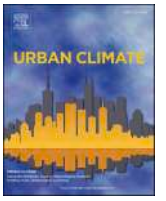
Urban Climate 66 (2026) 102840

Contents lists available at ScienceDirect

Urban Climate

journal homepage: www.elsevier.com/locate/uclim



Equity-oriented GIS-MCDA mapping of urban rooftops for green roofs and photovoltaic systems: competition and synergies in Padua, Italy☆

Abdullah Ahmadi [a,b], Daniele Codato [a,b,*], Francesca Peroni [a,c], Massimo De Marchi [a,b]

[a] Department of Civil, Environmental and Architectural Engineering, University of Padova, via Marzolo 9, 35131 Padova, Italy
[b] Jean Monnet Centre of Excellence on Just Fossil Fuel Transition, via Marzolo 9, 35131 Padova, Italy
[c] School of Geographical Sciences and Urban Planning, Arizona State University, USA

ARTICLE INFO

Keywords:
Rooftop green infrastructure
Photovoltaic systems
Vulnerability mapping
Sustainable energy action plan
Urban heat islands
GIS modeling
Urban climate justice

ABSTRACT

Climate change and urbanization intensify environmental risks and deepen social inequalities, calling for equitable adaptation and mitigation strategies. Urban rooftops provide untapped multifunctional spaces for integrated climate actions. Yet, their assessment is often limited to single-technology approaches, neglecting integrated perspectives. This study presents the Rooftops for Equity and Sustainability (RT4ES) model, a GIS-based multi-criteria decision analysis combining rooftop suitability with vulnerability-informed prioritization. Using open-access spatial data, RT4ES evaluates the feasibility of extensive and intensive green roofs, rooftop gardens, and photovoltaic systems, integrating socio-economic and environmental vulnerability indices. Applied to Padua (Italy), the model identifies 11.67 km^2 of net suitable rooftops across 29,493 buildings, emphasizing eastern, northeastern, and central areas where feasibility and vulnerability converge. Overall rooftop greening opportunity yields around 10.94 km^2 of additional vegetated surfaces, which corresponds to 20.95% of the inventoried on the ground greenspace stock. Concerning rooftop PVs potential, this yields around 302% of municipal household electricity consumption. Results suggest that individual and co-locating green roofs and photovoltaics enhances both energy efficiency and ecosystem services. By incorporating social and environmental vulnerability, RT4ES reorients priorities toward compact, underserved neighborhoods, fostering inclusivity and resilience. This open-source, replicable tool supports equitable multifunctional rooftop planning aligned with local and international frameworks.

1. Introduction

Urbanization continues to accelerate worldwide, increasing environmental pressures in cities. More than half of the global population currently lives in urban areas, a figure projected to reach 68% by 2050 (United Nations, Department of Economic and Social Affairs, Population Division, 2019). Urban centers also account for around 75% of global energy consumption, and produce 70% of

☆ This article is part of a Special issue entitled: 'Climate Change and Cities' published in Urban Climate.

* Corresponding author.
E-mail address: daniele.codato@unipd.it (D. Codato).

https://doi.org/10.1016/j.uclim.2026.102840
Received 17 October 2025; Received in revised form 22 December 2025; Accepted 16 February 2026
Available online 24 February 2026

energy-related CO_2 emissions (International Energy Agency, 2021). Meanwhile, global warming has increased average surface temperatures by about 1.1 °C above pre-industrial levels (Lee et al., 2023). Together, these trends make cities pivotal points for both climate mitigation and adaptation efforts. Consequently, climate hazards, including Urban Heat Island (UHI) effect, flash flooding, air pollution, and biodiversity loss, are already intensifying, harming both the environment and individuals, with low-income and marginalized communities bearing a disproportionate burden (Calvin et al., 2023; Harlan et al., 2006).

During the past decade, urban planners have recognized the role of ecosystem services in addressing climate-related urban risks, including those mentioned above (Carter and Fowler, 2008; Dong et al., 2020; Kumar et al., 2025; Santos et al., 2016). In this context, Green Infrastructure (GI), such as parks, street trees, urban forests, and urban agriculture, can help mitigate these hazards while delivering co-benefits for climate change adaptation, public health, and urban equity (Chen et al., 2024; Codato et al., 2024; Demuzere et al., 2014). Among GI options, Green Roofs (GRs) and Rooftop Gardens (RG) stand out because they retrofit underutilized rooftop space to deliver building and neighborhood scale cooling, attenuate surface runoff, improve air quality, and provide habitat for biodiversity (Kostadinović et al., 2023; Madre et al., 2014; Marín et al., 2023). Among GR options, the most considered typologies are Extensive Green Roofs (EGR), lightweight vegetated systems with shallow substrates (typically less than 10–15 cm) and low-growing, stress-tolerant plant communities; Intensive Green Roofs (IGR), deeper-substrate systems (greater than 15 cm) that support more diverse plantings (e.g., lawns, shrubs, small trees); and Rooftop Gardens (RG), accessible roof landscapes for amenity and/or food production (Harada and Whitlow, 2020; Oberndorfer et al., 2007; Ma et al., 2024a).

In the most recent EU strategies, GRs are considered strategic solutions to restore ecosystem services and to adapt cities to climate change. According to the EU Soil Strategy for 2030, roofs enable the reuse of land that is already occupied or sealed, as reported by the Land Take Hierarchy (European Commission, 2021). The EU Biodiversity Strategy for 2030 highlights the role of GRs as strategic interventions that should be included in the new Urban Greening Plans, contributing to biodiversity, climate resilience, and improved urban sustainability and equity planning (European Commission, 2020). In fact, in densely built cities, rooftops typically constitute 20–25% of the planimetric urban surface (Nguyen Dang et al., 2022). Given the limited ground-level space and the extensive sealing of surfaces, this roofscape provides additional opportunities, mitigates some ecosystem services lost with imperviousness, and simultaneously providing a further or alternative platform for decarbonization strategies (Dong and He, 2023). Moreover, even small and simple GRs can provide moments of restoration for citizens where more substantial interventions and public spaces are not feasible (Mesimäki et al., 2019). However, as reported by scientific literature, there are different constraints to the adoption of these solutions. As reported by Liberalesso et al. (2020), despite the recognized environmental and social value of GRs, a persistent mismatch between their broader benefits and financial assessments, driven by high upfront and maintenance costs, limits private investment, pressuring municipalities worldwide to rely on incentive policies, particularly financial subsidies and regulatory obligations, to support their adoption. Moreover, while in some countries, as for example China, accelerated urbanization has led to a rapid expansion of buildings and, as a consequence, of new roofs, in European countries, the limited space does not allow new buildings. Therefore, the majority of efforts should be related to retrofitting existing buildings, avoiding greenwashing of some GRs and, at the same time, testing different technologies other than traditional GRs, that could be heavy for existing and old constructions (Wójcik-Madej et al., 2026; Yan et al., 2026).

A widely recognized role of rooftops is also their use for hosting Photovoltaic Systems (PVs). Renewable energy sources are increasingly deployed to enhance security of supply, mitigate climate change, and reduce household energy costs (Baranes et al., 2017). In Europe, PVs generation increased by approximately 36 TWh in 2023, reaching around 9% of total EU electricity (Brown and Jones, 2024). The Intergovernmental Panel on Climate Change (IPCC) identifies rapid electricity decarbonization, driven by cost declines in PVs (and storage), as pivotal for near-term mitigation, reinforcing the rationale for building-integrated PVs to cut operational emissions and reduce exposure to fossil-fuel price volatility (Clark et al., 2008). Beyond conventional rooftop installations, more recent solutions such as building-integrated photovoltaics (BIPV) extend solar harvesting beyond rooftops to facades, skylights, and other envelope elements, particularly in dense urban centers where roof area is scarce (Martín-Chivelet et al., 2022; Ni et al., 2025). However, despite their potential, robust city-scale assessments of BIPV remain constrained by data availability, modeling complexity, and regulatory and economic barriers (Dehghanimadvar et al., 2022; Ni et al., 2023).

Given this background, these rooftops' technologies are promoted in spatial planning by EU policymakers as a viable strategy to improve climate mitigation and adaptation, energy transition, and overall urban resilience (Cruz Torres et al., 2023). However, at both academic and policy levels, rooftop interventions are typically treated as single-technology responses. Although there is a growing interest in combining these two technologies, the existing academic literature remains fragmented, as most studies focus on isolated performance aspects rather than on the integrated and scalable synergies between these systems (Yan et al., 2026). This fragmentation results in analyses that evaluate either GRs or PVs for isolated purposes, such as microclimate regulation, renewable energy, or CO_2 emissions (Islam et al., 2023; Melius et al., 2013; Rowe, 2010). For instance, a systematic review by Abdalazeem et al. (2022) shows that only a limited number of studies (28) jointly examine the integration between PVs and GRs, in relation to the performance of three main parameters (UHI mitigation, energy-saving and indoor thermal comfort), while most articles (157) analyzed GRs individually. As a result, the performance of these combined systems, across different climatic contexts, needs more in-depth investigation, especially during winter season, which is not explicitly addressed in any of the reviewed studies.

This lens often overlooks the gains from assessing multiple systems together, synergetic opportunities, thus limiting socio-environmental benefits and opportunities for collective, synergistic, multifunctional uses. For example, recent studies shows improved performance from integrated “bio solar” configurations that co-locate PVs with vegetated roofs, rather than deploying a single use (Van Der Roest et al., 2023). For example, Alonso-Marroquin and Qadir (2023) reported how the integration of PVs with GRs enhanced indoor thermal comfort by approximately 6% compared to conventional PVs, while simultaneously lowering photovoltaic operating temperatures by up to 8 °C and contributing to extending the life of PVs modules.

The integration of the two systems presents multiple technical, economic, and contextual challenges that continue to limit the widespread adoption of PV and GRs solutions across different regions (Shafique et al., 2020). As already mentioned, there is a lack of comprehensive experimental data on the synergies among GRs and PVs, on the appropriate location and separation height of the PV system on the GR (Baumann et al., 2019; Osma-Pinto and Ordóñez-Plata, 2019), and on the most suitable plant types for reducing, for example, the surface temperature of photovoltaic panels. Moreover, a key challenge to the widespread adoption of PVs and GRs systems lies in the lack of mature industrial design solutions and long-term maintenance frameworks, coupled with limited awareness among practitioners and stakeholders of their sustained performance and efficiency benefits (Fouad et al., 2017). The main technical difficulties include limited awareness of their benefits, especially in developing countries, high initial system costs, the lack of supportive laws and regulations, and geographical and architectural constraints such as insufficient rooftop space and limited solar exposure in dense urban contexts (Karakaya and Sriwannawit, 2015; Liberalesso et al., 2020; Olowu et al., 2018; Zhang et al., 2012).

Ensuring that GI and renewable energy solutions do not generate socio-environmental expropriation, displacement, or the reinforcement of elite-driven interests, requires a justice-oriented approach to their design and implementation (Mohtat and Khirfan, 2021). Scholars have progressively highlighted how GI and nature-based solutions may drive rising property values and rents, contributing to processes of gentrification, intensifying the exposure and vulnerability of marginalized groups, and ultimately leading to the displacement of socio-economically disadvantaged populations (Anguelovski et al., 2019; Brown et al., 2012; Juhola, 2016). These risks make clear that the success of GRs and PVs cannot be assessed solely in technical or environmental terms. Rather, their planning and deployment must be grounded in a careful evaluation of where and for whom such interventions are implemented, ensuring benefits for both ecosystems and citizens' well-being, while contributing to just and equitable urban planning. In this sense, as emphasized by Anguelovski et al. (2024), climate hazard planning should explicitly prioritize the needs and protection of people, particularly those most vulnerable.

Previous studies have focused mainly on the technical and economic feasibility aspects of GRs and PVs. They mainly used multicriteria analyses (hereafter MCDA as the acronym for Multicriteria Decision Analysis) coupled with Geographic Information Systems (GIS) to map suitable rooftops based on factors such as roof area and slope, load-bearing capacity, shading effect, or exposure to sunlight (Favretto, 2018; Clark et al., 2008; Greene et al., 2011; Palmer et al., 2018).

These studies have greatly advanced the ability to quantify the potential of rooftops in urban planning. However, much of the literature treats these technologies deployment as a purely physical optimization exercise, giving little attention to where planning would most benefit both citizens and their surroundings. As a result, relatively little attention is being paid to integrating climate

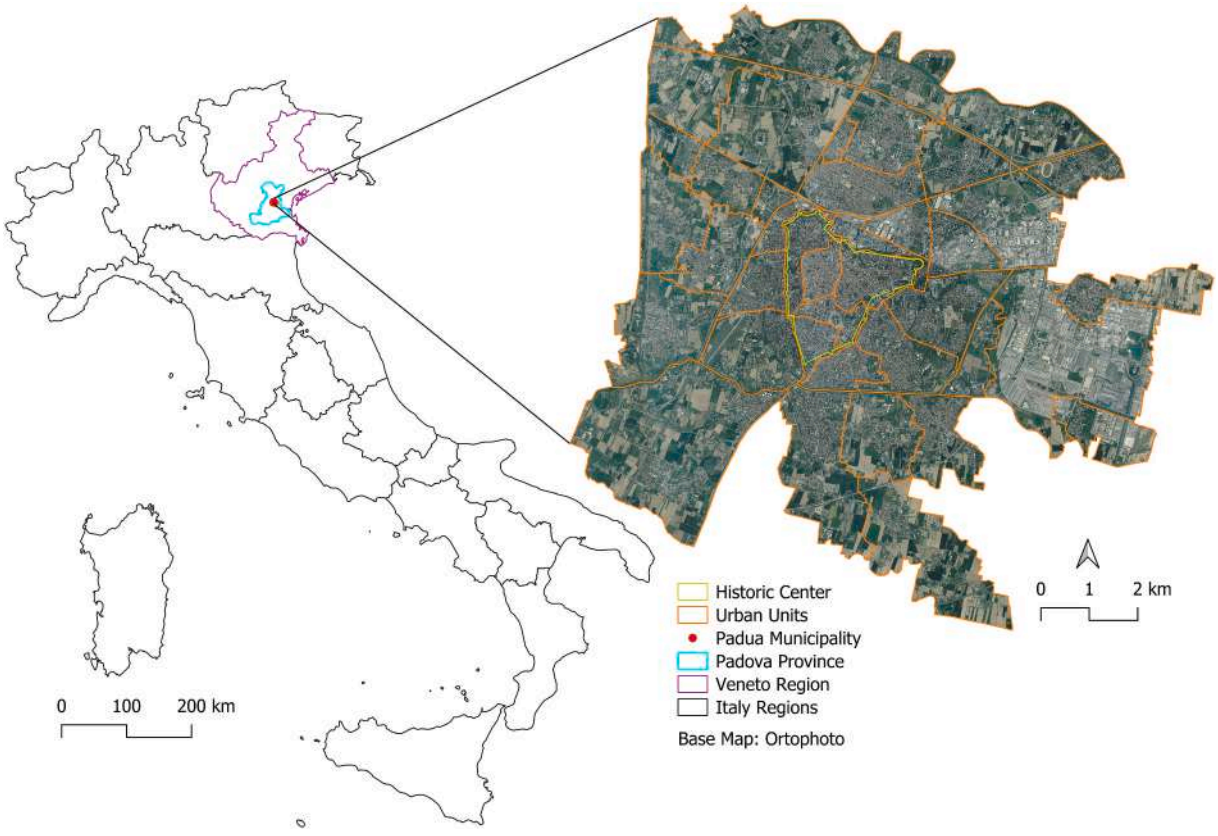


Fig. 1. Spatial context of the study area, including the municipality boundary and the forty Urban Units (UUs), which are used for sub-municipal management and statistical purposes.

justice and equity criteria into GI planning. Caniglia et al. (2017) agree that there are multiple ways to achieve urban resilience, but not all promote social and environmental justice. Therefore, GI performance regarding urban resilience is a complex issue that requires more thorough quantitative research encompassing not only physical suitability, but also socio-economic and environmental aspects.

Based on these premises, this research develops a GIS-MCDA framework to evaluate rooftop suitability for GI retrofitting and renewable energy integration, aiming to support more just and equitable urban planning. It focuses on identifying how different rooftop strategies (GRs, RG, and PVs), can jointly contribute to environmental performance and social resilience.

The specific objectives are: (i) to assess the physical and spatial suitability of rooftops for different GI and PVs options; (ii) to analyze their potential synergies and competition in terms of space and function (Slootweg et al., 2023); and (iii) to construct a composite socio-economic and environmental vulnerability index to locate Urban Units (UUs) where interventions can deliver the highest co-benefits. The framework is applied to the municipality of Padua, Italy, a medium-sized European city (Busato et al., 2014; Codato et al., 2024; Pristeri et al., 2021).

2. Materials and methods

2.1. Study area

The study area encompasses the city of Padua (45.4167° N, 11.8667° E) in Italy's Veneto region. The municipality is situated on a 93.3 km^2 alluvial plain, has approximately 210,000 inhabitants (Comune di Padova, 2024), and functions as a major cultural, economic, and academic hub in northeastern Italy. Fig. 1 shows the location of the Padua municipality in Italy, its historical center and the forty Urban Units (UUs, for UUs names see Supplementary Material 4.1), which are used for sub-municipal management and statistical purposes.

Padua's climate and environmental challenges are compounded by climate change and by the rapid urban expansion that followed World War II (Peroni et al., 2023). The city exhibits a pronounced UHI effect, with air temperatures in the densely built core reaching up to 7 °C higher than surrounding rural areas, resulting from extensive soil sealing and high building density (Todeschi et al., 2022). During summer 2022, persistent heatwaves saw daytime maxima consistently exceed 35 °C, exacerbating heat-related health risks for vulnerable populations, particularly the elderly and socio-economically disadvantaged groups (Pappalardo et al., 2023).

Soil sealing statistics vary slightly depending on the scale of analysis and methodology. The Italian Institute for Environmental Protection and Research (ISPRA) monitoring of sealed soil across Italy shows a consolidated percentage above 47% after 2006, gradually increasing to about 49% in 2023, with Padua ranking fifth among Italian municipality in terms of soil sealing (ISPRA, 2024). Pristeri et al. (2021), in their investigation of Padua's green spaces (including agricultural areas) based on high-resolution 2015 imagery and other relevant data, report that approximately 56% of Padua's territory is green, meaning that around 44% is not. Moreover, 80% of the green areas are privately owned, which limits public access and contributes to the inequitable distribution of ecosystem services. This extensive impervious cover has amplified surface runoff, diminished groundwater recharge, and elevated flood risk. Consequently, frequent flood events exceed drainage capacity, damaging public facilities and private properties (Bortolini and Brasola, 2022). The retreat of traditional agriculture, driven by urban expansion and pollution, has further reduced biodiversity and eroded local ecological knowledge, diminishing the landscape's resilience (Souviney et al., 2024; Peroni et al., 2023). This ownership disparity further exacerbates socio-spatial inequalities, as vulnerable neighborhoods experience reduced accessibility to public green areas.

Table 1
Summary of datasets utilized in this study.

Dataset	Description	Source	Format	Reference Year
Orthophoto	High-resolution aerial imagery used for photointerpretation and validation	Veneto Region Geoportal	Raster (20 cm/pixel)	2021
Digital Surface Model (DSM) and Digital Terrain Model (DTM)	Derived from LiDAR-based surveys	Municipality of Padua	Raster (50 cm/pixel)	2023
Land Surface Temperature (LST)	Derived from Landsat 8–9 OLI/TIRS C2 L2.	USGS Earth explorer	Raster (30 m/pixel)	2023
Buildings footprint	Data from the topographic database including building geometries and usage	Municipality of Padua	Vector (polygon)	2023
OpenStreetMap (OSM) buildings footprint	Data from the OSM project	OpenStreetMap	Vector (polygon)	2025
Impervious Surfaces	Data from the topographic database including on the ground impervious surfaces	Municipality of Padova	Vector (polygon)	2023
Socio-Demographic Data	Statistical data at the level of Urban Units (UUs)	Municipality of Padua (Comune di Padova, 2024)	Spreadsheet	2024
Economic data	Number of taxpayers and their income per ZIP code	Ministry of Economy and Finance	Spreadsheet and vector (polygon)	2024
Urban Units (UUs) of Padua	40 urban units, sub-municipal divisions used for administrative and statistical purposes	Municipality of Padua	Vector (polygon)	2023
Green Spaces (Private)	Private green spaces within the study area	Derived from Pristeri et al. (2021)	Vector (polygon)	2021
Public parkings	Green spaces managed by Municipality of Padua	Municipality of Padua	Vector (polygon)	2023

Strategic deployment of available rooftop space and GI can address these interconnected environmental challenges by mitigating UHI effects, managing stormwater, and supporting biodiversity by expanding accessible green spaces among other ecosystem services. This approach directly operationalizes Padua's policy frameworks, notably the Boeri masterplan's afforestation targets and the Municipal Green Plan, advancing SDG 11's mandate for inclusive, resilient urban development (Comune di, 2019; Comune di Padova, 2024).

2.2. Input dataset

This study was based entirely on publicly accessible datasets and open-source software. Spatial and statistical analyses were performed in Google Earth Engine (GEE) (accessed August 2025) and QGIS software (version 3.40.7). All spatial layers were converted to the Monte Mario / Italy Zone 1 (EPSG:3003) coordinate system. A list of the datasets is provided in Table 1 and their utilization explained in methodology.

2.3. Methodology

This research employs a two-step spatial analysis framework, widely adopted in recent literature, to (a) identify suitable rooftops and (b) prioritize these rooftops based on socio-economic and environmental vulnerability criteria (Grunwald et al., 2017; Palmer et al., 2018). Specifically, we developed a GIS-MCDA based framework, the Rooftops for Equity and Sustainability (RT4ES) model, to identify rooftops suitable for GRs and PVs applications and to prioritize those suitable rooftops within UUs that require targeted greening, and solar energy investments, thereby enhancing urban climate resilience through social and environmental equity planning in Padua. In Fig. 2, a summary of the overall workflow described in the following sections is presented, while the complete research and methodological framework is provided as a graphical abstract in Supplementary Material 5.

2.3.1. Rooftops suitability analysis

For the first part of the RT4ES model, the identification of potentially suitable rooftops involved several preprocessing steps. First, we computed a normalized Digital Surface Model (nDSM) by subtracting the Digital Terrain Model (DTM), representing the bare-earth surface, from the Digital Surface Model (DSM), which captures the elevation of all visible objects, including buildings and vegetation. This subtraction isolates above-ground structures (Beumier and Idrissa, 2014; Khoshelham et al., 2010). A 5 × 5 pixel window median filter was then applied to the nDSM to suppress LiDAR noise and artifacts, such as rooftop chimneys, staircase landings and other perturbing rooftop objects such as overhanging trees, while preserving roof edges. From this dataset, a slope raster (in degrees) was generated. To retain only true building heights, zero-height nDSM pixels were converted to No Data, thereby preventing flat ground and non-roof surfaces from influencing slope calculations. Next, the cleaned slope raster was masked using vector building footprints, ensuring that only rooftop pixels remained for suitability analysis. Finally, slope pixels were reclassified into four categories using the 'Reclassify by Table' algorithm (see Table 2), with class 4 masked as it corresponds to building edges.

Before quantitative filtering, we overlaid the classified slope raster atop the high-resolution orthophoto to visually inspect and qualitatively validate the result.

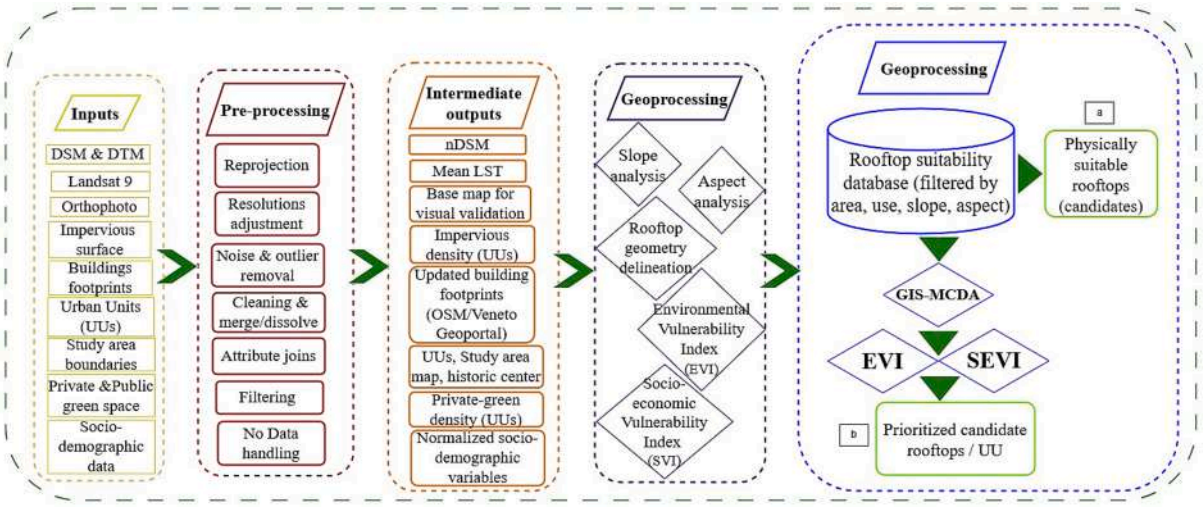


Fig. 2. Schematic overview of the RT4ES methodological framework, showing the sequential stages from multi-source data input and GIS pre-processing through intermediate outputs, geo-processing analyses, and final multicriteria decision analysis for rooftop suitability and priority analysis. Acronyms: DSM (Digital Surface Model), DTM (Digital Terrain Model), nDSM (normalized Digital Surface Model), LST (Land Surface Temperature), UUs (Urban Units), EVI (Environmental Vulnerability Index), SEVI (Socio-economic Vulnerability Index), GIS-MCDA (Geographic Information System-Multi-Criteria Decision Analysis).

Table 2
Slope classes with slope range and relevant assigned roof types.

Class	Slope range	Roof type
1	0–10°	Flat
2	10–30°	Low slope
3	30–60°	Steep
4	60–90°	Edge

For each slope class, we applied the 'Zonal Statistics' tool to compute per-building metrics, including minimum, maximum, median, sum, and raster cell count statistics. To enable intervention-specific assignment, the dominant slope class of each roof was then propagated into a dedicated attribute field ('Roof Class'). This is accomplished with the QGIS expression in the building layer's 'Attribute Table', evaluating the class count, and populating a new column, so that each rooftop can be directly managed and mapped for further suitability analysis. To complete the rooftop-suitability database, we first computed the planimetric area of each classified rooftop polygon, followed by applying minimum-area filters corresponding to intervention type:

- GRs & PVs: greater than 100 m^2, with no existing formal standard, we adopt a 100 m^2 minimum, consistent with common literature thresholds, economically viable for PVs, and comparable to typical GRs deployments (Lambarki et al., 2022; Mutani and Todeschi, 2020; Rafida, 2004; Santos et al., 2016);
- RG: greater than 30 m^2, in line with Padua municipality for community gardens, 30 m^2 as a practical minimum area for community allotment plots in urban contexts (Comune di, 2019).

Roof aspects were analyzed according to the cardinal points (0°-360°) using the aspect tool in QGIS environment, and north-facing facets (between 315° and 45°) were identified as those receiving least annual insolation compared to other three directions. For PVs suitability on sloped roofs (10–45°), we excluded north-facing facets in the final available suitable area (see Supplementary Material 4.3). Moreover, to support intervention-specific rooftop assignments, rooftop geometries were classified into residential and non-residential categories using building-use attributes primarily derived from the municipal topographic database, complemented, where necessary and when available, with data extracted from OpenStreetMap (OSM) database (www.openstreetmap.org). The process included merging building characteristics from OSM into the topographic database (from the Padua Municipality), completing and updating missing buildings categories in the Padua Municipality building footprint database, and filtering out geometries that did not meet the criteria for the final suitability analysis database (e.g., minimum area and building use). This categorization enabled us to:

a) Restrict IGR and RG deployment to potentially structurally robust, non-residential or institutional buildings with adequate deck load capacity;
b) Tailor PVs deployment on low-slope roofs, mounted roof (no tilt racking), and on large industrial rooftops where structural capacity and layout efficiency enable high-capacity arrays; by contrast, flat roofs (less than 10°) generally require sloped racking;
c) Assign EGR to mainly residential structures with lower dead-load tolerances, leveraging their lightweight substrate systems, the number of EGRs on non-residential roofs is negligible.

In Table 3, the rooftop suitability criteria are presented, defining maximum slope, minimum contiguous area, and eligible building-use for four types of interventions: IGR, EGR, RG, and PVs, thereby establishing the main criteria for suitability analysis.

After careful visual investigation, shading criteria were not included due to data limitation and because Padua's predominantly low-rise urban fabric results in minimal inter-roof shading. High-resolution orthophotos further confirmed relatively homogenous roofscape with negligible shadowing effect. Finally, load-bearing capacity was not modeled due to data limitations and the prospective nature of our analysis; structural assessments must be conducted on a case-by-case basis prior to installation (Slootweg et al., 2023).

These criteria in Table 3 guided the identification of rooftops that potentially accommodate either IGR, EGR, RG, or PVs alone or two or more systems together. Based on the resulting suitability layers, spatial overlays were performed to detect UUs where multiple systems could coexist (synergy) or compete for the same rooftop surface (competition). This procedure enabled the quantification of multifunctional opportunities and spatial constraints within the existing urban fabric.

2.3.2. Prioritization of suitable rooftops

The results from the first phase of the study can stand alone, identifying rooftops suitable for urban greening and solar energy production in a European mid-sized city. For equitable, climate justice-oriented urban planning, implementation should prioritize roofs that maximize social and environmental co-benefits, serving communities facing existing environmental deficits. To move from only suitability analysis of greenery and solar energy production, in this step, we analyze the equitable prioritization of suitable rooftops as well.

Identifying optimal locations for GI interventions requires the simultaneous evaluation of multiple, often competing, spatial and non-spatial variables. To address this complexity, the present study integrates a GIS-MCDA, a methodological pairing widely recognized for its effectiveness in spatial decision-making (Chen et al., 2010; Malczewski, 2006). GIS-based MCDA enables the systematic integration of diverse criteria, physical, environmental, and socio-economic, into a composite suitability index, allowing for transparent and replicable prioritization of spatial units. Its strength lies in accommodating conflicting objectives and assigning relative

Table 3
Rooftop intervention thresholds: maximum permissible slope, minimum contiguous area, and building-use eligibility for each intervention type.

Intervention	Maximum Slope	Minimum Area	Building Use
Intensive Green Roof (IGR)	$\leq 10^{\circ}$ – engineered systems require near-flat surfaces to prevent substrate slippage and ensure even moisture retention (Kim et al., 2021; Mentens et al., 2006; Rafida, 2004).	$\geq 100\ m^2$ – although no strict scientific minimum exists, adopted for consistency with common engineering and municipal practice (Lambarki et al., 2025; Rafida, 2004).	Non-residential only – often for higher dead-load capacity (Wu et al., 2025).
Extensive Green Roof (EGR)	$10–30^{\circ}$ – retains water effectively up to moderate pitches (Mentens et al., 2006; (Rafida, 2004).	$\geq 100\ m^2$ – although no strict scientific minimum exists, adopted for consistency with common engineering and municipal practice (Rafida, 2004).	Residential and non-residential – lighter loads capacity.
Urban Rooftop Garden (RG)	$\leq 10^{\circ}$ – flat roofs chosen to support larger, cost-effective rooftop gardens (Mentens et al., 2006; Xie et al., 2024).	$\geq 30\ m^2$ – practical minimum for community-scale gardening (Comune di, 2019).	We considered all building types: flexible urban agriculture use.
Solar Photovoltaics (PVs)	Optimal: ≤ 10 and $10–45^{\circ}$ – aligns with local latitude for peak irradiance. Exclusion of north-facing facets on sloped roofs. (Jacobson and Jadhav, 2018).	$\geq 100\ m^2$ – aligned with green-roof convention to enable cost-effective PV array layouts.	All building types – broad PV applicability, for flat roofs, only non-residential buildings.

importance to each criterion, thereby supporting balanced decision-making under uncertainty (Jankowski, 1995). This approach has been extensively applied in land use planning and environmental management to identify suitable sites for greening and PVs implementations, optimizing its ecosystem service delivery, and tailor interventions to the specific characteristics and constraints of each location (Bousquet et al., 2023; Meerow and Newell, 2017; Pochodyła-Ducka et al., 2025). As a result, in the second part of the RT4ES model, suitable rooftops are prioritized at the UU scale by integrating socio-economic and environmental vulnerability indicators.

The rooftop suitability proportion was calculated as the ratio of suitable rooftop area to the total rooftop area within each UU and subsequently normalized using the min–max method (see Supplementary Material 1). Next, a composite Socio-economic Vulnerability Index (SEVI) was developed by first calculating either the density or proportion of each selected indicator at the UU level, followed by normalization using the min–max method to the scale of (0–1) (see Supplementary Material 2). The normalized indicators were then aggregated, assuming equal weighting, into a single composite index representing socio-economic vulnerability across the study area. As detailed in Table 4, six socio-economic indicators were selected to measure vulnerability at the UU scale: low income, migration background, elderly residents, minors, household size, and elderly living alone. The rationale for each socio-economic criterion is also summarized in the same table. Full details on the calculation of socio-economic density and proportions are provided in Supplementary Material 2.

Similarly, an Environmental Vulnerability Index (EVI) was developed by aggregating normalized environmental indicators, each rescaled to a (0–1) range to ensure comparability. For analyzing EVI, four criteria according to Table 5 were considered: private green space, public parking, land surface temperature (LST) and impervious surface per UU. Complete description on the LST calculation formula, the list of satellite images used for LST calculation, the GEE code, the LST mean and 90th percentile maps, and the private green and public parking coverage maps are provided in Supplementary Material 3. Table 5 provides the full description and rationale for each EVI criterion.

2.3.3. GIS-MCDA

Following normalization and aggregating the indicators in 2.3 Methodology, the integration of multiple criteria was accomplished via a Weighted Linear Combination (WLC) technique (see Supplementary Material 1), that was selected for its transparency and ease of implementation and executed within the QGIS environment (Bousquet et al., 2023). In this procedure, each standardized vector layer, representing physical suitability (suitable rooftops), SEVI and EVI indexes, was multiplied by its respective literature-informed and expert discussion weight and subsequently summed to yield the RT4ES priority score for each rooftop intervention. We adopted a weighting of 0.25 for physical suitability, 0.35 for environmental vulnerability, and 0.40 for socio-economic vulnerability. This balance ensures that rooftop suitability, urban-environment stress, and social equity are each given appropriate emphasis in our final RT4ES prioritization framework (Apud et al., 2020; Bakolo et al., 2024; Croeser et al., 2021; Megyesi et al., 2024).

Finally, family density was analyzed as an additional spatial indicator to further contextualize the priority results. It was calculated as the total number of families within each UU divided by its area (families/km^2), representing the spatial concentration of residential households (family density map is provided in Supplementary Material 4.7). Although the SEVI already incorporated several demographics and socio-economic variables, family density was examined to capture population exposure rather than vulnerability. The resulting layer was classified using the quantile method, and only the first and fifth quantiles, representing the lowest and highest family densities, were visualized to support the subsequent spatial comparison with the priority mapping outcomes.

Table 4
Socio-economic indicators used to construct the composite Social Vulnerability Index (SEVI) at the urban unit scale, their purpose in vulnerability assessment and relative source.

Indicator	Reason for Vulnerability Assessment	Description	References
Taxpayers with annual income $<$ €10,000	Captures extreme economic deprivation, which diminishes capacity to prepare for and recover from environmental stressors (e.g., lack of assets for home improvements, limited insurance coverage).	Share of total taxpayers in each UU	(Cutter et al., 2003; Schmidtlein et al., 2008)
Households of $\geq$ 5 members	Indicates potential overcrowding and high dependency ratios, elevating risk during heat waves, pandemics, and resource shortages (e.g., more vulnerable individuals per dwelling).	Share of the total in each UU	(Cutter et al., 2003; Frigerio and De Amicis, 2016; Schmidtlein et al., 2008)
Household with children under 2 years old	Young children are repeatedly identified as heat-susceptible in vulnerability studies.	Share of the total in each UU	(Khodadad et al., 2025)
Households with $\geq$ 1 member aged $\geq$ 60 years	Reflects age-related vulnerability, as older adults are disproportionately susceptible to heat stress, isolation, and mobility constraints during emergencies.	Share of the total in each UU	(Frigerio and De Amicis, 2016; Oudin Åström et al., 2011)
Residents with migration background	Captures language, cultural, and institutional barriers to accessing information and services, increasing risk of exclusion from preparedness and recovery efforts.	Share of the total in each UU	(Messeri et al., 2019)
65 years old living alone (social isolation)	Social isolation further elevates risk, multiple epidemiologic studies ties living alone to higher heat-related mortality.	Share of the total in each UU	(Pappalardo et al., 2023)

Table 5
Environmental Vulnerability Index (EVI) description and method.

Indicator	Description	Reason for Vulnerability Assessment	References
Private Green space	Percent of private green space area in each UU. Vector data from (Pristeri et al., 2021) were updated by subtracting 2023 building footprint.	UUs with less presence of private green spaces are more vulnerable to heat stress and reduced cooling. The absence of localized shading and evapotranspiration further intensifies UHI effects and heightens associated health risks.	(Egerer et al., 2024; Godoi et al., 2025; Pristeri et al., 2021)
Land Surface Temperature (LST)	Mean land surface temperature for the summer of 2023 at the UU level, processing in GEE Landsat 2 level 2 band 10.	Higher LST directly correlates with UHI intensity, increasing heat-related mortality and morbidity, particularly in low-income neighborhoods with limited adaptive capacity.	(Dimitriou et al., 2025; Pappalardo et al., 2023; Krenz and Amann, 2025)
Public Parking	Total public parking surface in m^2 to total families within each UU.	UUs with few public parks limits access to cool, restorative green spaces, exacerbating heat stress and reducing adaptive capacity, especially for lower socio-economic residents who rely on public rather than private greenery.	(Codato et al., 2024; Lin and Li, 2025; Zhang et al., 2024)
Impervious Surface	Percent of land covered by impervious surfaces in each UU.	Impervious surfaces amplify heat absorption and runoff, heightening flood and UHI risks, and exacerbating environmental inequities in urban areas with socioeconomic disparities.	(Liu et al., 2020; Ma et al., 2024b; Shi et al., 2023)

3. Results

3.1. Potential suitable rooftops

Across the study area, the model identifies 11.67 km^2 of net suitable rooftops across 29,493 buildings. Overall, rooftop suitability comprises overlapping suitability sets rather than discrete classes. Reporting each intervention according to its defined criteria, the citywide totals are: EGR (7.25 km^2 across 24,372 roofs), RG (3.69 km^2 across 5394 roofs), IGR (2.71 km^2 across 1194 roofs), and PVs (11.93 km^2 across 30,372 roofs).

Because suitability is not mutually exclusive: (i) flat roofs larger than 100 m^2 where PVs, IGR, and RG all qualify, and (ii) low-slope roofs where EGR and PVs both qualify, figures are reported independently and should not be aggregated. To resolve these overlaps in a policy-relevant way, we also analyze synergy (feasible co-location) and competition (either/or choices). Spatial patterns are consistent with expectations: EGR potential tracks the distribution of low-slope residential stock; IGR cluster on fewer, larger non-residential buildings; RG extend coverage beyond flat roofs smaller than 100 m^2 to include smaller and residential flat roofs; and PVs span flat, low-slope, and steep roofs, with north-facing facets excluded on sloped roofs. Table 6 reports the non-exclusive totals.

Fig. 3 maps rooftops classes based on roof's dominant slope class: flat roofs cluster in the east and north-east, largely within the non-residential stock of the industrial zone; low-slope roofs, the bulk of suitable area, are pervasive in the historical city center and adjacent UUs to the north, south, and west but are comparatively scarce in the east unlike flat roofs; sloped roofs are least prevalent and appear as scattered pockets across the study area on both residential and non-residential buildings.

Fig. 4 presents UU level potential suitability for four rooftop interventions (IGR, EGR, RG, and PVs), expressed in the percentage of suitable rooftop area to the total rooftop area. For better understanding, representative building-level overlays of suitable rooftop polygons on the study-area orthophoto are provided in the Supplementary Material 4.8.

Across UUs, the potential suitability for IGR, EGR, RG, and PVs exhibit notable spatial variation. High potential suitability for IGR and RG is concentrated in the eastern and north-eastern industrial districts, where large, flat non-residential roofs are common. By contrast, suitability is lowest in the historic core and adjacent western UUs, in particular southern and western ones. EGR exhibits high potential suitability in the historic center, scattered pockets in southern areas, and parts of the west zone, with the lowest potential

Table 6
Overall rooftop potential suitability by intervention (non-exclusive). Categories are not mutually exclusive; due to overlapping suitability, figures are reported independently and should not be summed. Photovoltaic totals exclude north-facing sloped roofs.

Intervention	Slope / Minimum Area	Building use	Exclusion of north-facing facets	Area (km^2)	Roof count
Intensive Green Roofs (IGR)	Flat (0–10°), ≥100 m^2	Non-residential	No	2.71	1194
Urban Rooftop Gardens (RG)	Flat (0–10°), ≥30 m^2	Residential & non-residential	No	3.69	5394
Extensive Green Roofs (EGR)	Low slope (10–30°), ≥100 m^2	Residential & non-residential	No	7.25	24,372
Photovoltaics (PVs)	Flat (Non-residential), Low slope (Residential & non-residential); Steep (Residential & non-residential) (30–45°), ≥100 m^2	As specified per slope/use	Excluded on sloped roofs	11.93	30,372

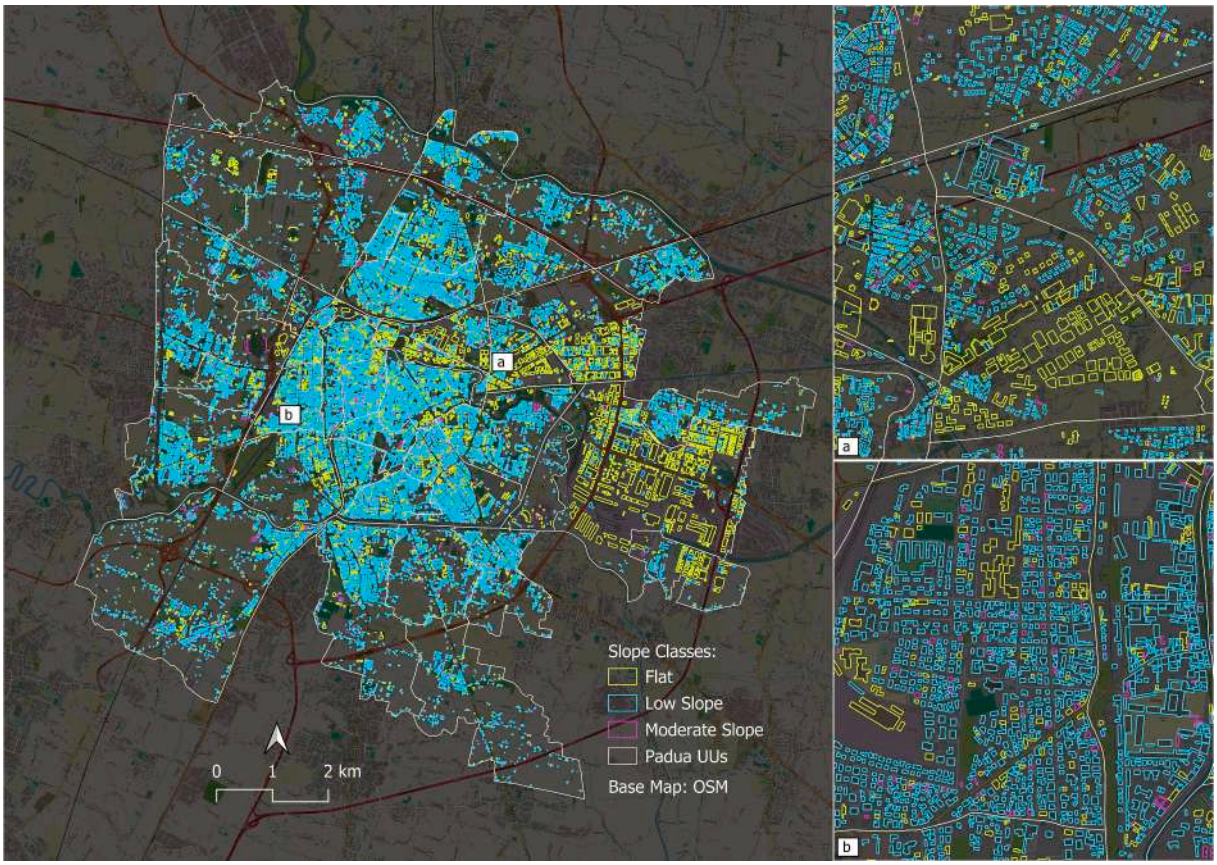


Fig. 3. Spatial distribution of roof types classified by roof's dominant slope class.

occurring in the eastern part of the city. PVs show similarly strong potential in the historic center and adjacent UUs in the north, as well as in southern UUs.

3.1.1. Spatial distribution of green roofs and solar panel competition and synergies

The RT4ES model also explored the geographical potential of rooftop space for supplying surplus greening and producing renewable energy by evaluating synergies and competition among the rooftop systems.

Low-slope roofs are suitable for both EGR and PVs as Fig. 4 shows, suitability reaches up to 90%, for EGR, that is also true for PVs, but they cannot be combined (Slootweg et al., 2023). Thus, the RT4ES model shows the overlap ranged between 16% and 90%. Some UUs show an overlap between 74% and 90%, requiring detailed attention to understand what should be prioritized to have the most optimal outcome for mitigating climate stressors and considering climate justice in urbanized areas. Fig. 5 maps the spatial distribution of this overlap.

RG, IGR, and PVs are suitable on flat roofs (up to 10°), with IGR on non-residential buildings, and RG and PVs on both residential and non-residential buildings. On flat, non-residential roofs larger than 100 m^2, these systems can be co-implemented; planners may select IGR or RG in combination with PVs according to local objectives and constraints. Fig. 6 maps the geographic potential for this synergy, simultaneously increasing greenery/food production and solar energy generation. As expected, synergy potential is highest in UUs where the underlying suitability of all three systems is greatest, notably in the eastern and north-eastern industrial districts with extensive flat-roof stock. In these areas, the synergy share reaches up to 80%.

The influence of building typology on rooftop potential trade-off and synergy is highlighted in Fig. 7, which provides a snapshot demonstrating how residential buildings are subject to spatial trade-offs, while non-residential buildings offer synergistic opportunity.

Padua's rooftop greening potential is substantial relative to existing ground-level green space. Combining (synergy and suitability) EGRs on low-slope roofs with RG on flat roofs, excluding IGR to avoid double counting on flat roofs as both IGR and RG share flat roofs and area larger than 100 m^2, yields 10.94 km^2 of additional vegetated surfaces. This corresponds to 20.95% of the inventoried green-space stock (52.23 km^2) and 11.78% of municipal land area (92.85 km^2). Using Pristeri et al. (2021) as baseline (56% vegetated cover), full uptake would raise citywide vegetated cover to around 67.8% (62.94 km^2).

Concerning rooftop PVs potential, average annual household electricity use in Italy was 2700 kWh yr^{-1} in 2023 (ARERA, 2023). For a simple order-of-magnitude estimate (Bandari et al., 2020), we assume a typical crystalline-silicon module rated at 350 Wp with an area of 1.6 m^2 (0.219 kWp m^{-2}). Applied to the 9.10 km^2 of PVs suitable rooftops (combining synergy and overall suitability,

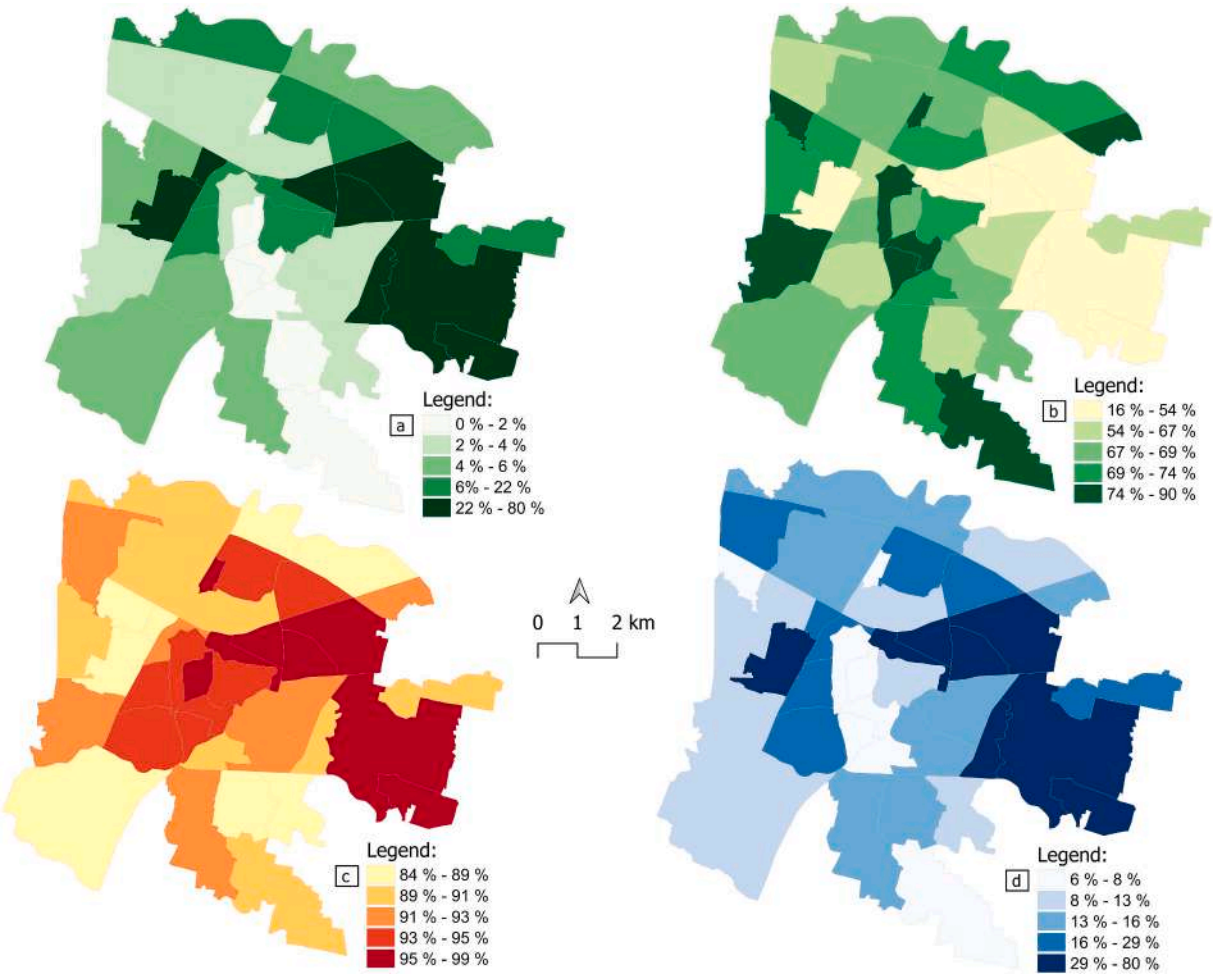


Fig. 4. Suitability potential per UU: proportion of each UU's total rooftop area classified as suitable for (a) IGR, (b) EGR, (c) PVs, and (d) RG. Values are expressed as percentages of suitable rooftop area for the respective system relative to the total rooftop area in the same UU. Data are classified by quantiles for visualization; the same method is applied in all subsequent figures.

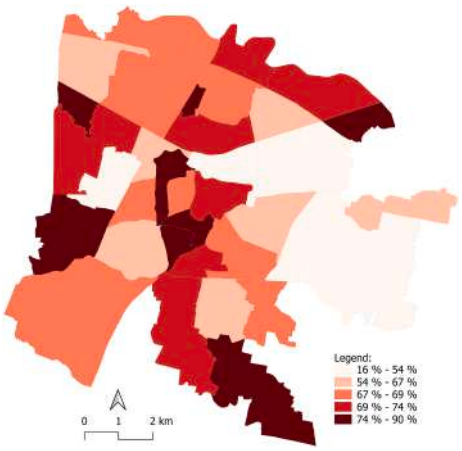


Fig. 5. The competition between EGR and PVs per UUs where these systems compete for space. Either EGR or PVs can be considered. Values are expressed as percentages of suitable rooftop area with respect to the total rooftop area in the same UU.

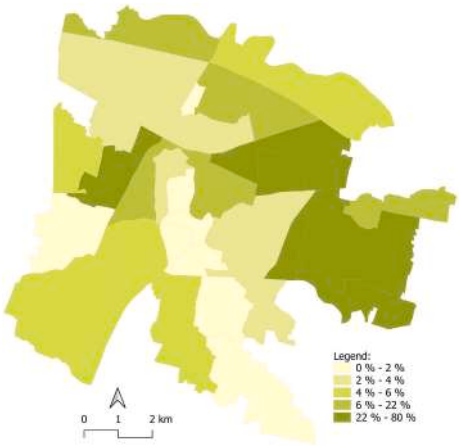


Fig. 6. The potential synergy of the IGR and RG and PVs per urban unit, expressed as percentages of suitable rooftop area with respect to the total rooftop area in the same UU.

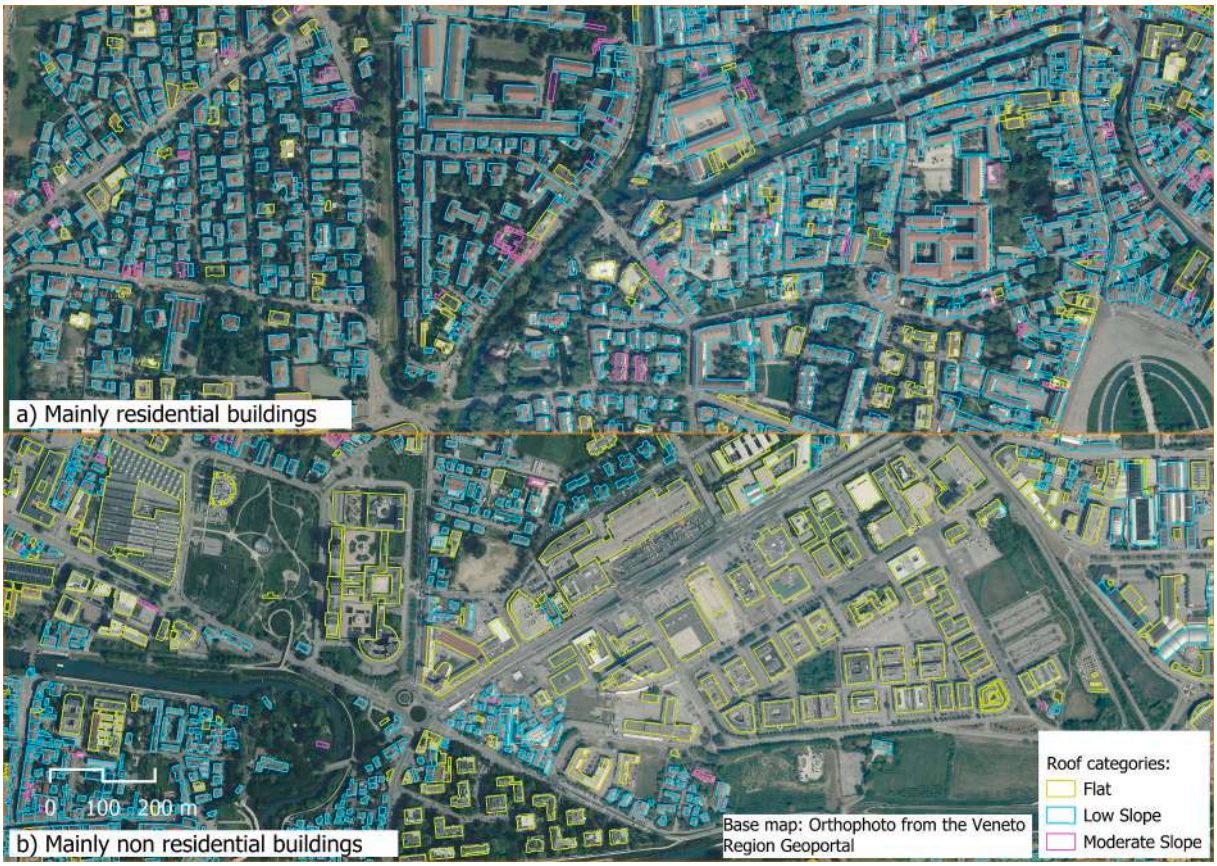


Fig. 7. Two examples of urban areas with different building uses: (a) Compact residential buildings with mainly low-slope roofs, where EGR and PVs show competing uses because of slope and building uses. (b) Non-residential buildings with large flat roofs that enable co-deployment (PVs + GR/RG). Rooftop slope categories based on roof's dominant slope class are shown to aid interpretation; together with building use, they define synergies and competition.

excluding north-facing roofs), this yields around 0.837 TWh yr^{-1}, or about 302% of municipal household electricity consumption (0.251 TWh in 2021) (Comune di Padova, 2024). Thus, the suitable rooftop surface is more than sufficient to meet current residential electricity demand in Padua.

3.2. Prioritization of potential suitable rooftops

3.2.1. Citywide pattern

Fig. 8 maps RT4ES priority rankings for deploying rooftop greening and solar energy production on suitable rooftops. High and very-high priorities cluster in the central, eastern, and north-eastern sectors, where dense stocks of suitable rooftops coincide with elevated social and environmental vulnerability scores. Intermediate priorities occur in a discontinuous inner-middle ring around the high and very high clusters and reflect moderate suitability and vulnerability. Low to very low priorities are predominantly peripheral, where socio-economic vulnerabilities are lower and agricultural/green land cover is more prevalent, improving environmental conditions, though with limited stock of suitable rooftops. These patterns support the validity of priority analysis, indicating that the RT4ES model reliably targets UUs with higher socio-economic and environmental stress.

Our analysis shows that the SEVI is spatially heterogeneous, with higher values concentrated in the northern UUs, and additional pockets around the historic center UUs, and parts of the east, south and west. These UUs coincide with higher shares of residents with a migration background, lower household incomes, larger households, minors, and higher proportions of older adults, including those living alone. By contrast, EVI exhibits a partly distinct pattern: deficits are highest in the north and northeast UUs, city center and UUs out of it, while peripheral areas generally exhibit lower EVI due to greater agricultural/pervious land and higher green coverage. A comparative map of SEVI and EVI is available in Supplementary Material 4.5.

When overlaid with family density, the results reveal that several UUs in the eastern and northeastern parts of the city with the highest intervention priority correspond to areas with relatively low concentrations of families. Conversely, UUs located in the urban core and northern sectors, which exhibit moderate priority levels, tend to have higher family densities (Fig. 8).

3.2.2. Intervention-specific findings

The spatial distribution of rooftop-intervention priorities shows consistent clustering of high and very high values in the eastern,

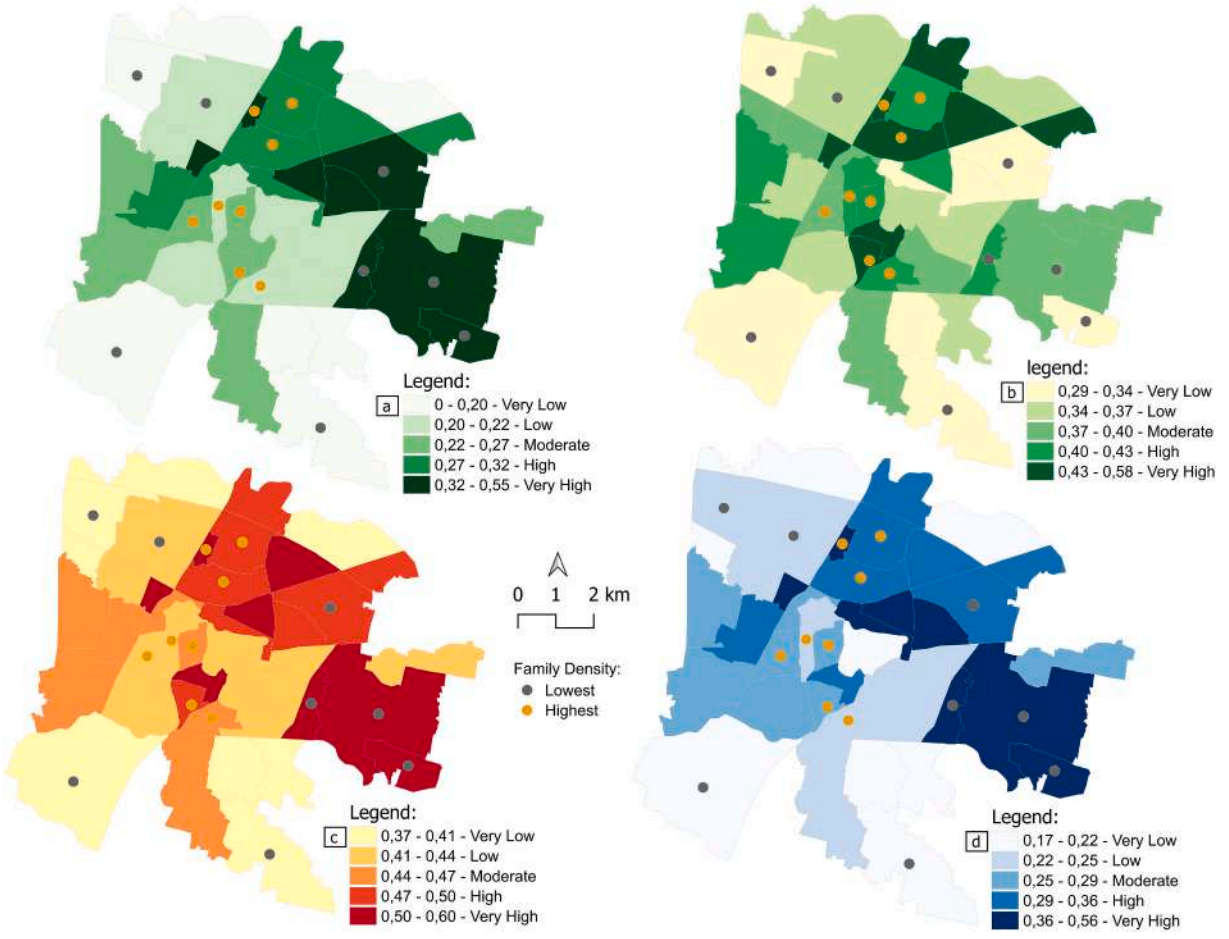


Fig. 8. Spatial distribution of priority ranking per UU for (a) IGR, (b) EGR, (c) PVs, and (d) RG. Each panel uses five quantiles per intervention (Very Low - Very High). Colors are not numerically identical across panels. Family density, represented by the first and fifth quantiles (lowest in grey; highest in orange), is overlaid to contextualize population exposure within the priority results.

north-eastern, and selected inner-city sectors, whereas peripheral units predominantly exhibit low or very low values. Differences across interventions reflect variation in structural requirements, feasibility constraints, and alignment with socio-economic and environmental demands (SEVI/EVI).

Intensive green roofs (IGR). Highest priorities cluster in the east and north-east UUs, where large non-residential and industrial roofs with adequate load-bearing capacity coincide with elevated SEVI/EVI. Adjacent UUs generally display intermediate priority, indicating candidate areas with moderate levels of roof suitability and SEVI/EVI vulnerability scores. Low to very low priorities dominate the southern, western, and outer northern sectors, consistent with limited structural suitability and lower composite socio-economic and environmental vulnerability scores.

Extensive green roofs (EGR). High and very high priorities are more broadly distributed, including the northern sector and the historic core. This pattern reflects EGR's lighter substrate and structural demands, which expand feasibility across a larger share of the residential stock. Intermediate priorities extend through central–western and eastern UUs, while low and very low values prevail in the outer periphery, where suitable roofs are sparse and SEVI/EVI values are lower.

Photovoltaic systems (PVs). PV priorities largely mirror the IGR distribution, with an expanded high-priority presence in the northern and historic center areas. This indicates that many roofs in these zones meet additional slope and building-use criteria, underscoring the complementarity between ecological and solar energy-producing rooftop strategies.

Rooftop gardens (RG). RG priorities generally follow IGR and PVs on flat roofs due to shared physical suitability filters. The minimum area threshold (greater than 30 m^2) enlarges the candidate roof set, elevating priority in some UUs; when this overlaps with higher SEVI/EVI, RG priority increases. However, RG feasibility also depends on access, irrigation, and amenity provisions not fully captured by spatial indicators, so results should be interpreted as indicative.

3.2.3. Synergy and competition

Fig. 9a illustrates RT4ES model synergistic opportunities for PVs, RG and IGR, revealing overall priority patterns to their suitability driven by rooftops suitability criteria as well as SEVI and EVI scores.

Eastern and north-eastern UUs, along with some pockets in the northwest are prioritized as high and very high areas. Moderate priority emerges in UUs outside the historic center, most consistently in northern areas, where balanced suitability and vulnerability suggest opportunities for co-implementation with site-specific enhancements. Low and very low priority occur mainly in urban core and peripheral UUs. City center has lower socio-economic and environmental vulnerability scores despite highly suitable rooftops. Peripheral UUs have smaller shares of suitable roof area and lower socio-economic and environmental vulnerability scores, with

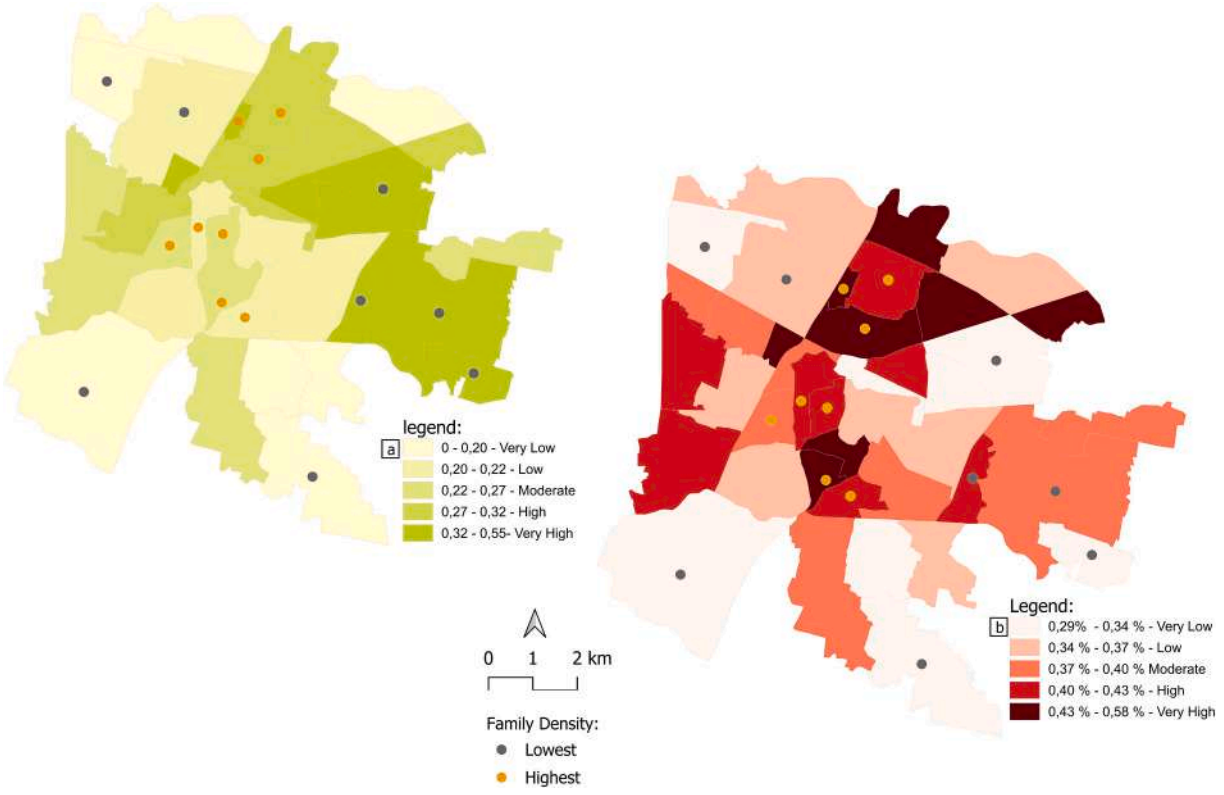


Fig. 9. Urban-unit–level prioritization under synergy and competition scenarios. (a) PVs, IGR and RG (synergy); (b) PVs and EGR (competition). Family density is represented by the first and fifth quantiles (lowest in grey; highest in orange).

additional scattered pockets across the study area.

Fig. 9b maps scenarios where one intervention competes for space with the other at the UU level. High and very high priorities cluster in the historic center, and north of the city, where high SEVI/EVI amplify the urgency for strategic rooftop intervention. Intermediate priorities scattered across the study area, particularly outside the historic center, west, south and east peripheries. Lower classes dominate northern peripheral UUs and some scattered pockets outside the city center and out of it in the southern part of the study area, encompassing a large share of UUs. These areas generally integrate smaller suitable roof shares with diminished SEVI/EVI, underscoring reduced intervention urgency but in the long term can be considered for urban planning.

4. Discussion

Urban areas face interconnected pressures, including climate change, rapid urbanization and persistent socio economic and environmental inequities (Byrne, 2020; Kohlhase, 2013). Addressing these challenges requires spatially explicit, evidence-based strategies that target limited resources where they yield the greatest socio-economic and environmental values (Peroni and Pappalardo, 2024). This study is the first to advance rooftop retrofit analysis by simultaneously quantifying the potential of multiple GI options (IGR, EGR, and RG) and PVs. By moving beyond previous approaches that typically assessed only physical suitability or examined each option in isolation, our GIS-MCDA framework at the UU scale integrates rooftop characteristics with SEVI and EVI indicators. This integration generates option-specific priority maps and equity-oriented rankings that highlight not only where interventions are technically feasible, but also where they can deliver the greatest combined social and environmental value, providing new insights into how cities can balance the deployment of GI and solar energy production, to support more equitable and sustainable urban transitions.

4.1. Advanced rooftop decision-making

Relative to prior city-scale studies, our analysis advanced rooftop decision-making in several ways. First, extending Langemeyer et al. (2020), who used spatial MCDA to prioritize GRs types by neighborhood ecosystem service demand, we evaluated multiple rooftop options on a common footing, PVs, RG, and GRs, and mapped co-location (synergy) versus exclusive-choice (competition) at the UU scale. Thus, we treated PVs–GRs co-deployment as an implementable class, consistent with findings that show modest PVs performance gains on vegetated roofs compared to conventional roofs (Van Der Roest et al., 2023) allowing also the creation of photovoltaic-green roof energy communities (Cruz Torres et al., 2023). Next, in contrast to Brenner et al. (2023), who localized roof-greening opportunities for UHI mitigation in Krefeld, Germany, while focusing on GRs alone, we provided a collective, multifunctional GI strategy that identifies where PVs, RG, IGR, and EGR should be prioritized together or separately, allowing urban planners to address UHI alongside other ecological benefits (e.g., runoff management, habitat provision, and air pollution abatement). Finally, as aforementioned, we embedded an equity and climate justice lens by integrating SEVI and EVI indicators, which shifted top ranks toward UUs with greater social–environmental risk, prioritizing the most disadvantaged groups, rather than simply toward areas with abundant roof supply. These neighborhoods are usually very compact, and the availability of green spaces is quite low. Even if this study did not quantify ecosystem service magnitudes or building-scale performance, it is demonstrated that the implementation of GRs could re-introduce some ecosystem services lost during urbanization process and soil sealing phenomenon, such as regulating ecosystem services (cooling, runoff reduction) (European Commission, 2021). These interventions, especially when strategically located in several structures in a neighborhood, can benefit not only a single building and its residents, but extend their effects on the surrounding citizen environment and communities (Netusil et al., 2022). It is worth mentioning also the role of RGs in enhancing cultural and supporting ESs and urban agro-biodiversity, thanks to their effectiveness in local food production, recreation and social cohesion (Specht et al., 2017). However, to move from potential suitability to implementation, particularly in high-cost projects, and to avoid gentrification and the rise of property values and rents in low income neighborhoods, the realization of GI in private owned or social housing structures should be supported by public incentives and permitting measures, such as tax abatement, bureaucratic simplifications, and targeted bonuses for PVs/GRs in high demand SEVI/EVI UUs (Anguelovski et al., 2022; Liberalesso et al., 2020, 2024; Van Der Roest et al., 2023).

4.2. Synergies and competition between rooftop solutions and social needs

Low-slope rooftops, which are primarily associated with residential buildings, represent an important spatial competition, allowing the implementation of either EGR or PVs. This pattern is crucial because the residential buildings across the study area host diverse SEVI groups. Therefore, the competition between implementing an EGR (to provide ecosystem services) and PVs (to provide clean energy) has significant, distinct effects on community well-being. As a result, understanding the interplay between the building typology suitable for intervention and the socioeconomic characteristics of the resident groups is paramount for effective policy-making and green infrastructure planning. In Table 7 a summary of this trade-off is provided (Cascone, 2024; Chen et al., 2023; Chen et al., 2024; Oberndorfer et al., 2007).

Synergistic (integrative) systems, occur when GR/RG and PVs are co-located on both residential and non-residential buildings, creating mutual benefits. The primary synergy is the cooling effect of the GR/RG: evapotranspiration from the vegetation lowers the ambient roof temperature, which mitigates the negative impact of high cell temperatures on PVs panel efficiency, thereby boosting annual energy yield (Talwar et al., 2023). In return, the PV panels provide partial shade, reducing plant thermal stress and water loss (Schindler et al., 2018). This integrative approach allows for the “stacking” of ecosystem services, combining on-site clean energy

Table 7
Comparison of rooftop PVs and EGR in terms of benefits achieved, benefits lost, and social needs addressed.

System Prioritized	Benefit Achieved	Benefit Lost	Social Needs Addressed
PVs	Direct, quantifiable energy savings and generation of green energy that mitigate CO_2 emissions (Cruz Torres et al., 2023; International Energy Agency, 2021; Zhang et al., 2025; Zsiborács et al., 2023).	Diffuse, neighborhood-scale ecosystem services (e.g., reduced urban heat island effect, flood control, and biodiversity gain) (Cristiano et al., 2021; Mentens et al., 2006; Mutani and Todeschi, 2020).	Energy equity and poverty: addresses household financial burden and local grid reliability (International Energy Agency, 2021; Li et al., 2023; Tan et al., 2023).
EGR	Collective, neighborhood-scale climate resilience benefits (mitigating UHI, stormwater management, and habitat provision).	Direct, measurable financial return from on-site energy production.	Climate vulnerability: addresses public health risks from extreme heat, property damage from flooding, and ecosystem services (Berardi et al., 2014; Coutts and Hahn, 2015; Netusil et al., 2022).

generation with the GR's primary functions of UHI mitigation, stormwater runoff retention, habitat provision, and air pollution abatement (De Cristo et al., 2025; DeNardo et al., 2005; Janhäll, 2015; Lin and Li, 2025; Madre et al., 2014; Williams et al., 2019).

4.3. From rooftop suitability to equity-oriented urban climate action

The RT4ES model advances urban climate mitigation and adaptation efforts by integrating rooftop suitability assessments with vulnerability-based prioritization, directing GI and PVs to Padua's most exposed UUs based on composite SEVI and EVI risk scores. The framework directly supports Padua's Sustainable Energy and Climate Action Plan (PAESC), which commits the city to emissions reductions by 2030 and climate neutrality by 2050 (Comune di Padova, 2024). For policymakers and urban planners, RT4ES serves as a decision-support system that translates suitability and vulnerability layers into spatially explicit recommendations, enabling GI and PVs deployment, guiding PAESC-aligned financing, and advancing climate justice and urban resilience. Our results provide urban planners with a typology- and density led-siting strategy: (i) prioritize biosolar (GR/RG + PV) on large, flat and non-residential roofs where they meet both energy demand and provide ecosystem services; (ii) prioritize GR/RG in compact, high-density residential blocks, especially high SEVI/EVI UUs, where adaptation co-benefits (cooling, runoff retention, and biodiversity provision) are greatest; and (iii) deploy PVs only on low-slope and moderate-slope roofs (residential buildings) where energy production needs outweighs ecosystem services provided by greening. Moreover, RG on public buildings can serve as an equitable complement to municipal efforts in establishing community gardens on the ground, particularly in UUs with limited private green space(Codato et al., 2024). Nationally, RT4ES is consistent with Italy's National Plan to Adaptation of Climate Change (Ministero dell'Ambiente e della Sicurezza Energetica (MASE), 2023), which emphasizes municipal, ecosystem-based measures to reduce climate hazards. At the European scale, it aligns with the EU Green Infrastructure Strategy's call for multifunctional natural networks that deliver resilience and co-benefits (European Commission, 2013), and complements the EU Strategy on Adaptation to Climate Change by prioritizing vulnerability-led, nature-based, risk-sensitive actions to safeguard urban populations by 2050 (European Commission, 2021).

Our findings on the spatial distribution of vulnerable populations and UHI effects were consistent with Pappalardo et al. (2023), who mapped heat-related risk in Padua during the 2022 heatwaves and identified hotspots in industrial and central areas with high concentrations of vulnerable residents. The very high/high priority areas in the east, northeast, and around urban core belt corresponded with those hotspots. We then translated those risk hotspots into action by integrating socio-economic and environmental vulnerability indexes with rooftop suitability to prioritize specific rooftop interventions to mitigate the negative environmental impacts of those hotspots. Comparison with family density adds a complementary equity perspective to the prioritization outcomes. The observed divergence between areas of highest priority and those with greater population exposure suggests that the SEVI/EVI framework, while effective in identifying vulnerability, may underrepresent zones where more households could benefit from interventions.

4.4. Data requirements and transferability of the RT4ES framework

Because RT4ES was built entirely with publicly accessible datasets and open-source tools, it is in principle transferable, particularly across Southern European cities with similar socio-economic and environmental risk profiles. Socio-economic indicators can be assembled from municipal or national census portals, while key environmental layers are openly available: vegetation cover from Sentinel-2 (e.g., NDVI) via the Copernicus Data Space Ecosystem; imperviousness from the Copernicus High Resolution Layer Imperviousness (10–100 m); and thermal context/LST proxies derived from Landsat Collection 2 thermal imagery, processed locally in QGIS or in GEE. Rooftop characteristics and slope details can leverage LiDAR-derived DSM/DTM and orthophotos commissioned by the municipalities and later released through their open-data portals. As mentioned in the introduction, especially in Europe, most countries provide free access to elevation data and high resolution orthophoto. Although such detailed products are available in some cases, they are not yet universally available, and their absence in many cities would either reduce the spatial accuracy of RT4ES or require coarser DEM/DSM alternatives. For building footprints, we combined the buildings extracted from the Veneto region topographic database with OSM building data. In the absence of local datasets, however, the EU EUBUCCO (Milojevic-Dupont et al., 2023) project could serve as a valid alternative. Together, these sources reproduce suitability and SEVI/EVI stack required to develop the

RT4ES model, that can be replicated in similar contexts.

5. Conclusion

This study supports rooftop suitability and prioritization research by evaluating four intervention types, EGR, IGR, RG, and PVs, on a common footing and by integrating SEVI and EVI vulnerability scores to rank suitable rooftops at the UU scale for integrated climate justice and urban resilience planning. The RT4ES model translates rooftop physical characteristics (slope, area, and building use) into equity-aware priorities, indicating where resources should be directed first.

Applied to the municipality of Padua, the model reveals marked spatial heterogeneity in rooftop potential and vulnerability across the urban fabric, from the historic center to residential, industrial and peripheral areas. Results show that suitable rooftops often support multiple interventions rather than a single exclusive system, with PVs exhibiting the widest applicability (11.93 km^2 across 30,372 roofs), followed by EGRs (7.25 km^2), while IGRs and RGs remain more context dependent. Overall, vegetated roofs could increase urban green cover from 56% to 67%, and the estimated PVs generation potential (0.47 TWh yr^{-1}) exceeds current residential electricity demand.

By coupling a reproducible potential suitability analysis with vulnerability-based prioritization, this study produces a clear equity-oriented spatial hierarchy, highlighting high-priority UUs beyond the historic center, particularly in northern and northeastern areas characterized by higher heat exposure, lower vegetation cover, and greater social vulnerability. Incorporating demographic indicators such as family density further strengthens the capacity of the RT4ES framework to guide equitable, multifunctional rooftop investments that enhance both urban resilience and social equity.

CRediT authorship contribution statement

Abdullah Ahmadi: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Daniele Codato:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Francesca Peroni:** Writing – review & editing, Validation, Supervision. **Massimo De Marchi:** Writing – review & editing, Validation, Funding acquisition.

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.

Acknowledgments

This research was funded by the Jean Monnet centre of Excellence on Just Fossil Fuel Transition (Erasmus plus, grant number 101175896 — JFFT — ERASMUS-JMO-2024- HEI-TCH-RSCH).

This article is part of the project RESTART | Urban Climate Justice and Community Participation: towards inclusive adaptation strategies (HORIZON-MSCA-2023-PF-01, Grant agreement ID: 101150830), PI Francesca Peroni.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.uclim.2026.102840.

Data availability

Data will be made available on request.

References

Abdalazeem, M.E., Hassan, H., Asawa, T., Mahmoud, H., 2022. Review on integrated photovoltaic-green roof solutions on urban and energy-efficient buildings in hot climate. Sustain. Cities Soc. 82, 103919. https://doi.org/10.1016/j.scs.2022.103919.

Alonso-Marroquin, F., Qadir, G., 2023. Synergy between photovoltaic panels and green roofs. Energies 16 (13), 13. https://doi.org/10.3390/en16135184.

Anguelovski, I., Irazábal-Zurita, C., Connolly, J.J.T., 2019. Grabbed urban landscapes: socio-spatial tensions in green infrastructure planning in Medellín. Int. J. Urban Reg. Res. 43 (1), 133–156. https://doi.org/10.1111/1468-2427.12725.

Anguelovski, I., Connolly, J.J.T., Cole, H., Garcia-Lamarca, M., Triguero-Mas, M., Baró, F., Martin, N., Conesa, D., Shokry, G., Del Pulgar, C.P., Ramos, L.A., Matheney, A., Gallez, E., Oscilowicz, E., Máñez, J.L., Sarzo, B., Beltrán, M.A., Minaya, J.M., 2022. Green gentrification in European and north American cities. Nat. Commun. 13 (1), 3816. https://doi.org/10.1038/s41467-022-31572-1.

Anguelovski, I., Kotsila, P., Lees, L., Triguero-Mas, M., Calderón-Argelich, A., 2024. From heat racism and heat gentrification to urban heat justice in the USA and Europe. Nat. Cities 2 (1), 8–16. https://doi.org/10.1038/s44284-024-00179-6.

Apud, A., Faggian, R., Sposito, V., Martino, D., 2020. Suitability analysis and planning of green infrastructure in Montevideo, Uruguay. Sustainability 12 (22), 9683. https://doi.org/10.3390/su12229683.

ARERA, 2023. Elettricità: bolletta in tutela quasi invariata a +0,4%. ARERA, Milan. https://www.arera.it/comunicati-stampa/dettaglio/it/com-stampa/23/230628 (accessed 17 August 2025).
Bakolo, C., Kayitete, L., De Dieu Tuyizere, J., Tomlinson, J., Fawcett, J., Alfaro, R.F., 2024. Identification of optimal locations for green space initiatives through GIS-based multi-criteria analysis and the analytical hierarchy process. Environ. Syst. Res. 13 (1), 46. https://doi.org/10.1186/s40068-024-00377-0.
Bandari, N., Raghavendra, K.V.G., Heo, S., Kumar, S.V.S.V.P.D., Uddin, W., Sama, L.K.R., Punnoose, D., Kim, H.-J., 2020. Efficient electricity management system for optimal peak/off-peak hour pricing. Electronics 9 (8), 1189. https://doi.org/10.3390/electronics9081189.
Baranes, E., Jacqmin, J., Poudou, J.-C., 2017. Non-renewable and intermittent renewable energy sources: friends and foes? Energy Policy 111, 58–67. https://doi.org/10.1016/j.enpol.2017.09.018.
Baumann, T., Nussbaumer, H., Klenk, M., Dreisiebner, A., Carigiet, F., Baumgartner, F., 2019. Photovoltaic systems with vertically mounted bifacial PV modules in combination with green roofs. Sol. Energy 190, 139–146. https://doi.org/10.1016/j.solener.2019.08.014.
Berardi, U., GhaffarianHoseini, A., GhaffarianHoseini, A., 2014. State-of-the-art analysis of the environmental benefits of green roofs. Appl. Energy 115, 411–428. https://doi.org/10.1016/j.apenergy.2013.10.047.
Beumier, C., Idrissa, M., 2014. Building Detection With Multi-View Colour Infrared Imagery. EARSeL eProceedings. 10.12760/01-2014-2-05.
Bortolini, L., Brasola, V., 2022. Simulating the impact of nature-based solutions on runoff control by using i-tree hydro: a case study in Padua (Italy). Acta Hortic. 1345, 351–358. https://doi.org/10.17660/actahortic.2022.1345.47.
Bousquet, M., Kuller, M., Lacroix, S., Vanrolleghem, P.A., 2023. A critical review of multicriteria decision analysis practices in planning of urban green spaces and nature-based solutions. Blue-Green Syst. 5 (2), 200–219. https://doi.org/10.2166/bgs.2023.132.
Brenner, J., Schmidt, S., Albert, C., 2023. Localizing and prioritizing roof greening opportunities for urban heat island mitigation: insights from the city of Krefeld, Germany. Landsc. Ecol. 38 (7), 1697–1712. https://doi.org/10.1007/s10980-023-01644-8.
Brown, S., Jones, D., 2024. Europe's electricity transition takes crucial strides forward: 2024 European Electricity Review. Ember (accessed 19 July 2025). https://ember-energy.org/app/uploads/2024/10/European-Electricity-Review-2024.pdf.
Brown, A., Dayal, A., Rumbaitis Del Rio, C., 2012. From practice to theory: emerging lessons from Asia for building urban climate change resilience. Environ. Urban. 24 (2), 531–556. https://doi.org/10.1177/0956247812456490.
Busato, F., Lazzarin, R.M., Noro, M., 2014. Three years of study of the urban Heat Island in Padua: experimental results. Sustain. Cities Soc. 10, 251–258. https://doi.org/10.1016/j.scs.2013.05.001.
Byrne, J., 2020. Urbanisation: Towns and Cities as Sites of Environmental (in)Justice. In: Environmental Justice. Routledge.
Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P.W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., 2023. In: Core writing team, Lee, H., Romero, J. (Eds.), IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland (no title).
Caniglia, B.S., Frank, B.F., Vallée, M., 2017. Resilience, Environmental Justice and the City. Routledge. https://doi.org/10.4324/9781315652054.
Carter, T., Fowler, L., 2008. Establishing green roof infrastructure through environmental policy instruments. Environ. Manag. 42 (1), 151–164. https://doi.org/10.1007/s00267-008-9095-5.
Cascone, S., 2024. Eco-innovative construction: integrating green roofs design within the BIM framework. Sustainability 16 (5), 5. https://doi.org/10.3390/su16051967.
Chen, Y., Li, K.W., He, Shawei, 2010. Dynamic multiple criteria decision analysis with application in emergency management assessment. In: 2010 IEEE International Conference on Systems, Man and Cybernetics, pp. 3513–3517. https://doi.org/10.1109/ICSMC.2010.5642410.
Chen, J., Kinoshita, T., Li, H., Luo, S., Su, D., Yang, X., Hu, Y., 2023. Toward green equity: an extensive study on urban form and green space equity for shrinking cities. Sustain. Cities Soc. 90, 104395. https://doi.org/10.1016/j.scs.2023.104395.
Chen, Y., Liu, Y., Slootweg, M., Hu, M., Tukker, A., Chen, W.-Q., 2024. Unlocking rooftop potential for sustainable cities: a systematic review. Front. Eng. Manag. https://doi.org/10.1007/s42524-024-4053-3.
Clark, C., Adriaens, P., Talbot, F.B., 2008. Green roof valuation: a probabilistic economic analysis of environmental benefits. Environ. Sci. Technol. 42 (6), 2155–2161. https://doi.org/10.1021/es0706652.
Codato, D., Grego, D., Peroni, F., 2024. Community gardens for inclusive urban planning in Padua (Italy): implementing a participatory spatial multicriteria decision-making analysis to explore the social meanings of urban agriculture. Front. Sustain. Food Syst. 8. https://doi.org/10.3389/fsufs.2024.1344034.
Comune di Padova. (2019). Documento del Sindaco – Padova 2030: Piano degli Interventi (preparatory/masterplan phases with Stefano Boeri Architetti). Padova: Comune di Padova. https://www.comune.padova.it/urbanistica/NUOVO_PI/2020_12_21_DocumentoSindaco-signed.pdf (accessed 13 July 2025).
Comune di Padova, 2024. PAESC di Padova – Rapporto di monitoraggio 2017-2023. Padova: Comune di Padova. https://www.comune.padova.it/sites/default/files/attachment/monitoraggioPAESC_Padova.pdf (accessed 12 July 2025).
Comune di Padova, 2024. Popolazione. Comune di Padova. https://www.comune.padova.it/sites/default/files/2025-04/Capitolo%202.pdf (accessed 10 July 2025).
Coutts, C., Hahn, M., 2015. Green infrastructure, ecosystem services, and human health. Int. J. Environ. Res. Public Health 12 (8), 8. https://doi.org/10.3390/ijerph120809768.
Cristiano, E., Deidda, R., Viola, F., 2021. The role of green roofs in urban water-energy-food-ecosystem nexus: a review. Sci. Total Environ. 756, 143876. https://doi.org/10.1016/j.scitotenv.2020.143876.
Croeser, T., Garrard, G., Sharma, R., Ossola, A., Bekessy, S., 2021. Choosing the right nature-based solutions to meet diverse urban challenges. Urban For. Urban Green. 65, 127337. https://doi.org/10.1016/j.ufug.2021.127337.
Cruz Torres, F., Babí Almenar, J., Rugani, B., 2023. Photovoltaic-green roof energy communities can uphold the European green deal: probabilistic cost-benefit analyses help discern economically convenient scenarios. J. Clean. Prod. 414, 137428. https://doi.org/10.1016/j.jclepro.2023.137428.
Cutter, S.L., Boruff, B.J., Shirley, W.L., 2003. Social vulnerability to environmental hazards*. Soc. Sci. Q. 84 (2), 242–261. https://doi.org/10.1111/1540-6237.8402002.
De Cristo, E., Evangelisti, L., Barbaro, L., De Lieto Vollaro, R., Asdrubali, F., 2025. A systematic review of green roofs' thermal and energy performance in the Mediterranean region. Energies 18 (10), 2517. https://doi.org/10.3390/en18102517.
Dehghanimadvar, M., Egan, R., Chang, N.L., 2022. Economic assessment of local solar module assembly in a global market. Cell Rep. Phys. Sci. 3 (2), 100747. https://doi.org/10.1016/j.xcrp.2022.100747.
Demuzere, M., Orru, K., Heidrich, O., Olazabal, E., Geneletti, D., Orru, H., Bhave, A.G., Mittal, N., Feliu, E., Faehnle, M., 2014. Mitigating and adapting to climate change: multi-functional and multi-scale assessment of green urban infrastructure. J. Environ. Manag. 146, 107–115. https://doi.org/10.1016/j.jenvman.2014.07.025.
DeNardo, J.C., Jarrett, A.R., Manbeck, H.B., Beattie, D.J., Berghage, R.D., 2005. Stormwater mitigation and surface temperature reduction by green roofs. Trans. Am. Soc. Agric. Eng. 48 (4), 1491–1496. Scopus.
Dimitriou, C., Michaelides, S., Themistocleous, K., Hadjimitsis, D.G., Papadavid, G., Gitas, I., Kyriakides, N., 2025. Assessing the Urban Heat Island (UHI) Effect Using Land Surface Temperature (LST) and Normalized Difference Built-Up Index (NDBI): A Case Study on Paphos, Cyprus. COMECAP 2025, p. 65. https://doi.org/10.3390/eesp2025035065.
Dong, X., He, B.-J., 2023. A standardized assessment framework for green roof decarbonization: A review of embodied carbon, carbon sequestration, bioenergy supply, and operational carbon scenarios. Renew. Sust. Energ. Rev. 182, 113376. https://doi.org/10.1016/j.rser.2023.113376.
Dong, J., Zuo, J., Luo, J., 2020. Development of a management framework for applying green roof policy in urban China: a preliminary study. Sustainability 12 (24), 10364. https://doi.org/10.3390/su122410364.
Egerer, M., Annighöfer, P., Arzberger, S., Burger, S., Hecher, Y., Knill, V., Probst, B., Suda, M., 2024. Urban oases: the social-ecological importance of small urban green spaces. Ecosyst. People 20 (1), 2315991. https://doi.org/10.1080/26395916.2024.2315991.
European Commission, 2013. Green Infrastructure (GI) — Enhancing Europe's Natural Capital (COM(2013) 249 final). Brussels: European Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52013DC0249 (accessed 13 August 2025).

European Commission, 2020. Communication from the Commission to the European Parliament, the Council. the European Economic and Social Committee and the Committee of the Regions (No. COM (2020) 380 final). https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020DC0380 (accessed 12 August 2025).
European Commission, 2021. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: EU soil strategy for 2030 – Reaping the Benefits of Healthy Soils for People, Food, Nature and Climate. European Commission (accessed 19 July 2025). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0699.
Favretto, A., 2018. Urban Heat Island analysis with Remote Sensing and GIS methods: an application in the Trieste area (North-East of Italy). Bollettino Della Società Geografica Italiana 1 (1), 215–229. https://doi.org/10.13128/bsgi.v1i1.101.
Fouad, M.M., Shihata, L.A., Morgan, E.I., 2017. An integrated review of factors influencing the perfomance of photovoltaic panels. Renew. Sust. Energ. Rev. 80, 1499–1511. https://doi.org/10.1016/j.rser.2017.05.141.
Frigerio, I., De Amicis, M., 2016. Mapping social vulnerability to natural hazards in Italy: a suitable tool for risk mitigation strategies. Environ. Sci. Pol. 63, 187–196. https://doi.org/10.1016/j.envsci.2016.06.001.
Godoi, N.M.I., Gomes, R.C., Longo, R.M., 2025. Contributions of urban green spaces to cities: a literature review. Sustainable Environ. 11 (1), 2464418. https://doi.org/10.1080/27658511.2025.2464418.
Greene, R., Devillers, R., Luther, J.E., Eddy, B.G., 2011. GIS-based multiple-criteria decision analysis. Geogr. Compass 5 (6), 412–432. https://doi.org/10.1111/j.1749-8198.2011.00431.x.
Grunwald, L., Heusinger, J., Weber, S., 2017. A GIS-based mapping methodology of urban green roof ecosystem services applied to a central European city. Urban For. Urban Green. 22, 54–63. https://doi.org/10.1016/j.ufug.2017.01.001.
Harada, Y., Whitlow, T.H., 2020. Urban rooftop agriculture: challenges to science and practice. Front. Sustain. Food Syst. 4. https://doi.org/10.3389/fsufs.2020.00076.
Harlan, S.L., Brazel, A.J., Prashad, L., Stefanov, W.L., Larsen, L., 2006. Neighborhood microclimates and vulnerability to heat stress. Soc. Sci. Med. 63 (11), 2847–2863. https://doi.org/10.1016/j.socscimed.2006.07.030.
International Energy Agency, 2021. Empowering cities for a net zero future: unlocking resilient, smart, sustainable urban energy systems. OECD. https://doi.org/10.1787/7a222c8b-en.
Islam, S., Alam, M.R., Rashid, K.J., 2023. Identification of potential rooftops for gardening and contributions of RTGs to improve the socio-economic condition and promote a sustainable urban environment in the changing climatic condition of Bangladesh. In: Urban Commons, Future Smart Cities and Sustainability. Springer, pp. 511–532.
ISPRA, 2024. Soil Sealing Assessment and Monitoring in the Mediterranean Coastal Watershed. ISPRA Istituto Superiore per La Protezione e La Ricerca Ambientale. https://www.isprambiente.gov.it/en/projects/soil-and-territory/soil-sealing-assessment-and-monitoring-in-the-mediterranean-coastal-watershed (accessed 15 August 2025).
Jacobson, M.Z., Jadhav, V., 2018. World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels. Sol. Energy 169, 55–66. https://doi.org/10.1016/j.solener.2018.04.030.
Janhäll, S., 2015. Review on urban vegetation and particle air pollution – deposition and dispersion. Atmos. Environ. 105, 130–137. https://doi.org/10.1016/j.atmosenv.2015.01.052.
Jankowski, P., 1995. Integrating geographical information systems and multiple criteria decision-making methods. Int. J. Geogr. Inf. Syst. 9 (3), 251–273. https://doi.org/10.1080/02693799508902036.
Juhola, S., 2016. Barriers to the implementation of climate change adaptation in land use planning: a multi-level governance problem? Int. J. Clim. Change Strategies Manage. 8 (3), 338–355. https://doi.org/10.1108/IJCCSM-03-2014-0030.
Karakaya, E., Sriwannawit, P., 2015. Barriers to the adoption of photovoltaic systems: the state of the art. Renew. Sust. Energ. Rev. 49, 60–66. https://doi.org/10.1016/j.rser.2015.04.058.
Khodadad, M., Sanei, M., Aguilar-Barajas, I., Cárdenas-Barrón, L.E., Ramírez-Orozco, A.I., Rizzo, A., Khan, A.Z., 2025. Green infrastructure site prioritization to improve urban flood resilience in Monterrey and Brussels using a decision support model. Sci. Rep. 15 (1), 10744. https://doi.org/10.1038/s41598-025-94851-z.
Khoshelham, K., Nardinocchi, C., Frontoni, E., Mancini, A., Zingaretti, P., 2010. Performance evaluation of automated approaches to building detection in multi-source aerial data. ISPRS J. Photogramm. Remote Sens. 65 (1), 123–133. https://doi.org/10.1016/j.isprsjprs.2009.09.005.
Kim, S.Y., Na, W., Jun, C., Seo, H., Kim, Y., 2021. Hydrological performance of green roof systems: a numerical investigation. Front. Environ. Sci. 9, 806697. https://doi.org/10.3389/fenvs.2021.806697.
Kohlhase, J.E., 2013. The new urban world 2050: perspectives, prospects and problems. Reg. Sci. Policy Pract. 5 (2), 153–166. https://doi.org/10.1111/rsp3.12001.
Kostadinović, D., Jovanović, M., Bakić, V., Stepanić, N., 2023. Mitigation of urban particulate pollution using lightweight green roof system. Energ. Buildings 293, 113203. https://doi.org/10.1016/j.enbuild.2023.113203.
Krenz, K., Amann, L., 2025. Urban heat island effect: examining spatial patterns of socio-demographic inequalities in greater London. Cities & Health 9 (5), 901–924. https://doi.org/10.1080/23748834.2025.2489854.
Kumar, P., Sahani, J., Corada Perez, K., Ahlawat, A., Andrade, M.D.F., Athanassiadou, M., Cao, S.-J., Collins, L., Dey, S., Di Sabatino, S., Halios, C.H., Harris, F., Horton, C., Inostroza, L., Jones, L., Rodding Kjeldsen, T., McCallan, B., McNabola, A., Kumar Mishra, R., Yao, R., 2025. Urban greening for climate resilient and sustainable cities: grand challenges and opportunities. Front. Sustain. Cities 7. https://doi.org/10.3389/frsc.2025.1595280.
Lambarki, R., Achbab, E., Maanan, M., Rhinane, H., 2022. Evaluation of the potential of green roofs applied to an urban fabric using GIS and remote sensing data case of the Nador City / Morocco. In: The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, pp. 177–184. https://doi.org/10.5194/isprs-archives-XLVI-4-W3-2021-177-2022. XLVI-4/W3–2021.
Lambarki, R., Elmostafa, A., Maanan, M., Rhinane, H., 2025. Assessing the potential of green roofs in urban areas: a multicriteria Boolean analysis utilizing GIS and remote sensing data in the city of Nador, Morocco. Green Technol. Sustainability 3 (2), 100171. https://doi.org/10.1016/j.grets.2025.100171.
Langemeyer, J., Wedgwood, D., McPhearson, T., Baró, F., Madsen, A.L., Barton, D.N., 2020. Creating urban green infrastructure where it is needed – A spatial ecosystem service-based decision analysis of green roofs in Barcelona. Sci. Total Environ. 707, 135487. https://doi.org/10.1016/j.scitotenv.2019.135487.
Lee, H., Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P., Trisos, C., Romero, J., Aldunce, P., Barrett, K., 2023. Climate change 2023: synthesis report. In: Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.
Li, Y., Chen, K., Ding, R., Zhang, J., Hao, Y., 2023. How do photovoltaic poverty alleviation projects relieve household energy poverty? Evidence from China. Energy Econ. 118, 106514. https://doi.org/10.1016/j.eneco.2023.106514.
Liberalesso, T., Oliveira Cruz, C., Matos Silva, C., Manso, M., 2020. Green infrastructure and public policies: an international review of green roofs and green walls incentives. Land Use Policy 96, 104693. https://doi.org/10.1016/j.landusepol.2020.104693.
Liberalesso, T., Silva, C.M., Cruz, C.O., 2024. Combined strategies for green roof incentive policies in Lisbon: evaluating the potentiality of concession grants and identifying priority intervention areas. Urban For. Urban Green. 99, 128451. https://doi.org/10.1016/j.ufug.2024.128451.
Lin, H., Li, X., 2025. The role of urban green spaces in mitigating the urban Heat Island effect: a systematic review from the perspective of types and mechanisms. Sustainability 17 (13), 6132. https://doi.org/10.3390/su17136132.
Liu, F., Zhao, Y., Muhammad, R., Liu, X., Chen, M., 2020. Impervious surface expansion: a key indicator for environment and urban agglomeration—A case study of Guangdong-Hong Kong-Macao Greater Bay Area by using Landsat data. J. Sens. 2020, 1–21. https://doi.org/10.1155/2020/3896589.
Ma, C., Yuan, C., Zhang, Y., Hu, H., 2024a. In: Social Science Research Network (Ed.), Mapping Utilizable Rooftop Areas to Meet Food Security Goal in Four High-Density Cities: A Deep Learning and GIS Integrated Approach. https://doi.org/10.2139/ssrn.4970797 (SSRN scholarly paper no. 4970797).
Ma, X., Miao, S., Masson, V., Wurtz, J., Zhang, Y., Wang, J., Huang, X.-Y., Yan, C., 2024b. The synergistic effects of urbanization and an extreme heatwave event on urban thermal environment in Paris. Urban Clim. 53, 101785. https://doi.org/10.1016/j.uclim.2023.101785.
Madre, F., Vergnes, A., Machon, N., Clergeau, P., 2014. Green roofs as habitats for wild plant species in urban landscapes: first insights from a large-scale sampling. Landsc. Urban Plan. 122, 100–107. https://doi.org/10.1016/j.landurbplan.2013.11.012.

Malczewski, J., 2006. GIS-based multicriteria decision analysis: a survey of the literature. Int. J. Geogr. Inf. Sci. 20 (7), 703–726. https://doi.org/10.1080/13658810600661508.
Marín, C., El Bachawati, M., Pérez, G., 2023. The impact of green roofs on urban runoff quality: a review. Urban For. Urban Green. 90, 128138. https://doi.org/10.1016/j.ufug.2023.128138.
Martín-Chivelet, N., Kapsis, K., Wilson, H.R., Delisle, V., Yang, R., Olivieri, L., Polo, J., Eisenlohr, J., Roy, B., Maturi, L., Otnes, G., Dallapiccola, M., Upalakshi Wijeratne, W.M.P., 2022. Building-integrated photovoltaic (BIPV) products and systems: a review of energy-related behavior. Energ. Buildings 262, 111998. https://doi.org/10.1016/j.enbuild.2022.111998.
Meerow, S., Newell, J.P., 2017. Spatial planning for multifunctional green infrastructure: growing resilience in Detroit. Landsc. Urban Plan. 159, 62–75. https://doi.org/10.1016/j.landurbplan.2016.10.005.
Megyesi, B., Gholipour, A., Cuomo, F., Canga, E., Tsatsou, A., Zihlmann, V., Junge, R., Milosevic, D., Pineda-Martos, R., 2024. Perceptions of stakeholders on nature-based solutions in urban planning: a thematic analysis in six European cities. Urban For. Urban Green. 96, 128344. https://doi.org/10.1016/j.ufug.2024.128344.
Melius, J., Margolis, R., Ong, S., 2013. Estimating Rooftop Suitability for PV: A Review of Methods, Patents, and Validation Techniques (No. NREL/TP–6A20-60593, 1117057; p. NREL/TP–6A20-60593, 1117057). https://doi.org/10.2172/1117057.
Mentens, J., Raes, D., Hermy, M., 2006. Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? Landsc. Urban Plan. 77 (3), 217–226. https://doi.org/10.1016/j.landurbplan.2005.02.010.
Mesimäki, M., Hauru, K., Lehvävirta, S., 2019. Do small green roofs have the possibility to offer recreational and experiential benefits in a dense urban area? A case study in Helsinki, Finland. Urban For. Urban Green. 40, 114–124. https://doi.org/10.1016/j.ufug.2018.10.005.
Messeri, A., Morabito, M., Bonafede, M., Bugani, M., Levi, M., Baldasseroni, A., Binazzi, A., Gozzini, B., Orlandini, S., Nybo, L., Marinaccio, A., 2019. Heat Stress Perception among Native and Migrant Workers in Italian Industries—Case Studies from the Construction and Agricultural Sectors. Int. J. Environ. Res. Public Health 16 (7), 1090. https://doi.org/10.3390/ijerph16071090.
Milojevic-Dupont, N., Wagner, F., Nachtigall, F., Hu, J., Brüser, G.B., Zumwald, M., Biljecki, F., Heeren, N., Kaack, L.H., Pichler, P.-P., Creutzig, F., 2023. EUBUCCO v0.1: European building stock characteristics in a common and open database for 200+ million individual buildings. Sci. Data 10 (1), 147. https://doi.org/10.1038/s41597-023-02040-2.
Ministero dell'Ambiente e della Sicurezza Energetica (MASE), 2023. Piano Nazionale di Adattamento ai Cambiamenti Climatici (PNACC). https://www.mase.gov.it/portale/piano-nazionale-di-adattamento-ai-cambiamenti-climatici-pnacc (accessed 17 July 2025).
Mohtat, N., Khirfan, L., 2021. The climate justice pillars Vis-à-Vis urban form adaptation to climate change: a review. Urban Clim. 39, 100951. https://doi.org/10.1016/j.uclim.2021.100951.
Mutani, G., Todeschi, V., 2020. The effects of green roofs on outdoor thermal comfort, urban Heat Island mitigation and energy savings. Atmosphere 11 (2), 123. https://doi.org/10.3390/atmos11020123.
Netusil, N.R., Lavelle, L., Dissanayake, S., Ando, A.W., 2022. Valuing the public benefits of green roofs. Landsc. Urban Plan. 224, 104426. https://doi.org/10.1016/j.landurbplan.2022.104426.
Nguyen Dang, H.-A., Legg, R., Khan, A., Wilkinson, S., Ibbett, N., Doan, A.-T., 2022. Social impact of green roofs. Front. Built Environ. 8. https://doi.org/10.3389/fbuil.2022.1047335.
Ni, P., Yan, Z., Yue, Y., Xian, L., Lei, F., Yan, X., 2023. Simulation of solar radiation on metropolitan building surfaces: a novel and flexible research framework. Sustain. Cities Soc. 93, 104469. https://doi.org/10.1016/j.scs.2023.104469.
Ni, P., Zheng, H., Sun, H., Lei, F., Wang, Y., Qin, J., Wang, W., Song, J., Yue, Y., Yao, S., Bi, W., Zhang, D., Zhang, X., Yan, J., Tao, Y., Yan, Z., Qin, G., Lin, B., He, B.-J., 2025. Building integrated photovoltaics that move beyond rooftops. Cell Rep. Phys. Sci. 6 (8), 102725. https://doi.org/10.1016/j.xcrp.2025.102725.
Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R.R., Doshi, H., Dunnett, N., Gaffin, S., Köhler, M., Liu, K.K.Y., Rowe, B., 2007. Green roofs as urban ecosystems: ecological structures, functions, and services. BioScience 57 (10), 823–833. https://doi.org/10.1641/B571005.
Olowu, T.O., Sundararajan, A., Moghaddami, M., Sarwat, A.I., 2018. Future challenges and mitigation methods for high photovoltaic penetration: a survey. Energies 11 (7), 1782. https://doi.org/10.3390/en11071782.
Osma-Pinto, G., Ordóñez-Plata, G., 2019. Measuring factors influencing performance of rooftop PV panels in warm tropical climates. Sol. Energy 185, 112–123. https://doi.org/10.1016/j.solener.2019.04.053.
Oudin Åström, D., Bertil, F., Joacim, R., 2011. Heat wave impact on morbidity and mortality in the elderly population: a review of recent studies. Maturitas 69 (2), 99–105. https://doi.org/10.1016/j.maturitas.2011.03.008.
Palmer, D., Koumpli, E., Cole, I., Gottschalg, R., Betts, T., 2018. A GIS-based method for identification of wide area rooftop suitability for minimum size PV systems using LiDAR data and photogrammetry. Energies 11 (12), 3506. https://doi.org/10.3390/en11123506.
Pappalardo, S., Zanetti, C., Todeschi, V., 2023. Mapping urban heat islands and heat-related risk during heat waves from a climate justice perspective: a case study in the municipality of Padua (Italy) for inclusive adaptation policies. Landsc. Urban Plan. 238, 104831. https://doi.org/10.1016/j.landurbplan.2023.104831.
Peroni, F., Pappalardo, S.E., 2024. Climate justice in future cities: geographical perspectives for inclusive urban resilience and adaptation. Landsc. Urban Plan. 244, 104998. https://doi.org/10.1016/j.landurbplan.2023.104998.
Peroni, F., Codato, D., Buscemi, L., Cibrario, M., Pappalardo, S.E., De Marchi, M., 2023. Rethinking urban riparian ecosystems as a frontline strategy to counter climate change: mapping 60 years of carbon sequestration evolution in Padua, Italy. Front. Clim. 5, 1235886. https://doi.org/10.3389/fclim.2023.1235886.
Pochodyła-Ducka, E., Burandt, P., Glińska-Lewczuk, K., 2025. GIS-based framework for assessing priority locations for blue-green infrastructure implementation in urban areas. Ecol. Indic. 176, 113718. https://doi.org/10.1016/j.ecolind.2025.113718.
Pristeri, G., Peroni, F., Pappalardo, S.E., Codato, D., Masi, A., De Marchi, M., 2021. Whose urban green? Mapping and classifying public and private green spaces in Padua for spatial planning policies. ISPRS Int. J. Geo Inf. 10 (8), 538. https://doi.org/10.3390/ijgi10080538.
Rafida, S., 2004. FLL Guideline. https://www.academia.edu/14476032/FLL_Guideline (accessed 11 July 2025).
Rowe, D., 2010. Green roofs as a means of pollution abatement. Environ. Pollut. 159, 2100–2110. https://doi.org/10.1016/j.envpol.2010.10.029.
Santos, T., Tenedório, J., Gonçalves, J., 2016. Quantifying the city's green area potential gain using remote sensing data. Sustainability 8 (12), 1247. https://doi.org/10.3390/su8121247.
Schindler, B.Y., Blaustein, L., Lotan, R., Shalom, H., Kadas, G.J., Seifan, M., 2018. Green roof and photovoltaic panel integration: effects on plant and arthropod diversity and electricity production. J. Environ. Manag. 225, 288–299. https://doi.org/10.1016/j.jenvman.2018.08.017.
Schmidtlein, M.C., Deutsch, R.C., Piegorsch, W.W., Cutter, S.L., 2008. A sensitivity analysis of the social vulnerability index. Risk Anal. 28 (4), 1099–1114. https://doi.org/10.1111/j.1539-6924.2008.01072.x.
Shafique, M., Luo, X., Zuo, J., 2020. Photovoltaic-green roofs: a review of benefits, limitations, and trends. Sol. Energy 202, 485–497. https://doi.org/10.1016/j.solener.2020.02.101.
Shi, Z., Li, X., Hu, T., Yuan, B., Yin, P., Jiang, D., 2023. Modeling the intensity of surface urban heat island based on the impervious surface area. Urban Clim. 49, 101529. https://doi.org/10.1016/j.uclim.2023.101529.
Slootweg, M., Hu, M., Vega, S.H., van't Zelfde, M., van Leeuwen, E., Tukker, A., 2023. Identifying the geographical potential of rooftop systems: space competition and synergy. Urban For. Urban Green. 79, 127816.
Souviney, M.M., Mattalia, G., Pieroni, A., 2024. Impacts of industrialization on foraging in Peri-urban areas. Insights from Padua, NE Italy. Hum. Ecol. 52 (3), 653–665. https://doi.org/10.1007/s10745-024-00513-5.
Specht, K., Reynolds, K., Sanyé-Mengual, E., 2017. Community and social justice aspects of rooftop agriculture. In: Orsini, F., Dubbeling, M., De Zeeuw, H., Gianquinto, G. (Eds.), Rooftop Urban Agriculture. Springer International Publishing, pp. 277–290. https://doi.org/10.1007/978-3-319-57720-3_17.
Talwar, P., Verma, N., Khatri, H., Ahire, P.D., Chaudhary, G., Lindenberger, C., Vivekanand, V., 2023. A systematic review of photovoltaic-green roof systems in different climatic conditions focusing on sustainable cities and societies. Sustain. Cities Soc. 98, 104813. https://doi.org/10.1016/j.scs.2023.104813.
Tan, H., Kotamarthi, R., Wang, J., Qian, Y., Chakraborty, T.C., 2023. Impact of different roofing mitigation strategies on near-surface temperature and energy consumption over the Chicago metropolitan area during a heatwave event. Sci. Total Environ. 860, 160508. https://doi.org/10.1016/j.scitotenv.2022.160508.

Todeschi, V., Pappalardo, S.E., Zanetti, C., Peroni, F., Marchi, M.D., 2022. Climate justice in the City: mapping heat-related risk for climate change mitigation of the urban and Peri-urban area of Padua (Italy). ISPRS Int. J. Geo Inf. 11 (9), Article 9. https://doi.org/10.3390/ijgi11090490.

United Nations, Department of Economic and Social Affairs, Population Division, 2019. World Urbanization Prospects 2018: Highlights (ST/ESA/SER.A/421). https://population.un.org/wup/assets/WUP2018-Highlights.pdf (accessed 14 August 2025).

Van Der Roest, E., Voeten, J.G.W.F., Cirkel, D.G., 2023. Increasing solar panel output with blue-green roofs in water-circular and nature inclusive urban development. Build. Environ. 244, 110704. https://doi.org/10.1016/j.buildenv.2023.110704.

Williams, K.J.H., Lee, K.E., Sargent, L., Johnson, K.A., Rayner, J., Farrell, C., Miller, R.E., Williams, N.S.G., 2019. Appraising the psychological benefits of green roofs for city residents and workers. Urban For. Urban Green. 44, 126399. https://doi.org/10.1016/j.ufug.2019.126399.

Wójcik-Madej, J., Sowińska-Świerkosz, B., Pérez Luque, G., Michalik-Śnieżek, M., 2026. Retrofitting existing buildings by the use of modular green roofs. Build. Environ. 287, 113900. https://doi.org/10.1016/j.buildenv.2025.113900.

Wu, Y., Furuya, K., Xiao, B., Ma, R., 2025. Optimizing urban green roofs: an integrated framework for suitability, economic viability, and microclimate regulation. Land 14 (9), 1742. https://doi.org/10.3390/land14091742.

Xie, P., Barbarossa, V., Erisman, J.W., Mogollón, J.M., 2024. A modeling framework to assess the crop production potential of green roofs. Sci. Total Environ. 907, 168051. https://doi.org/10.1016/j.scitotenv.2023.168051.

Yan, Q., Yu, J., Dong, N., 2026. Evaluating the carbon benefits and economic efficiency of photovoltaic-green roof systems in China: a nationwide application analysis. Environ. Impact Assess. Rev. 117, 108224. https://doi.org/10.1016/j.eiar.2025.108224.

Zhang, X., Shen, L., Chan, S.Y., 2012. The diffusion of solar energy use in HK: what are the barriers? Energy Policy 41, 241–249. https://doi.org/10.1016/j.enpol.2011.10.043.

Zhang, J., Zhang, H., Qi, R., 2024. A study of size threshold for cooling effect in urban parks and their cooling accessibility and equity. Sci. Rep. 14 (1), 16176. https://doi.org/10.1038/s41598-024-67277-2.

Zhang, Z., Qian, Z., Chen, M., Zhu, R., Zhang, F., Zhong, T., Lin, J., Ning, L., Xie, W., Creutzig, F., Tang, W., Liu, L., Yang, J., Pu, Y., Cai, W., Pu, Y., Liu, D., Yang, H., Su, H., Yan, J., 2025. Worldwide rooftop photovoltaic electricity generation may mitigate global warming. Nat. Clim. Chang. 15 (4), 393–402. https://doi.org/10.1038/s41558-025-02276-3.

Zsiborács, H., Vincze, A., Pintér, G., Hegedűsné Baranyai, N., 2023. A comparative examination of the electricity saving potentials of direct residential PV energy use in European countries. Sustainability 15 (8), 6490. https://doi.org/10.3390/su15086490.