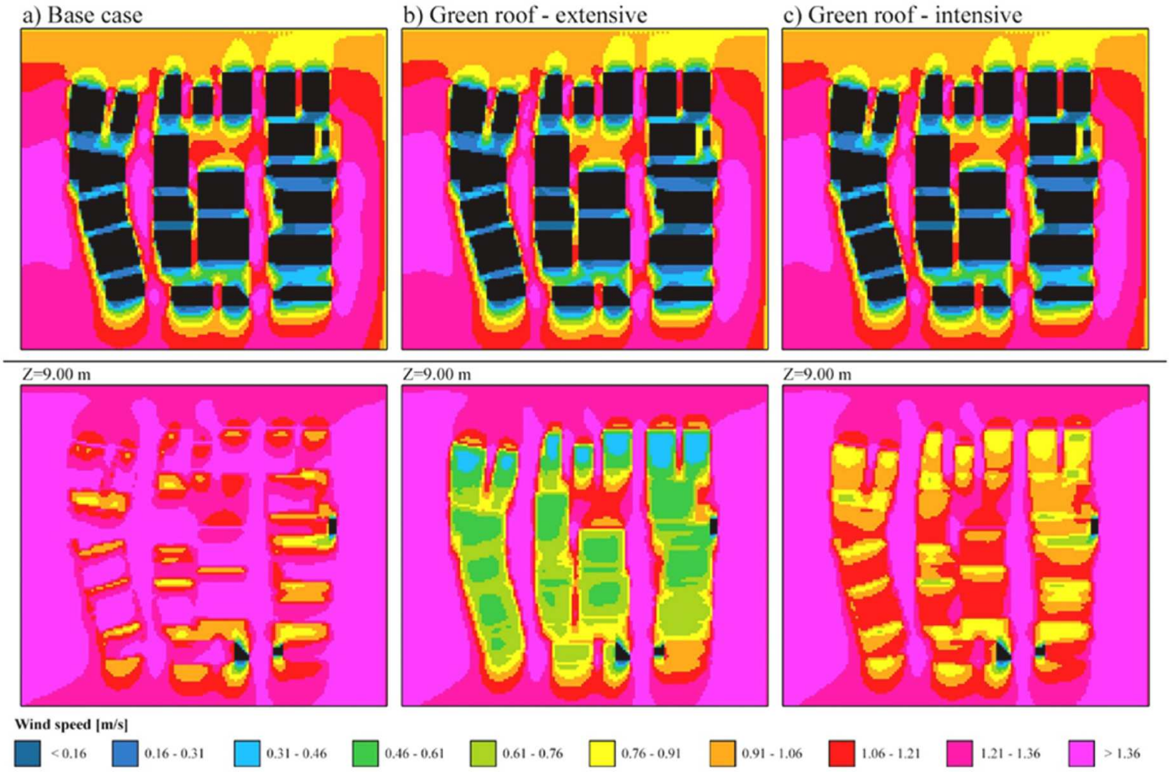

Fig. 9. Variation in wind speed [m/s] considering 2 different height levels (z = 1 m and z = 9 m). Month: March.

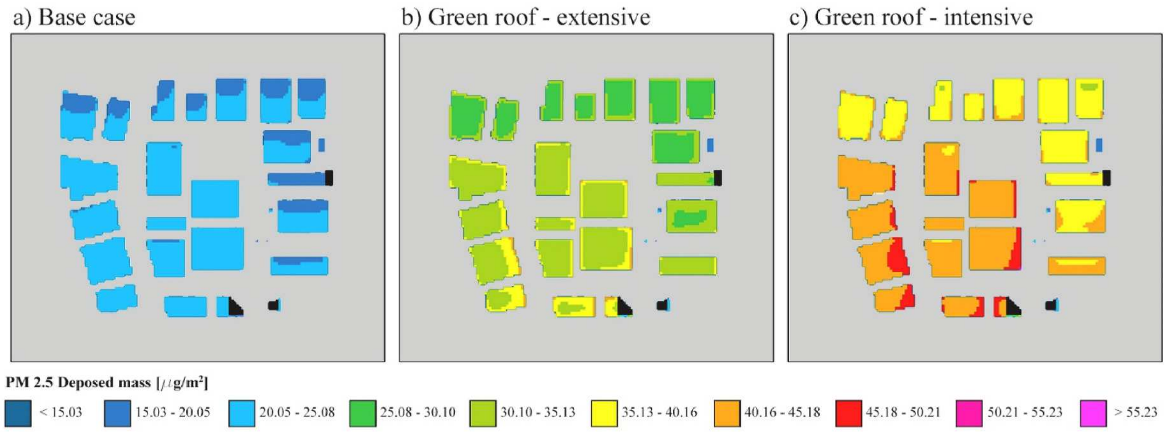

Fig. 10. Variation in the amount of the deposed mass of $PM_{2.5}$ [$\mu g/m^2$]. Month: March.

result can be easily justified by the reduced amount of pollutant sources introduced in this portion during the modelling phase since vehicular traffic was mainly supposed to occur on public roads.

Once the analysis of each measure's potential was completed, Design Builder was used to correlate the impact of the extensive green roof installation and the energy performance of the industrial facility. As detailed in the method section, the case study building was modelled including the surrounding ones simply as geometrical elements. The stratigraphy selected for roofing elements retrofitting increases thermal insulation and reduces the overall mass at the roof level at the same time. This is a key point to improve structural response in case of seismic actions for industrial buildings adopting precast concrete frames as load-bearing elements. Reducing seismic mass at the roof level lower stresses on columns and can prevent the connections from collapsing.

Fig. 16 shows the heat losses and gains [kWh] through the different components of the external envelope and those due to the external infiltration and ventilation during the winter season. The installation of the extensive green roof results in a significant reduction in heat losses through the external envelope of about 13%, going from 29 380 kWh in the base case to 25 467 kWh in the green roof configuration. As reported in the literature, it is worth noticing that most heat losses occur because of the external infiltration (~40%) for both configurations. As highlighted in the graph, the roof proved to show the highest share of heat losses in the current condition configuration, suggesting the opportunity to primarily act on roof stratigraphy when considering industrial buildings retrofitting initiatives. Considering redevelopment with the extensive green roof solution, roof-related heat losses decrease by about 75%. Anyway, the heat flux is partially redistributed as certified by the increase registered in heat losses occurring through external walls and windows, 9% and 8% respectively. Due to the overall reduction of heat

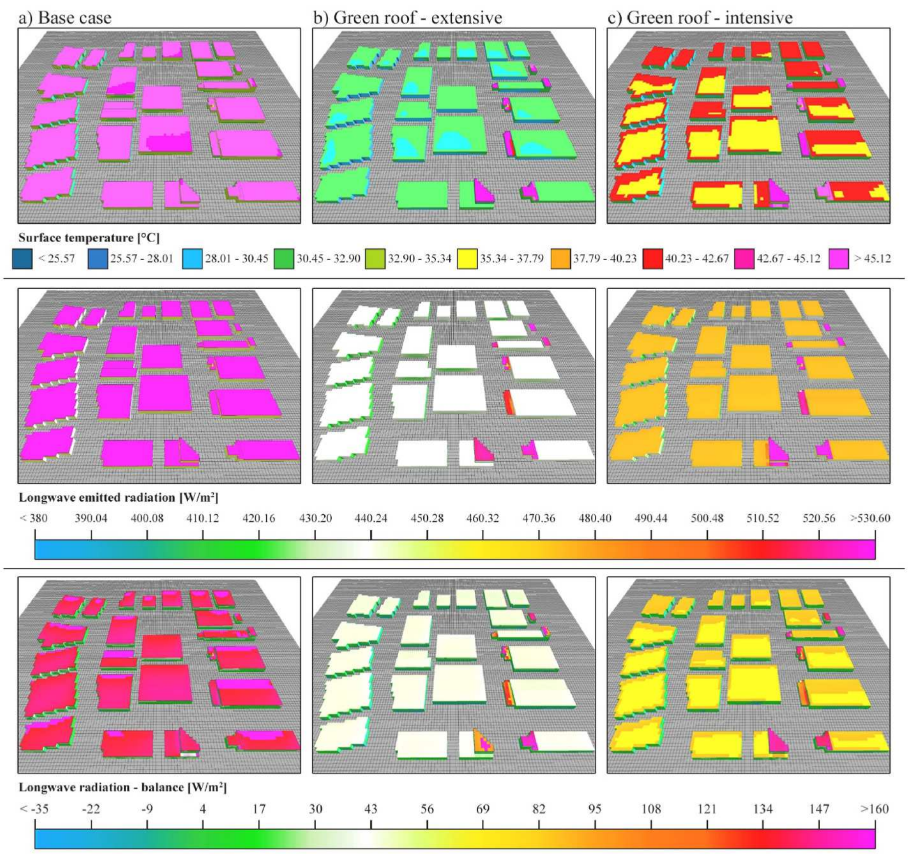

Fig. 11. Variation in surface temperature at roof level [°C], longwave emitted radiation [W/m^2] and balance (emitted minus incoming) [W/m^2]. Month: July.

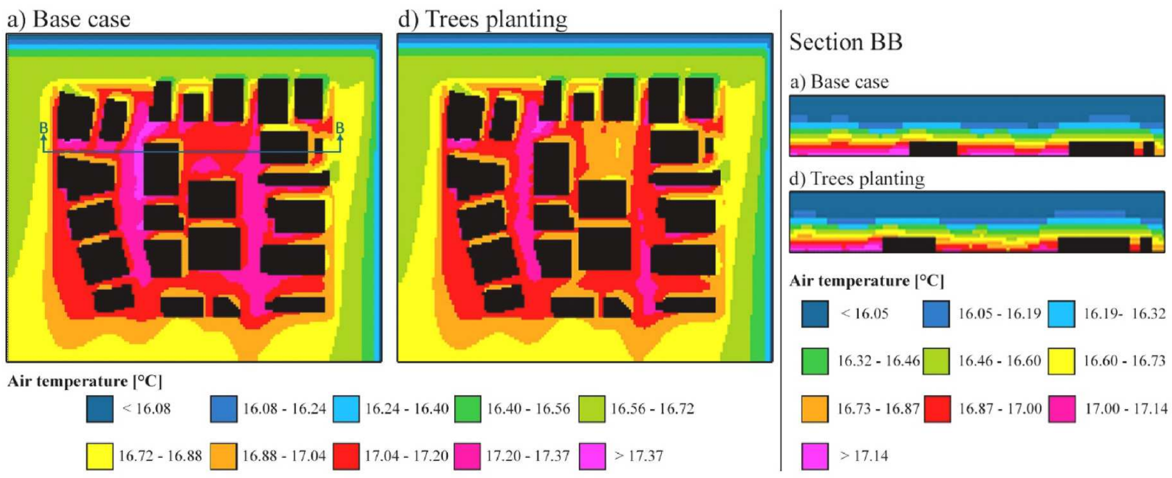

Fig. 12. Variation in the outdoor air temperature [°C] in case of trees planting (d). Month: March.

losses, indoor air temperature rises and, consequently, the heat gains through the ground floor are reduced by about 10% as well.

Figs. 17 and 18 illustrate the heating and cooling energy demand for the winter and summer seasons respectively. The implementation of an extensive green roof leads to an improvement in the yearly energy performance of the building. During the winter season, heating consumption can be cut by about 15% (Base case: 160 840 kWh and Green roof: 136 369), with maximum energy saving potential registered during October with a reduction of 19%. By contrast, the lowest gain (−13%) is achieved for March, where the average value of the external air temperature starts increasing. As regards the summer season, the substitution of the existing roof stratigraphy results in a reduction in cooling demand of about 14% considering the introduction of an air-to-air heat pump as previously specified. The highest advantage is obtained in May with energy saving up to 37%.

The reduction of building energy needs during summertime is strictly related to the outer and inner surface temperature of the roof stratigraphy as well. Fig. 19 illustrates the difference in the value of the outer and inner surface temperature of the roof slab for both configurations analysed. Focusing on the former, the maximum difference registered is equal to 15 °C. Significant considerations can be formulated by comparing these results and the outputs of ENVI-met simulation. A

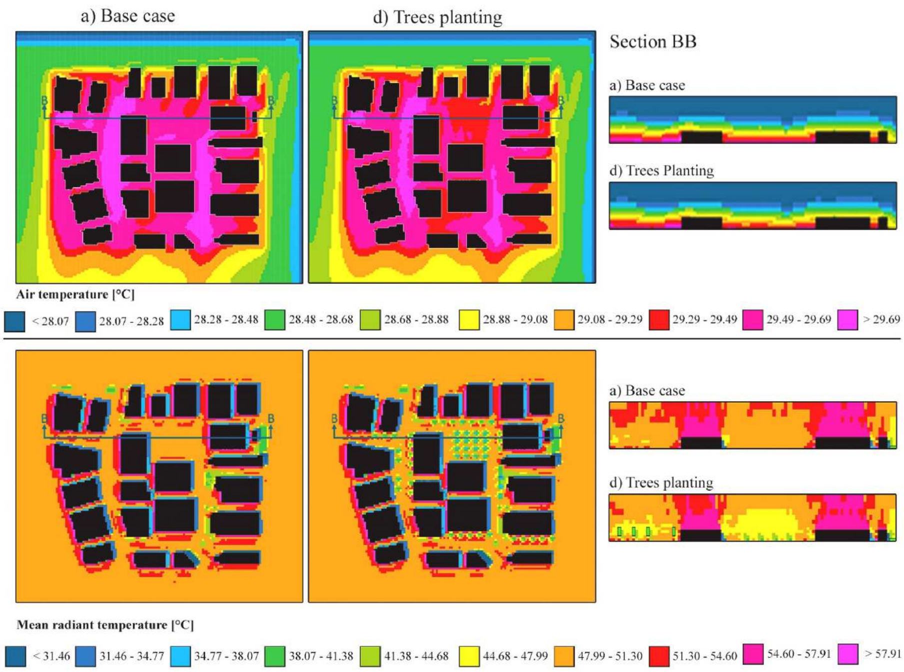

Fig. 13. Variation in the outdoor air and mean radiant temperature [°C] in case of trees planting (d). Month: July.

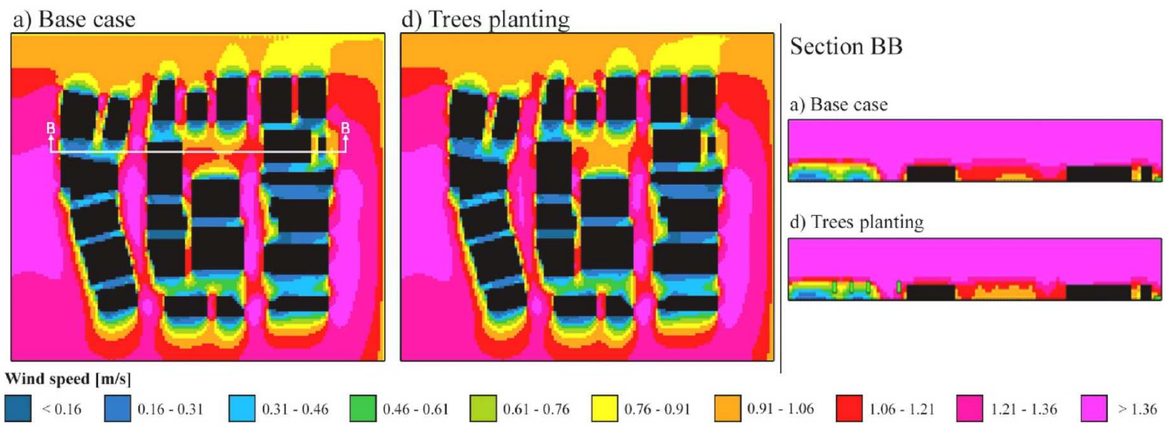

Fig. 14. Variation in the wind speed [m/s] in case of trees planting (d). Month: March.

difference of 9 °C between the current and retrofit configuration is retrieved in both software simulations considering the reference time chosen for ENVI-met results analysis (14th July at 3 p.m.). Contrary to what is observed during the daytime, the surface temperature in the case of the green roof is higher at night than in the base case. This is mainly due to the presence of the thermal mass represented by the substrate layer (0.08 cm). The inner surface temperature was affected to a lesser extent, with a reduction still noticeable and equal to 1.5 °C during the last hours of the afternoon while only a slight variation between the 2 configurations can be outlined at nighttime. Considering these detailed outputs, indoor thermal comfort is investigated. The cooling system is turned off when running this simulation to exclusively focus on the effects induced by roof retrofitting. The predicted percentage of dissatisfied (PPD) was chosen in this case as a reference index to evaluate workers' wellbeing [82]. Following extensive green roof adoption, PPD decreases by about 10% with an average reduction of about 4% during occupied hours over a reference week in July (13th – 20th).

4. Discussion

The research presented in the paper let to outline some considerations about the influence of some green mitigation strategies (extensive/intensive green roof and tree planting) on several micro-climate parameters within an industrial district located in North Italy. The analysis was conducted also at the building level considering a representative case study building and evaluating the energy consumption during both winter and summer seasons. In this case, two configurations are compared: an existing building with traditional roof finishing and with the possible installation of an extensive green roof. Concerning outdoor air temperature, the extensive green roof is the most effective option to tackle the urban heat island effect. A difference of 1 °C and 1.5 °C for March and July respectively was registered by comparing the base case and the retrofit configuration. Many authors in the literature affirm that the introduction of horizontal greenery can positively impact UHI [87]. Imram et al. [88] affirm that the UHI effect would be reduced by 1 °C–3.8 °C increasing the percentage of the roof covered with greenery, while Cortes et al. [89] register lower variation ranging between 0.2 °C and 0.4 °C. Cascone et al. [90] affirm that with a

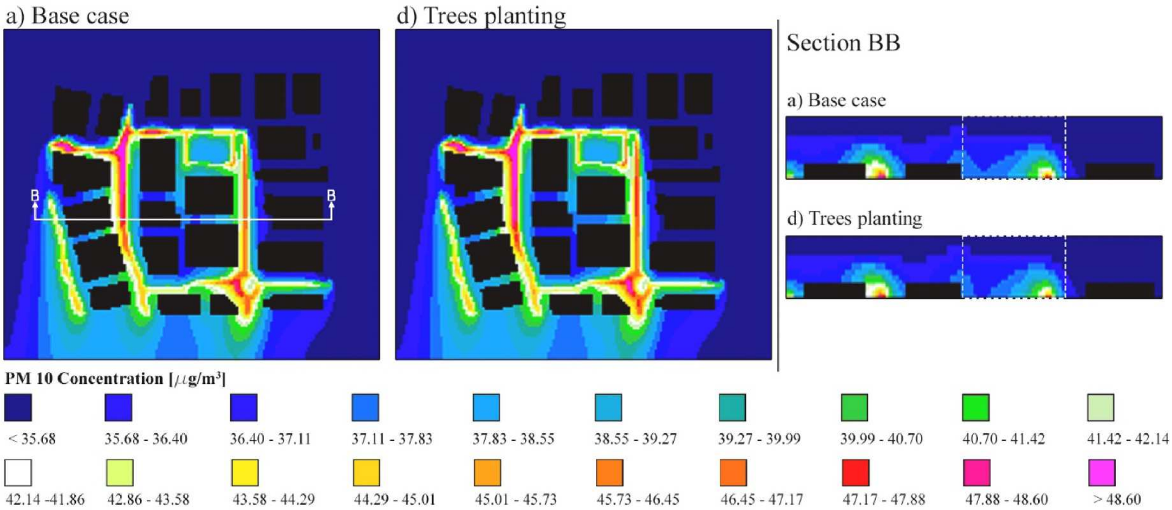

Fig. 15. Variation in the PM_{10} concentrations [μg] in case of trees planting (d). Month: March.

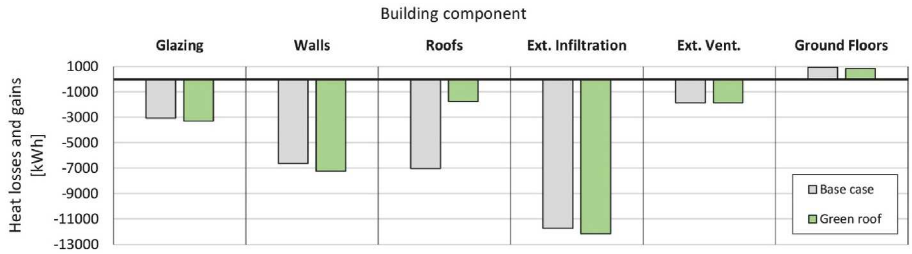

Fig. 16. Heat losses and heat gains during the winter season.

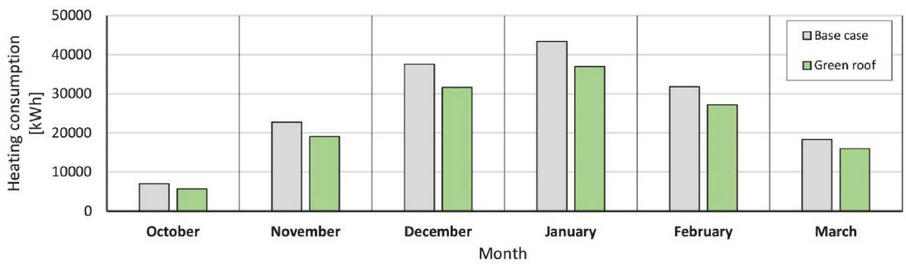

Fig. 17. Heating consumption [kWh] during the winter period.

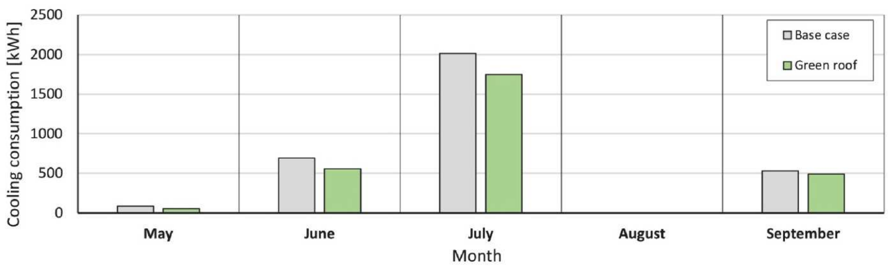

Fig. 18. Cooling consumption [kWh] during the summer months.

combination of different green infrastructures including green roofs, a reduction of about 8 °C can be achieved for the universal thermal climate index. The results obtained for the case study area considered in this study are hence comparable with the ones currently available in literature even if referring to urban districts with different intended use. Moreover, Afshari et al. [45] outline that green roofs can decrease UHI by 16%. In the research here presented, a hypothetic coverage of 100% is considered, complying with the results obtained by Ref. [28] that highlight a strong negative correlation factor (−0.56) between the increase in green covering and UHI mitigation. As demonstrated also in

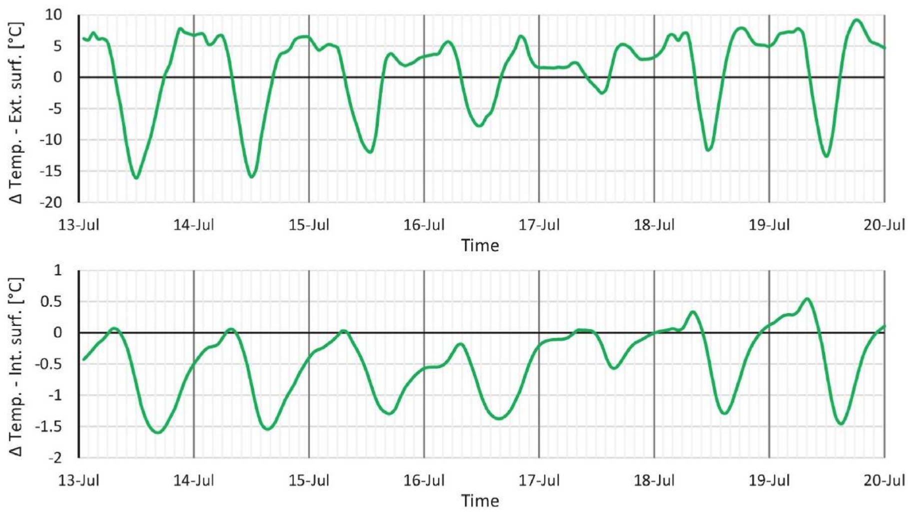

Fig. 19. Trend of the difference in the values of the outer and inner surface temperature considering the base case and the introduction of the extensive green roof stratigraphy. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the paper, the most significant variation on micro-climate parameters can be registered close to the greening layers. Such a result suggests that installing horizontal greenery on the roofs of high-rise buildings would not produce significant results at the pedestrian level as mentioned by other authors in the literature [91]. As far as wind speed is concerned, it is worth noticing that at 1 m height, any change is retrieved. This aspect has direct consequences also on pollution concentration in urban canyons since it tends to increase when poor ventilation occurs [26] as well as human pedestrian exposure. For this reason, green roofs show better behaviour than green facades concerning air quality. The latter, being installed next to pedestrian paths and being located on vertical walls of urban canyons, can produce some undesired effects by slowing down wind flows and negatively affecting their pollutants' removal potential. According to the literature, this is particularly true when wind direction is parallel to road alignment [92]. The possible correlation between wind speed and the deposed mass of $PM_{2.5}$ is deeper investigated. It is possible to point out that the meteorological factors affect pollution removal to a lesser extent with respect to vegetation characteristics and their removal capacity of particulate matter, as retrieved also in the literature [21]. In this regard, the intensive green roof is the most efficient configuration with a maximum deposed mass equal to 50.21 $\mu g/m^2$, even if it is characterised by a lower reduction in wind speed. In literature, many authors conclude that green roofs can improve air quality at the pedestrian level because of the removal capacity of vegetation [12,16,18]. In general greenery strategies perform better in ameliorating the energy performance of buildings rather than in ensuring better air quality [93]. Focusing on roofs' external surface temperature, a reduction of about 15 °C occurs when an extensive green roof is considered, contributing to saving energy for cooling purposes during the summer season. These results are in line with the outputs of several research in the literature [48]. For instance, it is demonstrated that this parameter decreases between 20 °C [94] and 14 °C considering the Milan climate zone [95] with green roof installation. As far as surface temperature, the reduction in the external one results obviously in a decrease in the internal one, as demonstrated by other authors in the literature [96]. The decrease in heat flux is significant as well with a decrement of 17% registered for the extensive green roof compared to the base case. As regards trees installation in the manufacturing site analysed, the obtained results demonstrated that this type of mitigation strategy mainly affects the micro-climate parameters and pollutants concentration at the local level rather than at the district scale, where the influence is not noticeable. Similar considerations were also proposed by Ref. [97]. For this reason, considering the whole industrial district, the installation of green roofs must be preferred because of their higher effectiveness in preventing or mitigating urban heat island effect. The characteristics of the tree species selected are crucial in this type of analysis since they include foliage properties, geometrical dimensions and vegetation cycle [98]. In the context of the research here discussed, a medium-size tree was chosen because to properly fit the public urban space available. Furthermore, an evergreen type of tree is considered because the highest values of particulate matter concentration are registered in the winter months. The results related to pollution concentration are anyway affected by some uncertainties, mainly due to the limited capacity of the software to model $PM_{2.5}$, especially in high-density urban districts, as stated by other authors in the literature [24,99]. At the building level, the energy simulations performed highlighted that the green roof can surely improve the energy performance of the buildings, as retrieved also in the literature [46,47]. In the case study, a reduction of heating and cooling consumption equal to about 15% for both winter and summer periods is registered. A lower energy-saving potential during the summer season is hence assessed in this case with respect to the values retrievable in literature. Such a result is mainly related to the surface mass and density of the technological solution chosen for roof retrofit (extensive green roof), lower than the ones that characterised the existing roof stratigraphy (precast concrete slab). As far as building energy balance is concerned, it is worth noticing that improving the energy performance of the roof allows to reduce the heat losses during the winter period through this building component by 75%. Moreover in industrial facilities, characterised by roofing surfaces far wider than ordinary buildings, roofs are usually the weakest envelope component with respect to heat losses [100]. Similar behaviour is retrieved also with reference to the case study considered, in which higher energy saving can be hence obtained by acting on roofs instead of external walls. Other retrofitting strategies for industrial buildings focusing on roofing elements can be retrieved from the literature. For instance, high albedo roofs are analysed by other researchers concerning both building performance and UHI [101,102]. Mastrapostoli et al. [103] evaluate the adoption of cool roof technological solutions, resulting in a substantial reduction of energy needs for cooling (73%). These results seem to be more promising than the one obtained by introducing green roofs that, according to the outputs collected following Design Builder simulations, only result in a 15% reduction in cooling energy demand. However, this result can be justified by the different infiltration rates considered when performing this kind of analyses. In the case of the research here discussed the low airtightness level assumed tends to limit the effectiveness of installing a green roof since hot air is still allowed to enter the building during the hottest months of the year. External infiltration heat losses are the most significant contribution (about 40%) considering the energy balance during the winter period as well. Despite being so influential on the overall energy performance of industrial and manufacturing buildings, the uncertainties connected with their correct quantification [104] are widely discussed in the literature.

5. Conclusions

In conclusion, 2 different typologies of green roofs and planting trees are considered as possible mitigation strategies within an industrial district. The positive effects on both micro-climate parameters and pollutants concentration at the district level as well as on energy performance at the building level are evaluated based on the results of environmental and energy simulation. An extensive green roof proves to be the best retrofit technological solution to ameliorate the urban heat island effect and the energy performance of the building in both winter and summer seasons. Following its adoption in all industrial facilities within the district, a reduction of external outdoor temperature of 1.5 °C is registered along with a decrease of about 15 °C in the value of roof external surface temperature. Both these results positively affect the urban heat island effect, improving comfort conditions also at the pedestrian level. Being strictly related to results about the external surface temperature, the emitted longwave radiation is also investigated. The extensive green roof lets to obtain a decrease of 17% with respect to the current state configuration. As far as the deposed mass of $PM_{2.5}$ is concerned, the results demonstrate that the solution with grass finishing (intensive green roof) is the best-performing one. In this regard, vegetation properties are proven to have a greater influence than meteorological characteristics on microclimate conditions. Intensive roof causes a reduced decrease of wind speed at roof level compared to both traditional finishing and extensive green roof but allows achieving the highest value of the deposed mass of $PM_{2.5}$ (maximum peak of 50.21 $\mu g/m^2$) being captured by blades of grass. For the tree planting solution, an evergreen species is chosen to be implemented in environmental simulation. The highest pollutant concentration is registered during winter months as also air quality monitoring data illustrate for the case study district. The air pollutant removal capacity of vegetation species is mainly due to foliage and its properties [23,25]. Evergreen vegetation species should be preferred to guarantee their effectiveness when mostly needed. It is worth highlighting that trees affect the micro-climate parameters mainly at the local level. An effective decrease in mean radiant temperature of 10 °C is outlined and it positively affects pedestrian comfort within the tree planting area. The effectiveness of the extensive green roof technological solution is demonstrated at the building level as well with reference to a selected industrial facility. Firstly, it is the best option because of the lower weight considering the several issues affecting this kind of building, often old and not adequately designed in terms of structural, environmental and energy requirements. Secondly, an energy saving potential equal to about 15% was pointed out in both winter and summer seasons. The roof's external surface temperature is expected to decrease by about 9 °C following the implementation of a green roof, according to the outputs obtained in both ENVI-met and Design Builder simulations retrieved.

Considering the cited background and the obtained results, it is possible to point out that green roofs represent an effective and strategical mitigation measure at both district and building levels to be used to tackle the urban heat island effect as well as to ameliorate the energy performance of industrial facilities. Certainly, this kind of mitigation strategy should be evaluated also from a life cycle cost perspective to evaluate the initial investment cost and the maintenance one during the building lifetime to possibly validate the economic suitability of the retrofitting intervention as well. Furthermore, it should be necessary to estimate the water consumption even if the extensive green roof technological solution does not require a significant amount of water for greenery maintenance. Based on the previous results, coupling the green roof technological solution with a photovoltaic system to produce electrical energy by renewables should be evaluated [105] since vegetation layers can contribute to avoiding PV panels overheating. At the same time, the possible combination of different mitigation strategies (e.g., vertical greenery [106]) should be investigated at the building level. Anyway, in literature there is a substantial lack of studies considering integrated redevelopment measures for industrial buildings and several other strategies should be tested addressing both building performances and environmental conditions at the district level for manufacturing sites. For this purpose, measures other than the ones already mentioned in this research should be evaluated such as green wall installation, paving-removal initiatives and consequent flowerbeds planting, hedges and green barriers implementation. Even if the outputs of this research are strictly related to the climate characteristics of the site and the morphological characteristics of the industrial district chosen, the same methodology could be applied in case of other industrial sites located in different climate zone to validate the results obtained or to suggest alternative retrofitting measures and mitigation strategies.

CRediT authorship contribution statement

Cecilia Ciacci: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Data curation, Conceptualization. **Neri Banti:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Data curation, Conceptualization. **Vincenzo Di Naso:** Supervision, Methodology, Formal analysis. **Frida Bazzocchi:** Supervision, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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