Politecnico di Torino

Master's degree Program in

Digital Skills for Sustainable Societal Transitions

A.Y. 2025/2026

Graduation Session – February 2026

Mitigating Urban Building Energy Demand Through Nature-Based Solutions

A Case Study in Mirafiori, Turin

Supervisor: Candidate:

    Sara Torabi Moghadam   Jun Wei

Co-Supervisor:

    Maria Ferrara

    Virginia Pellerey

    Sebastiano Anselmo

Table of Contents

List of Figures

List of Tables

Acronyms

Abbreviation	Full term
CDD	Cooling Degree Days
EU	European Union
GFA	Gross Floor Area
GIS	Geographic Information System
HDD	Heating Degree Days
IGR	Intensive Green Roofs
IUCN	International Union for Conservation of Nature
NbS	Nature-based Solutions
PVGIS	Photovoltaic Geographical Information System
RES	Renewable Energy Systems
SDGs	Sustainable Development Goals
SVR	Surface-to-Volume Ratio
TABULA	Typology Approach for Building Stock Energy Assessment
UBEM	Urban Building Energy Modeling
UHI	Urban Heat Island
WWR	Window-to-Wall Ratio

Acknowledgement

I would like to express my deepest and most sincere gratitude to my thesis advisors, Sara Torabi Moghadam, Maria Ferrara, Virginia Pellerey, and Sebastiano Anselm, for their continuous guidance, patience, and generous support throughout this research. Their thoughtful comments, constructive critiques, and in-depth discussions consistently guided this work toward a more rigorous and scientifically grounded direction. Each meeting and round of feedback brought new clarity and often reshaped my understanding of the research, contributing decisively to the development and quality of this thesis.

I am also sincerely grateful to the SDG11 Lab for providing access to high-quality spatial datasets and for offering a stimulating academic environment in which ideas could be openly discussed and refined. The opportunity to work and learn within the lab greatly enriched both the methodological and conceptual aspects of this study.

I would like to thank my family for their unwavering encouragement, trust, and unconditional support throughout my academic journey. Their presence and understanding gave me the confidence and stability needed to pursue this research with focus and determination.

Finally, I would like to express my heartfelt thanks to my classmates and colleagues at Politecnico di Torino. Sharing this journey with such dedicated peers created a strong sense of solidarity and motivation. Learning, discussing, and growing alongside them has been an invaluable part of my experience and has shaped not only this work, but also my personal and academic development.

Jun Wei

Feb. 2026

Abstract

Nature-based Solutions (NbS) are increasingly considered as passive strategies to mitigate urban building energy demand by enhancing the thermal performance of building envelopes, primarily through modifications to effective U-values. However, their reported energy-saving performance varies widely across studies, limiting their effective integration into urban energy planning. This research investigates how and to what extent different NbS contribute to the reduction of building energy demand in urban contexts, with a specific focus on green roofs, green walls, and urban trees.

A systematic literature review is first conducted to synthesize existing evidence on the energy impacts of NbS. Both qualitative and quantitative analyses are applied. Qualitatively, the review identifies climate zone and study scale as key factors explaining the variability of reported energy savings. Quantitatively, energy impacts are standardized using relative (%) and absolute (kWh/m²·year) indicators, distinguishing cooling, heating, and total energy demand. The results show that green roofs generally achieve higher relative energy savings, while green walls tend to deliver higher absolute energy reductions. In contrast, studies addressing the impact of urban trees on building energy demand remain limited and report comparatively low energy-saving effects.

Based on these findings, a district-scale assessment framework is developed to estimate the potential reduction in building energy demand through NbS retrofitting in existing urban areas. The method first identifies spatially suitable areas for NbS interventions and subsequently evaluates building energy demand before and after implementation to quantify potential energy savings. Applied to the Mirafiori district in Turin, Italy, the results indicate that retrofitting approximately 8% of roof area with green roofs and 18% of façade area with green walls could respectively account for about 70% of district-level heating energy savings and 90% of cooling energy savings. Energy reductions are further reported per gross floor area and per NbS intervention area, enabling comparison across spatial scales. Associated indirect CO_2 reductions are derived as a secondary outcome of reduced energy demand, while direct carbon sequestration by urban trees is assessed separately. In Mirafiori, urban tree planting across 16.8% of suitable area is estimated to deliver a total direct CO_2 reduction of approximately 1,476 t/year.

Overall, the case study confirms and contextualizes the literature findings, particularly demonstrating the substantial potential of green roofs and green walls to reduce building energy demand at the urban scale in Cfa climate zones, alongside the complementary role of urban trees in CO_2 sequestration. These results provide a coherent reference for both academic research and urban policy development.

Chapter 1 – Introduction

1.1 – Background

Climate change and global warming have emerged as major threats to human society, primarily driven by energy consumption and greenhouse gas emissions (Nejat et al., 2015). According to the Intergovernmental Panel on Climate Change (IPCC), the global average surface temperature from 2011 to 2020 was 1.09 °C higher than the pre-industrial level (1850-1900), reflecting a clear and accelerating warming trend (Calvin et al., 2023). This climatic shift is not merely an environmental concern; it directly influences public health, ecosystem stability, and socio-economic development worldwide.

Rapid urbanization has intensified these challenges. Cities, characterized by high built density, anthropogenic heat release, and reduced vegetation cover, are particularly vulnerable to the Urban Heat Island (UHI) effect, where urban areas exhibit significantly higher temperatures than adjacent rural regions. This effect heightens heat stress, exacerbates health risks, and increases cooling demand.

Demographic trends further reinforce these issues. By 2024, the global population reached 8.2 billion, with around 55% living in urban areas, and this proportion is projected to rise to 68% by 2050. Cities already account for about 75% of global energy consumption and 70% of greenhouse gas emissions (IEA, 2024), making them critical arenas for addressing the intertwined crises of climate change and energy demand. Within cities, the building sector stands out as the second-largest energy consumer, responsible for 40% of final energy use and nearly one-third of greenhouse gas emissions (Mastouri et al., 2020). The UHI effect further increases cooling demand, with typical urban buildings consuming on average 13% more energy for cooling than comparable rural counterparts, thereby intensifying the energy crisis (Santamouris, 2014).

In response to accelerating global climate change, the Paris Agreement adopted in 2015 set the ambitious objective of limiting the rise in global temperature to well below 2°C, while pursuing efforts to cap warming at 1.5°C above pre-industrial levels. The Agreement also emphasizes achieving net-zero greenhouse gas emissions in the second half of the 21st century (UNFCCC, 2015). Meanwhile, the United Nations proposed the Sustainable Development Goals (SDGs) as a globally shared development framework that aims to harmonize social progress, economic growth, and environmental protection (United Nations, 2015). Among these goals, the European Union (EU) has shown strong commitment to implementing the SDGs by 2030, particularly in relation to climate action, clean energy transition, and sustainable urban development. In 2019, the EU introduced the European Green Deal, a comprehensive policy roadmap targeting climate neutrality by 2050, promoting a more resilient, inclusive, and low-carbon socio-economic transformation (European Commission, 2019).

These intertwined global challenges underscore the urgent need for effective approaches to reduce building energy demand and associated CO_2 emissions, especially in densely populated urban areas. In this context, NbS have gained increasing attention as sustainable and multifunctional strategies capable of simultaneously improving building thermal

performance and delivering environmental co-benefits. The International Union for Conservation of Nature (IUCN) formally defined NbS in 2025 as "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al., 2025). In urban environments, NbS commonly involve introducing or enhancing natural elements—such as parks, wetlands, street trees, green roofs, rain gardens, and ecological corridors—to mitigate UHI effects, reduce stormwater runoff, improve air quality, enhance biodiversity, and promote healthier living environments (European Environment Agency, 2021).

Urban green infrastructure, which includes features such as urban trees, green roofs, and green walls, are examples of NbS often employed as municipal climate mitigation and adaptation strategies (Xiao et al., 2023). Given the findings of many existing studies, these NbS have the potential to mitigate the UHI effect, lower both ambient and indoor temperatures, lower energy consumption, and decrease CO_2 emissions.

Among these, green roofs and green walls directly integrate vegetation with the building envelope, providing benefits such as shading and surface cooling. These effects can reduce energy consumption and associated CO_2 emissions. Simulations by Alexandri and Jones (2008) further showed that green roof systems can substantially reduce roof surface temperatures, with peak reductions of up to 26.1 °C and daytime average reductions of up to 12.8 °C under hot-climate conditions such as Mumbai and Riyadh.. Moreover, an evaluation of a five-storey building at the University of British Columbia Okanagan campus showed that full green roof and full green wall scenarios reduced annual cooling energy consumption by 3.2% and 7.3%, respectively, compared with the baseline model (Sailor, 2008).

Similarly, urban trees have been shown to provide substantial carbon sequestration benefits. Research in Montreal demonstrated that full urban tree coverage can offset approximately 17% of life-cycle CO_2 emissions for an all-electric laboratory and 3% for a single-detached house, highlighting the potential of trees to contribute to carbon reduction at both institutional and residential buildings (Xiao et al., 2023).

The importance of these interventions is further reflected in policy frameworks such as the EU Biodiversity Strategy, which requires cities with more than 20,000 inhabitants to develop Urban Greening Plans by the end of 2021. These plans should incorporate biodiversity-enhancing NbS, including urban forests, green roofs, green façades, and street trees, to support the target of planting three billion trees by 2030 (Bettina Wilk et al., 2021). In parallel, under the European Green Deal framework, the Energy Efficiency Directive establishes binding measures to reduce end-use energy consumption and improve heating and cooling efficiency, thereby reinforcing the role of passive and NbS in enhancing building energy performance and supporting the decarbonization of the built environment (Hayes et al., 2022).

Despite the growing body of evidence on the thermal and energy-related benefits of green roofs, green walls, and urban trees, existing studies remain fragmented. Most research examines a single NbS type in isolation and relies on methods, indicators, and scales that

vary substantially across studies. This inconsistency limits the ability to conduct systematic cross-type comparisons and prevents the reporting of comparable thermal performance data (Bartesaghi Koc et al., 2018). Therefore, this study aims to conduct a comprehensive assessment of the energy and carbon impacts of green roofs, green walls, and urban trees across buildings in different climate zones.

1.2 - Research question

In recent years, NbS have attracted increasing attention, with the number of publications rising sharply since 2022, indicating that NbS has become a rapidly developing research hotspot (Figure 1). However, despite this growing interest, applications of NbS in the urban built environment remain limited. Studies on building-related NbS—such as green roofs, green walls, and urban trees—account for only about 9% of all NbS research, and most of these focus on ecosystem regulation, health, or biodiversity rather than building energy consumption and greenhouse gas emissions (Li et al., 2023). This highlights a significant research gap regarding the potential energy and carbon benefits of NbS in buildings. Therefore, this study addresses the following research question: what are the potential effects of implementing NbS on building energy consumption and CO_2 emissions?
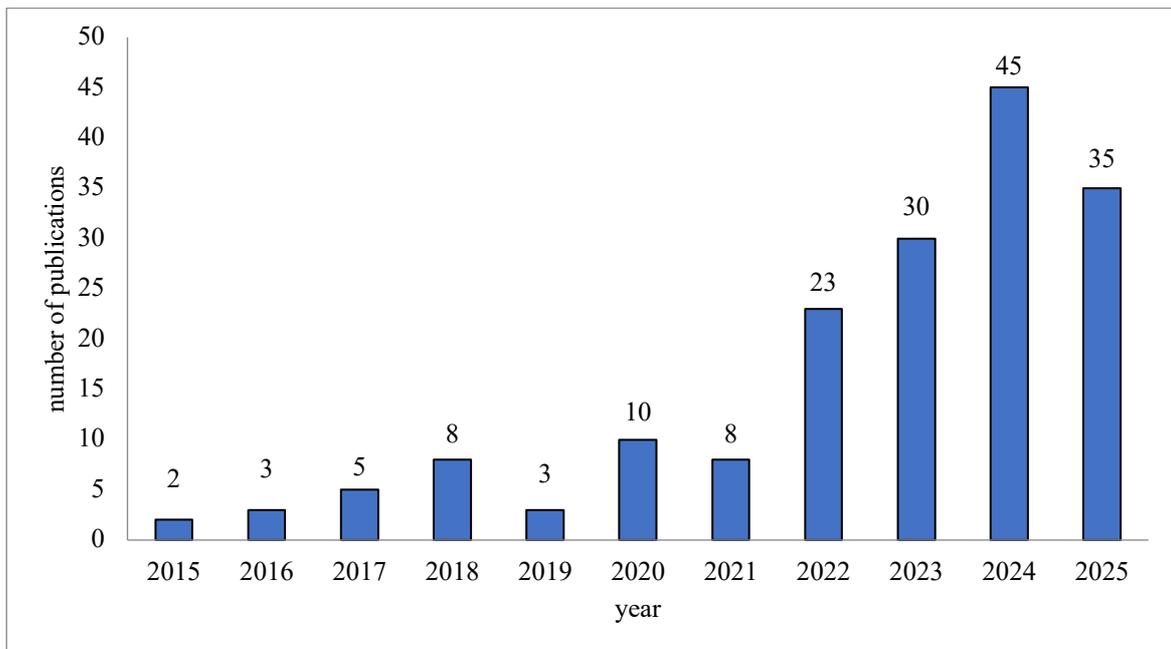
Figure 1: Annual number of publications by year (Scopus data)

1.2 – Research objectives

To answer the research question, the study first reviews existing academic evidence on the effects of NbS. Since current findings are scattered and context-dependent, a systematic review is used to synthesize what is known. To explore how these effects translate to a specific urban context, an empirical simulation is then applied to the Mirafiori district (Turin, Italy). The objectives of the study are:

Objective 1 - To summarize what existing studies have found about the impact of NbS on building energy consumption and CO_2 emissions.

<u>Objective 2</u> - To assess the potential energy and CO_2 impacts of implementing NbS in the Mirafiori district.

1.3 – Thesis structure

This thesis is organized around two main research objectives. The first objective is to summarize existing knowledge on the impacts of NbS on building energy consumption and CO_2 emissions. To address this objective, Chapter 2 presents a systematic literature review. The chapter outlines the search strategy, the development of the Literature NbS Abacus as a structured data extraction framework, and the synthesis of current findings on NbS in the built environment. It concludes by identifying research gaps and highlighting areas requiring further investigation, which inform the subsequent case study.

The second objective is to evaluate the potential energy and CO_2 impacts of implementing NbS in the Mirafiori district of Turin. Chapter 3 presents the case study analysis, conducted in two main stages. First, a suitability assessment is carried out to identify buildings and urban areas appropriate for different NbS interventions, considering spatial, structural, and site-specific constraints. Second, the potential energy and carbon impacts of the selected interventions are estimated and analyzed at the district scale. The resulting findings form the empirical basis for further comparison and interpretation.

Chapter 4 brings together the results from the literature review and the case study through a comparative discussion. The chapter examines the consistency and differences between literature-based evidence and case study outcomes, discusses the implications of the findings for sustainable urban development and low-carbon building strategies, and reflects on the main contributions, limitations, and directions for future research.

Finally, additional supporting materials, including detailed data tables and supplementary figures are provided in the Appendices.

Chapter 2 – Literature review

To address the first research objective, which is to summarize the current knowledge on how NbS influence building energy consumption and CO_2 emissions, a systematic literature review was conducted. Relevant studies were identified through database searches and screened according to predefined inclusion and exclusion criteria to ensure their relevance and rigor. The final set of publications was analyzed with respect to their research contexts, methodological approaches, and the reported effects of different NbS types on energy performance and carbon emissions. Through comparing and synthesizing these studies, common patterns, key influencing factors, and areas of inconsistency were identified, providing a basis for evaluating the current state of research and highlighting remaining knowledge gaps.

2.1 – Literature review methodology

2.1.1 – Search strategy

The literature search covered the period from January 2005 to June 2025. The starting point reflects the period during which the concept of NbS began to be formalized and increasingly adopted in building energy and urban research. The end point corresponds to the time when the literature review process for this study was initiated, ensuring that the dataset reflects the state of knowledge available up to that date. The search was conducted in Scopus and Web of Science, as these two databases provide broad and high-quality coverage of peer-reviewed research, thereby ensuring comprehensiveness and reducing the risk of missing relevant publications.

The selection of keywords was aligned with the research objective of examining the influence of NbS on building energy consumption and CO_2 emissions. The terms "Nature-Based Solutions" and "NbS" were used to ensure conceptual consistency, while "energy consumption," "energy performance," and "CO_2 emissions" were included to restrict the search to studies that examined the impacts of NbS on building energy use and CO_2 emissions, whether reported in quantitative measures or through qualitative performance assessments. In addition, several alternative keyword sets were tested during the pilot search stage. Narrow, technology-specific terms such as "green roof(s)" and "green wall(s)" were found to excessively narrow the search scope by prioritizing only certain NbS types and excluding others (e.g., green façades, urban trees). In contrast, broader terms such as "Urban Building Energy Modeling (UBEM)" and "Positive Energy District" yielded literature that was largely centered on urban energy system modeling rather than on the physical environmental performance of NbS. Therefore, these terms were not included in the final search strategy to maintain both conceptual focus and comprehensiveness.

To operationalize this search strategy, the following Boolean query was applied to titles, abstracts, and keywords in both databases:

("Nature-Based Solutions" OR "Nature Based Solutions" OR NbS)

AND

("energy consumption" OR "energy performance" OR " CO_2 emissions" OR "carbon emissions")

The PRISMA framework was adopted as the methodology for the literature review. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework is a widely adopted methodology for conducting systematic literature reviews. It provides a structured approach to identify, screen, and include studies, ensuring transparency and reproducibility. The process typically consists of three main stages:

(1) Identification

Two databases, Scopus and Web of Science, were searched, yielding 183 and 125 records, respectively. After removing duplicates, 210 unique records remained.

(2) Screening

All 210 records were screened based on their titles and abstracts to assess relevance to urban NbS and their impacts on building energy consumption and CO_2 emissions. At this stage, 150 records were excluded due to lack of relevance, leaving 60 reports for full-text assessment. All 60 reports were successfully retrieved and further assessed for eligibility. Studies were excluded for the following reasons: irrelevant NbS types, such as water, wetlands, or soils (n = 3); mismatch of impact indicators, e.g., reporting temperature, U-value, or thermal comfort rather than energy consumption or CO_2 emissions (n = 14); and other reasons, such as policy- or economics-focused perspectives (n = 13).

(3) Included

After this screening, a total of 30 studies were included in the final review dataset. (Figure 2)
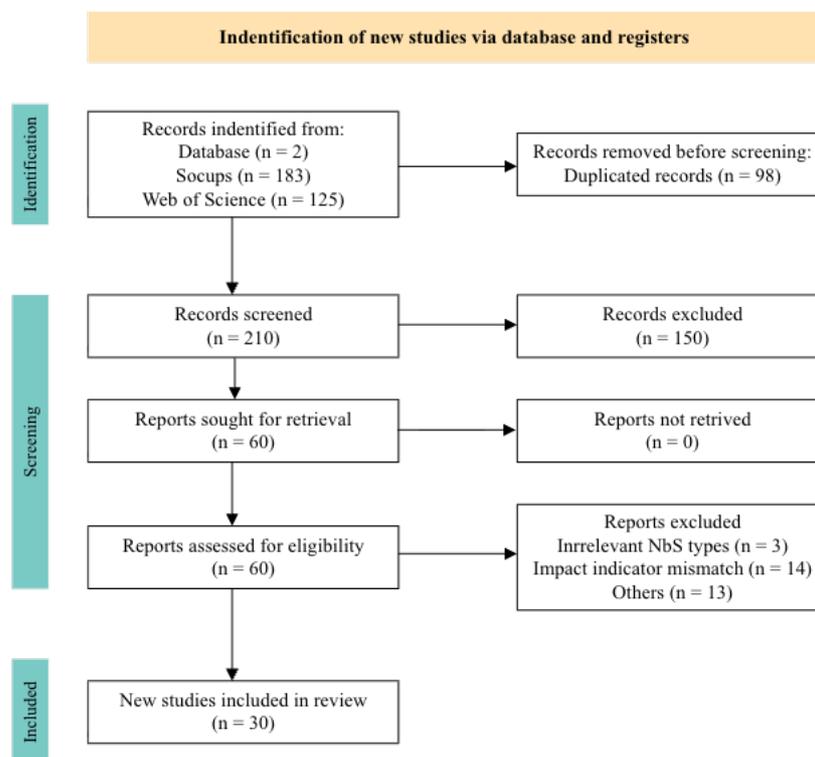
Figure 2: PRISMA flow diagram of the literature screening process

2.1.2 – Literature NBS Abacus

To facilitate systematic comparison across the selected studies, a structured data extraction table was developed. This table is referred to as the Literature NbS Abacus, where "Abacus" denotes a structured matrix designed to enable side-by-side evaluation of research characteristics and outcomes. The extracted information was grouped into four categories: (1) basic publication information, (2) study locations, (3) NbS characteristics, and (4) impacts on energy consumption and CO_2 emissions. This structure ensures that both the contextual conditions and performance outcomes of NbS interventions can be compared across different studies, regions, and NbS types.

(1) Basic publication information (title, year, author, journal, doi)

The first category included the title, authors, year of publication, journal, and DOI (Digital Object Identifier). Recording these items ensured accurate referencing and traceability and provided basic contextual information for understanding the scope of the reviewed studies.

(2) Study locations (location of case study, climate zones)

In the literature review, the location of each case study was recorded, as the effects of the same NbS can vary across different climates. For instance, a study of 67 buildings in China showed substantial differences in energy use and carbon emissions depending on climate (Zhao et al., 2024). To ensure consistency across studies, climate zones were assigned based on the Köppen–Geiger classification system, which is the most widely used method for categorizing global climate conditions. It distinguishes five primary climate groups: equatorial (A), arid (B), warm temperate (C), snow or boreal (D), and polar (E). A second letter in the classification considers precipitation patterns (e.g., Df for a snow climate that is fully humid), while a third letter considers air temperature (e.g., Dfc for a snow climate that is fully humid with a cool summer) (Kottek et al., 2006). This hierarchical coding enables standardized comparisons of climate conditions across regions, making it particularly suitable for evaluating the performance of NbS interventions in buildings under diverse climates.

(3) NbS characteristics (observed NbS type, suitable NbS locations, size of intervention)

As key components of urban green infrastructure, green roofs, green walls, and urban trees serve as major NbS that can mitigate urban heat, reduce energy consumption, and sequester carbon in the built environment. Green roofs are roofs covered with vegetation and growing media. They can be broadly classified according to substrate depth and plant type into extensive green roofs (EGR), semi-intensive green roofs (SGR), and intensive green roofs (IGR) (Besir & Cuce, 2018). Green roofs have attracted increasing attention due to their significant role in enhancing building thermal performance and reducing energy demand (Vijayaraghavan, 2016). For example, a study conducted in southern Italy found that during summer, green roofs without any insulation materials exhibited surface temperatures approximately 12 °C lower than conventional roofs, and even in winter, the temperature difference reached nearly 4 °C (Bevilacqua et al., 2016). Green walls refer to all systems that use specific plant species to green vertical surfaces. They can be classified into green façades and living walls (Harbiankova & Manso, 2025). In green façades, plants grow naturally on the building envelope with the growing medium on the ground, while living walls consist of

pre-planted vegetation integrated with a supporting structure, providing uniform coverage of the façade (Besir & Cuce, 2018). Vertical greening can reduce façade temperatures through shading, insulation, and evaporative cooling (Pérez et al., 2011). Urban trees are the tree component of urban green infrastructure. Multiple studies have shown that vegetation effects on urban microclimate are influenced by wind. For example, Taha et al. found that a single tree can affect air temperature downwind up to approximately five times its height, effectively mitigating daytime UHI effects (Taha et al., 1991). In addition to temperature regulation and enhancing thermal comfort, urban trees serve as long-term carbon sinks. A simulation study in Nanjing showed that when the spacing between street trees is 0.2 times the street width, carbon sequestration reaches its maximum, with a total of 1,862 tons over 40 years (Xi et al., 2023). Therefore, these three types of NbS are considered in this review.

For each NbS intervention, information was recorded on its suitable locations and the size of intervention. Recording suitable locations, these parameters is essential because not all urban surfaces or spaces can support a particular NbS type. For example, a study assessing the potential of green roofs in Valencia considered actual structural and site constraints, including roof area, maximum slope, and load-bearing capacity, to evaluate their effects on energy savings and CO_2 reduction (Zayas-Orihuela et al., 2024). Meanwhile, size of intervention was recorded to enable standardization of energy and CO_2 results, making cross-study comparison and quantitative analysis straightforward.

In addition to the three core NbS types, information on non-ecological building interventions was also recorded and analyzed. These include building renovations (e.g., façade insulation upgrades, window replacement) and Renewable Energy Systems (RES) (e.g., photovoltaic panels, solar thermal systems). While these strategies are not considered NbS in the strict sense, they frequently co-occur with NbS in practice and can influence building energy consumption and CO_2 emissions. Therefore, they are treated as a fourth category in the Literature NbS Abacus, allowing the review to evaluate their potential synergy and interaction effects with the three ecological NbS types, while clearly distinguishing them from true vegetation-based interventions.

(4) Impacts (impacts on energy consumption, impacts on CO_2 emissions)

To address Objective 1, as outlined in Chapter 1, this review focuses on summarizing existing studies on the impacts of NbS on building energy consumption and CO_2 emissions. During the literature screening, only outcomes directly related to energy use and carbon emissions were recorded, rather than other related factors such as temperature, thermal comfort, or biodiversity. For energy consumption impacts, cooling energy savings in summer, heating energy savings in winter, and total annual energy savings were documented separately. When studies did not report quantitative results directly, the energy savings were manually calculated using following equation, where E_{init} is the initial energy consumption and E_{post} is the energy consumption after the intervention.

$$Energy\ saving\ (\%) = (E_{init} - E_{post})\ /\ E_{init}\ \times 100$$

Qualitative findings were also recorded when no numerical data were available. For instance, intensive green roofs exhibited the lowest mean U-value, indicating high energy-saving

potential, even though no quantitative energy reduction was provided (Harbiankova & Manso, 2025).

For CO_2 impacts, CO_2-related outcomes were recorded, including CO_2 sequestration or capture, CO_2 emissions reduction, CO_2 concentration, and life cycle carbon emission offset. These indicators collectively capture the multiple pathways through which NbS can influence carbon, from direct uptake by vegetation to reductions in building-related emissions and changes in local CO_2 levels. Life cycle carbon emission offset was included as a standardized metric expressing the proportion of total building life cycle emissions mitigated by NbS interventions.

Finally, the methods and software used to obtain these results were also documented to ensure transparency and comparability across studies.

2.2 – Literature review results and discussion

2.2.1 – Distribution by intervention type and geography

This review encompasses 30 selected studies covering a variety of NbS, predominantly green roofs, green walls (including green facades and living walls), and urban trees. Additionally, several studies incorporated conventional solutions, such as Renewable Energy Sources (RES) or building renovation, for comparative analysis or integrated assessment. In terms of research volume, green roofs remain the dominant subject in current academia, appearing in 15 articles, followed by urban trees with 12 articles, and green walls with 8 articles. Research focusing on RES or building renovation accounts for 5 articles, which are discussed either independently or in combination with green roofs and walls to evaluate the comprehensive benefits of hybrid strategies (Figure 3).
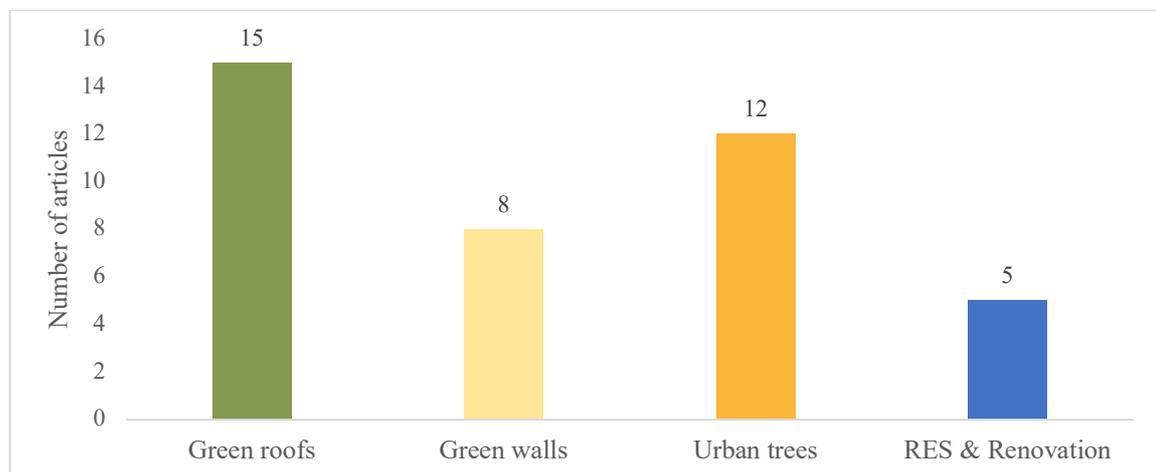
Figure 3: Distribution of reviewed articles by intervention type

To further explore the geographical patterns of NbS research, Figure 4 presents a stacked bar chart illustrating the distribution of different NbS types across continents. The figure highlights not only the overall dominance of European case studies but also reveals how the focus on specific NbS solutions varies by region. Green roofs appear consistently across all continents, while studies on urban trees and green walls show a more uneven distribution, reflecting regional research priorities and contextual suitability.
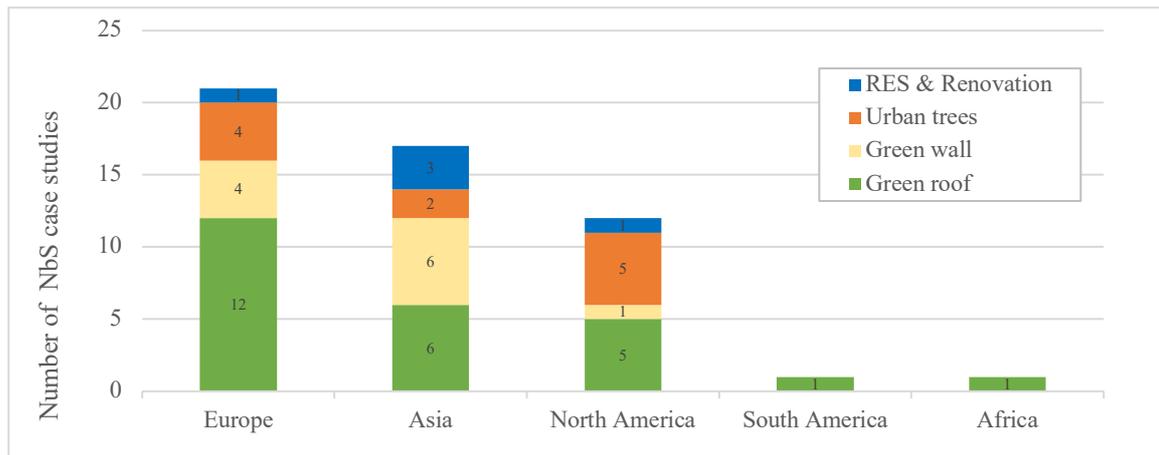
Figure 4: Distribution of NbS types across continents

Figure 5 further illustrates the spatial distribution of the selected case studies, highlighting clear geographical clustering patterns. Europe emerges as the most represented region, with a particular concentration in Southern European countries such as Spain, Italy, and Portugal, which together account for 11 out of the 52 reviewed case studies. This distribution is partly associated with the hot and dry summer climate of the Mediterranean region, which results in high cooling demands and a strong interest in passive cooling strategies.

It should be noted that this geographical dominance is also influenced by a methodological bias, as the term Nature-based Solutions is more commonly used in European academic and policy contexts, whereas similar interventions in other regions are often referred to as green infrastructure or related concepts. Consequently, studies from Europe are more likely to be captured by searches explicitly targeting NbS-related terminology.

Asia ranks second, with China contributing the largest share of studies, particularly in rapidly urbanizing regions such as the Yangtze River Delta. This trend reflects the growing emphasis on Sponge City initiatives—an urban planning approach aimed at enhancing stormwater management, urban resilience, and climate adaptation through nature-based and green infrastructure solutions. North America, mainly represented by the United States, follows as the third most studied region, benefiting from early implementation of building energy efficiency standards and sustainable urban planning practices.
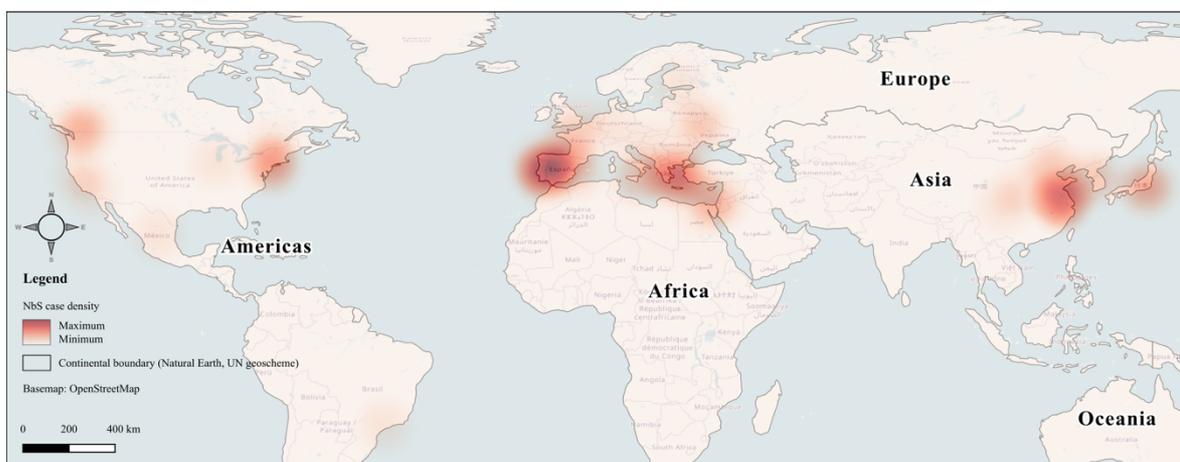
Figure 5: Geographic distribution heatmap of case studies

A cross-analysis of NbS types and geographical locations reveals significant regional preferences. Half of the green roof case studies concentrate in Europe, largely due to mature mandatory regulations and financial subsidy policies for green roofs across European nations. For example, the new European strategy explicitly promotes nature-based adaptation solutions, whose implementation would enhance climate resilience and contribute to achieving the objectives of the European Green Deal, thereby emphasizing the opportunity for a green transformation (European Commission, 2021). The distribution of green walls is relatively balanced between Europe and Asia; however, the application logic in Asian cities is more pronounced. Due to the high density and high plot ratios typical of Asian metropolises, ground-level green space is limited, making vertical greening an optimal solution to increase greenery and address ecological and aesthetic needs within constrained land resources. Notably, research on urban trees is more prevalent in North America than in Europe. This is mainly due to the more mature Urban Forest management concepts and systems in North America; for instance, several US cities have explicitly set canopy cover targets of 40 %, driving substantial empirical research.

The case studies included in this review cover 39 cities. Analysis based on the Köppen-Geiger classification system reveals that the vast majority of NbS research is concentrated in Temperate climate zones, particularly the Mediterranean zone. This phenomenon occurs because the intense solar radiation and high temperatures in these climates maximize the shading and evapotranspiration cooling benefits of NbS, making them highly valuable for research and application. Conversely, research in arid and extreme climate regions is relatively scarce. This is primarily because water limitations in extreme environments make vegetation survival and maintenance extremely difficult, and potential irrigation requirements may offset energy-saving benefits. Given that NbS efficacy is highly dependent on environmental context, subsequent calculations of impacts on building energy consumption and carbon dioxide emissions should be evaluated according to climate zones (see Figure 6 and Figure 7).
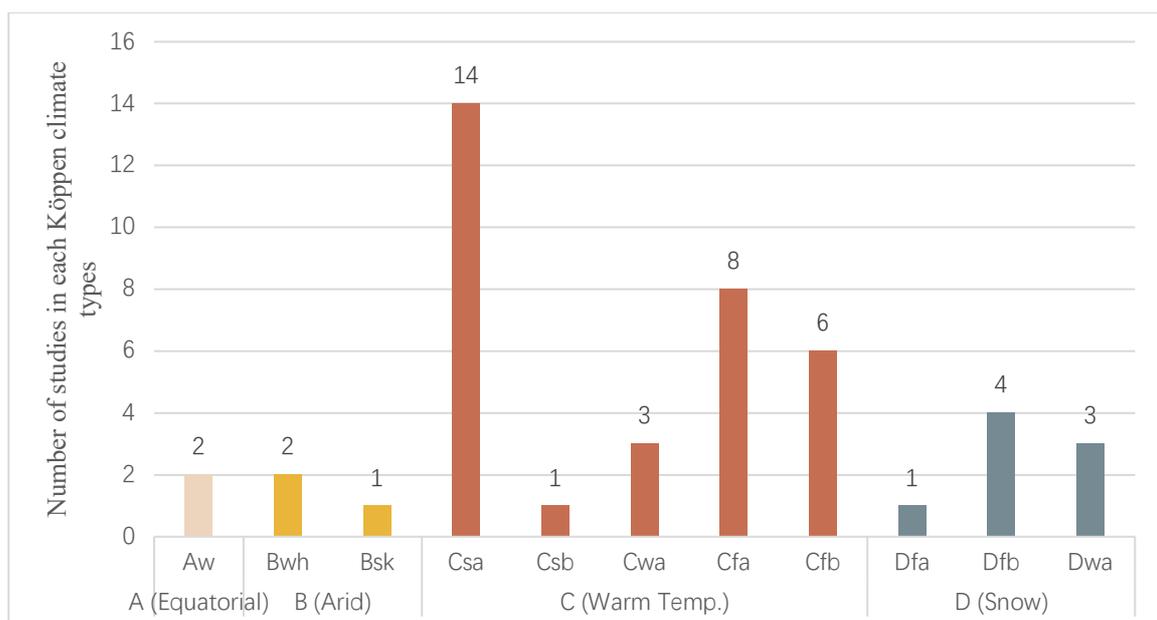
Figure 6: Number of studies across Köppen-Geiger climate zones
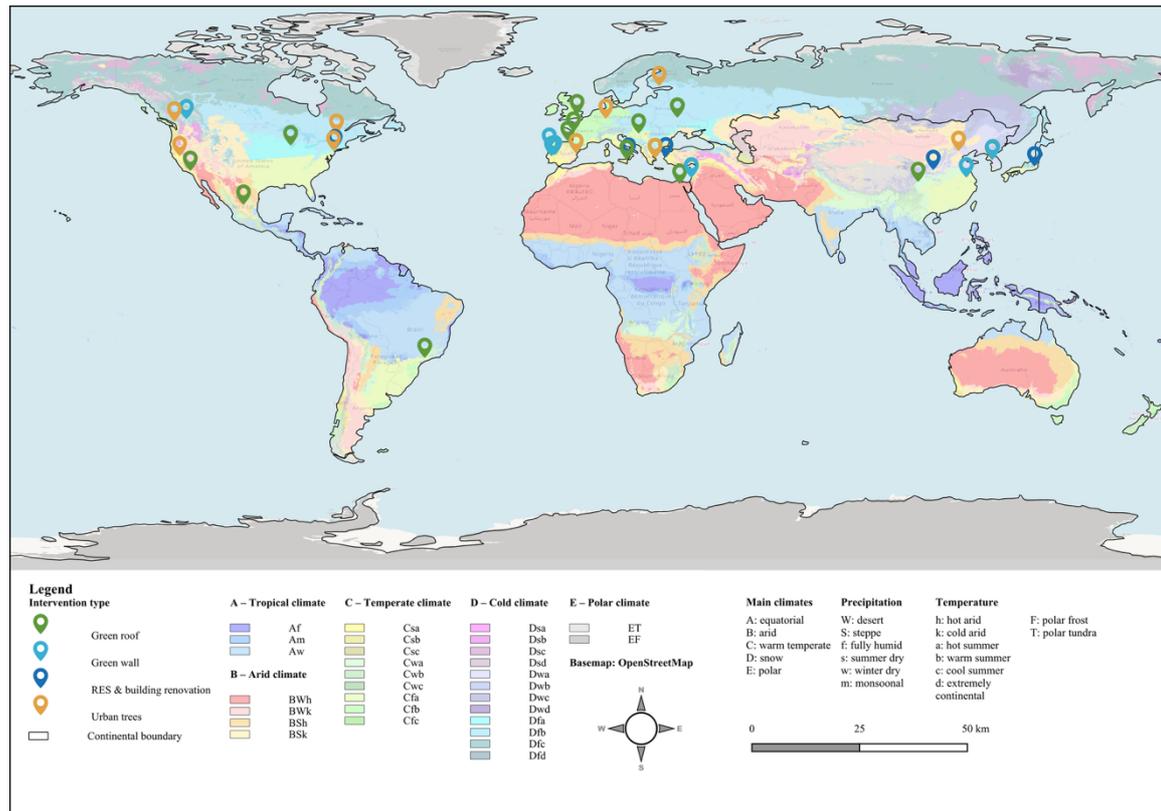
Figure 7: Case study locations across Köppen-Geiger climate zones

2.2.2 – Impacts on energy performance

NbS and conventional solutions influence building energy consumption through distinct mechanisms. NbS (green roofs, green walls, and urban trees) primarily rely on biophysical processes: in summer, they intercept solar radiation via shading from canopies and vines, while regulating microclimates through evapotranspiration to reduce cooling loads; in winter, the vegetation and substrate layers act as additional insulation, minimizing heat loss (Manso & Castro-Gomes, 2015). In contrast, conventional solutions (building renovation and RES) rely on engineering interventions. Renovation blocks heat exchange by enhancing the airtightness and thermal performance of the envelope, such as through external insulation or high-performance glazing (Engström et al., 2018), while RES focuses on the supply side, substituting fossil fuels or grid electricity with low-carbon alternatives (Mangano & Laganà, 2024). Although conventional solutions are technologically mature and highly controllable, NbS offer unique ecological added value.

To systematically evaluate the energy-saving performance of NbS, this study compiles and synthesizes reported results from the literature in a structured table (Table 1), organized by NbS type, climate zone, study location, spatial scale, energy-saving indicators, and references. NbS are first grouped by intervention type, and further classified according to the Köppen–Geiger climate system, separating cooling-dominant climates (Mediterranean: Csa, Csb; Humid Subtropical: Aw, Cfa, Cwa) from heating-dominant climates (Continental: Dfa, Dfb, Dwa; Oceanic: Cfb), followed by mixed-demand arid climates (Bwh, Bsk), in order to examine the role of climatic context in shaping NbS effectiveness.

Energy-saving outcomes are reported separately for cooling, heating, and total energy

demand, and average values are calculated independently for each category, as aggregating these end-uses would obscure their distinct seasonal and climatic relevance. Absolute energy savings are expressed in kWh/m²·year, representing annualized values. For studies reporting total annual savings in kWh, data were normalized by the total conditioned floor area and the reported intervention period to obtain annual savings per unit area, enabling cross-study comparison. In contrast, values reported using heterogeneous units (e.g., kWh/m²·day, GJ/day, GWh/year) or derived from short-term or seasonal observations were not included in average calculations but are retained in the table to preserve the completeness of the evidence base.

The spatial scale of analysis is explicitly distinguished as city-scale, building-scale, or sample-scale. Sample-scale studies, such as the experimental work by Stefano Cascone (2022), which compared three green roof systems using identical test plots (1.25 m × 1.25 m) under Mediterranean summer conditions, are treated separately from building- and city-scale assessments, as their results reflect localized thermal performance rather than integrated building or urban energy demand. Studies that could not be normalized by area or reported only aggregated ranges were excluded from average calculations but are fully documented in Table 1. Together, this structured approach provides a transparent foundation for the subsequent scatter-based analyses of NbS energy-saving performance across climates and scales.

Table 1: Energy saving by NbS and conventional solution

NbS type	Energy saving type	Climate zone	Location	Scale	Energy saving		References
					Relative [%]	Absolute [kWh/m²/y]	
Green roof	Cooling	Csa	Catania, Italy	Sample	–	0.92 kWh/m²/d	(S. Cascone, 2022)
	Cooling	Csa	Badajoz, Spain	Building	54.00	28.37	(Gómez et al., 2021)
	Cooling	Csa	Evora, Portugal	Building	36.00	10.63	(Gómez et al., 2021)
	Cooling	Csb	Porto, Portugal	Building	35.00	1.11	(Gómez et al., 2021)
	Cooling	Aw	Chetumal, Mexico	City	45.00	–	(Ávila-Hernández et al., 2020)
	Cooling	Aw	Colima, Mexico	City	42.00	–	(Ávila-Hernández et al., 2020)
	Cooling	Cfa	Sao Paulo, Brazi	Building	83.21	–	(Jia et al., 2024)
	Cooling	Cfa	Yokohama, Japan	Building	1.90	0.03 GJ/d	(Dong & Asawa, 2025)
	Cooling	Cfb	Bilbao, Spain	Building	53.70	16.84	(Azkorra-Larrinaga et al., 2023)
					84.20	26.35	

NbS type	Energy saving type	Climate zone	Location	Scale	Energy saving		References
					Relative [%]	Absolute [kWh/m²/y]	
	Cooling	Cfb	London, UK	Building	78.63	–	(Jia et al., 2024)
	Cooling	Bwh	La Paz, Mexico	City	31.00	–	(Ávila-Hernández et al., 2020)
	Cooling	Bsk	Okanagan, Canada	Building	3.20	–	(Xiao et al., 2023)
	Heating	Csa	Los Angeles, US	Building	80.37	–	(Jia et al., 2024)
	Heating	Csa	Athens, Greece	Building	11.40	–	(Xiao et al., 2023)
	Heating	Cfa	Sao Paulo, Brazi	Building	87.92	–	(Jia et al., 2024)
	Heating	Dfb	Southern Finland	Sample	38.00	–	(Xiao et al., 2023)
	Heating	BWh	Cairo, Egypt	Building	85.65	–	(Jia et al., 2024)
	Total	Csa	Valencia, Spain	City	3.00	55.30 toe/y	(Zayas-Orihuela et al., 2024)
					10.60	10.24 toe/y	
	Total	Csa	Athens, Greece	Building	37.00	–	(Liu et al., 2021)
					4.00	–	
					2.00	–	
	Total	Csa	Izmir, Türkiye	City	3.70	0.03 kWh/m²/d	(Turhan et al., 2023)
					14.43	0.12 kWh/m²/d	
	Total	Cfa	Nanjing, China	Building	–	7.60	(Yang et al., 2023)
	Total	Cfa	New York, US	City	0.43	377.80 GWh/y	(Engström et al., 2018)
	Total	Cwa	Incheon, Korea	Building	3.70	90.90 GJ/y	(Liu et al., 2021)
	Total	Dfa	Chicago, US	City	14.00	–	(Xiao et al., 2023)
	Total	Cfb	Osijek, Croatia	Building	55.20	36.88	(Savić et al., 2024)
	Total	Cfb	La Rochelle, France	Building	6.00	–	(Liu et al., 2021)
Green wall	Cooling	Csa	Rehovot, Israel	Building	20.00	30.43	(Yungstein & Helman, 2023)

NbS type	Energy saving type	Climate zone	Location	Scale	Energy saving		References
					Relative [%]	Absolute [kWh/m²/y]	
	Cooling	Csa	Gush Dan, Israel	Building	8.90	–	(Zuckerman & Lensky, 2023)
	Cooling	Csa	Badajoz, Spain	Building	47.00	24.67	(Gómez et al., 2021)
	Cooling	Csa	Evora, Portugal	Building	12.00	3.61	(Gómez et al., 2021)
	Cooling	Csb	Porto, Portugal	Building	14.00	0.43	(Gómez et al., 2021)
	Cooling	Cs	Mediterranean region	Building	34.00	–	(Xiao et al., 2023)
	Cooling	Cfa	Nanjing, China	Building	12.16	55.69	(Cao et al., 2024)
	Cooling	Dwa	Goyang, South Korea	Building	63.60	8.78	(Im & Gil, 2024)
					45.20	5.71	
	Cooling	Bsk	Okanagan, Canada	Building	7.30	–	(Xiao et al., 2023)
Urban trees	Cooling	Csa	Valencia, Spain	City	10.00	–	(Prades-Gil et al., 2024)
					20.00	–	
					30.00	–	
	Cooling	Csa	Sacramento, California	Building	2.30	–	(Ko, 2018)
					5.20	–	
	Cooling	Cfa	Yokohama, Japan	Building	4.40	0.07GJ	(Dong & Asawa, 2025)
	Cooling	Dwa	Beijing, China	City	60.00	–	(Zhang et al., 2014)
	Cooling	Cfb	Vancouver, British Columbia	Building	90.00	–	(Ko, 2018)
	Heating	Cfa	Twin Rivers, New Jersey	Building	14.00	–	(Ko, 2018)
	Total	–	21 cities in California	City	2.50	–	(Jia et al., 2024)
RES & building renovation	Cooling	Cwa	Xianyang, China	Building	53.64	62.10	(Xin et al., 2024)
					65.81	76.41	
	Cooling	Cfa	Yokohama, Japan	Building	15.00	0.24GJ/d	(Dong & Asawa, 2025)
	Heating	Dfb	Poland	City	68.53	–	(Vranayova et al., 2023)

NbS type	Energy saving type	Climate zone	Location	Scale	Energy saving		References
					Relative [%]	Absolute [kWh/m²/y]	
					50.00	–	
Total	Csa	Reggio Calabria, Italy	Building		–	281.67	(Mangano & Laganà, 2024)
Total	Csa	Athens, Greece	City		12.70	–	(Komninos, 2022)
Total	Csa	New York, US	City		0.25	220 GWh/y	(Engström et al., 2018)
					1.53	1360 GWh/y	
Total	Cfb	Frankfrut, Germany	City		12.70	–	(Komninos, 2022)
Total	Dfb	Helsinki, Stockholm	City		12.70	–	(Komninos, 2022)

2.2.2.1 – Energy performance of green roofs

For green roofs, the distributions of cooling, heating, and total energy reduction differ markedly, even within the same climate zone, indicating distinct response patterns across energy end uses. As shown in Figure 8.

Cooling energy reduction exhibits the largest dispersion among the three dimensions. The reported values span a wide range, from very low to exceptionally high levels, with upper-bound reductions observed across multiple climate zones, including Csa, Cfa, and Cfb. Moreover, pronounced variability is evident within the same climate zone, particularly in Csa, where cooling energy reduction rates differ substantially across studies.

Heating energy reduction shows a contrasting distribution pattern. High reduction rates are concentrated in selected climate zones, notably BWh, Csa, and Cfa, where values can approach or exceed 80%. However, such high heating energy reductions are not observed consistently across all climates, and heating data points remain sparse or comparatively low in other zones, including Aw and Dfb.

Total energy reduction presents a distinctly different and more constrained distribution. Most data points are clustered at relatively low values, with the majority of reported total energy savings remaining below 15%. This indicates that, when aggregated over the year, the combined effects of cooling and heating reductions result in a substantially attenuated overall energy-saving outcome. Only a limited number of cases, such as those observed in Cfb climates, deviate from this general trend.

Overall, even within the same climate zone, the three energy dimensions display clearly differentiated ranges: cooling energy reduction is typically distributed around moderate-to-high values (approximately 35–55%, with higher extremes), heating energy reduction tends to cluster at high levels (around 80%) in selected climates, whereas total energy reduction remains comparatively limited, generally falling within a narrow range of approximately 2–15%.

Figure 8: Scatter plot of relative energy saving induced by green roofs across climate zones

2.2.2.2 – Energy performance of green walls

The scatter distribution of cooling energy reduction for green walls (Figure 9) indicates a predominantly moderate performance with substantial variability across climate zones. Most reported values cluster below 20%, while a limited number of cases exhibit markedly higher reductions, exceeding 40%. This heterogeneous distribution suggests that the cooling performance of green walls is highly context-dependent rather than uniformly driven by climate conditions alone.

Differences in research scale and baseline comparison settings further contribute to the observed variability. For instance, the relatively high cooling energy reductions reported for Goyang, South Korea (63.60% and 45.20%) result from direct comparisons between green wall façades and highly exposed glass and steel surfaces, rather than conventional opaque envelopes (Im & Gil, 2024). This comparison framework amplifies the relative improvement achieved by vegetation and partially explains why these values are higher than those reported in most building-scale studies employing standard façade references.

A comparison between cases under similar climatic conditions further illustrates the distinction between relative and absolute energy savings. Although both Rehovot, Israel and Badajoz, Spain are located in hot-summer Mediterranean climates (Csa), the reported relative cooling energy reduction is higher in Badajoz (47%) than in Rehovot (20%), while the corresponding absolute energy savings are comparable (24.67 and 30.43 kWh/m²·y, respectively) (Gómez et al., 2021; Yungstein & Helman, 2023). This example highlights that higher percentage reductions do not necessarily translate into proportionally larger absolute energy savings, as the latter remain strongly constrained by baseline cooling demand and building characteristics.

Additional insight into the role of climate is provided by a set of simulations conducted

within a single study under otherwise identical modeling assumptions. The cooling energy reductions reported for Badajoz (Csa), Evora (Csa), and Porto (Csb) decrease from 47.00% to 12.00% and 14.00%, with corresponding absolute savings of 24.67, 3.61, and 0.43 kWh/m²·y, respectively (Gómez et al., 2021). Since the intervention strategies, building geometry, and simulation framework are consistent across these cases, the observed differences can be primarily attributed to climatic characteristics, particularly the intensity and duration of cooling demand. This comparison demonstrates that climate exerts a measurable influence on green wall performance.
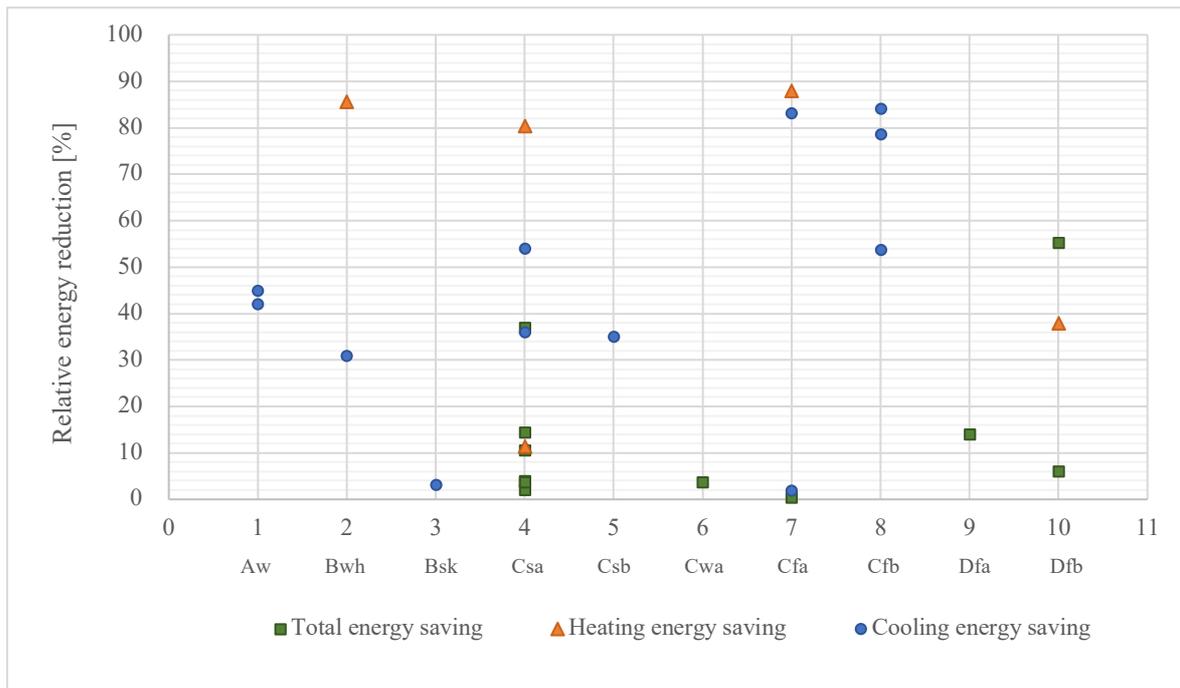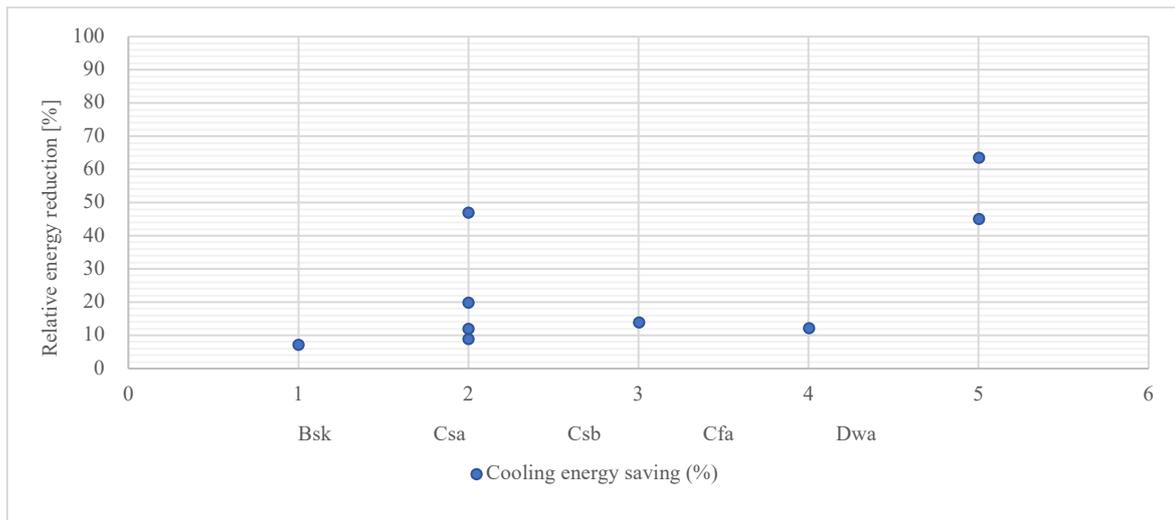

Figure 9: Scatter plot of relative energy saving induced by green walls across climate zones

2.2.2.3 – Energy performance of urban trees

For urban trees, the reported energy-saving performance shows a more scattered and data-limited distribution, with cooling energy reduction being the dominant and almost exclusive indicator. As illustrated in the Figure 10, most data points are concentrated in Csa climates, where relative cooling energy reductions typically range from 10% to 30%, while only a few high values appear in other climate zones.

This concentration is mainly driven by the Valencia (Spain) case, where greening scenarios with ΔNDVI of 0.15, 0.3, and 0.45—with ΔNDVI representing the increase in vegetation density—resulted in significant cooling reductions averaging 10%, 20%, and up to 30%, respectively (Prades-Gil et al., 2024). The presence of multiple points within the same climate zone therefore reflects different greening intensities under otherwise comparable climatic conditions, rather than independent regional variability.

Outside Csa climates, cooling energy savings show greater dispersion, including relatively high values in Cfb (≈90%) and Dwa (≈60%), but these results are isolated and based on individual case studies. Overall, the distribution indicates that urban tree cooling performance is highly case-specific, and no clear monotonic trend across climate zones can be inferred from the current dataset.

Heating energy savings are rarely reported for urban trees, with only one available data point, highlighting that existing studies predominantly focus on cooling benefits. In addition, reported cooling reductions at the building scale tend to be higher than those at the city scale,

reflecting the localized nature of shading and microclimatic effects induced by trees.
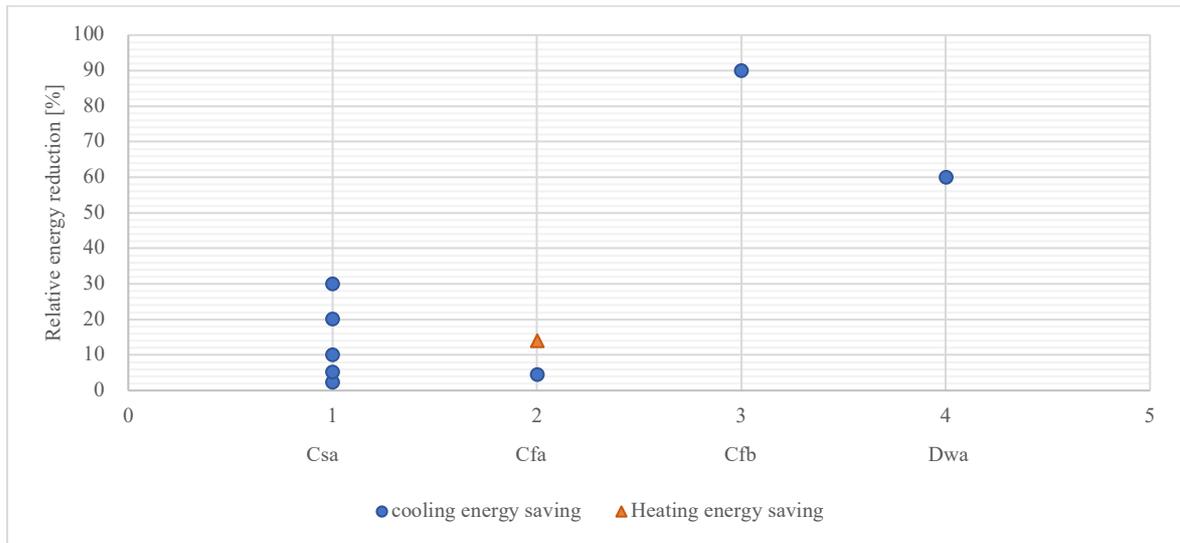
Figure 10: Scatter plot of relative energy saving induced by urban trees across climate zones

2.2.2.4 – *Energy performance of RES and building renovation*

Compared with green roofs, green walls, and urban trees, RES and building renovation measures show a more compact scatter distribution, especially for total energy savings. As shown in Figure 11, most total energy reduction values cluster in the low to medium relative range (<15%), whereas cooling and heating energy savings frequently exceed 50%. This pattern highlights a clear contrast between end-use–specific improvements and aggregated total energy performance.

Despite the generally modest total energy reductions, high heating energy savings are observed in some city-scale cases, such as Poland (Dfb climate), where heating energy reductions reach 68.53% and 50.00% (Vranayova et al., 2023). At the same time, total energy savings in RES and renovation studies remain relatively limited in percentage terms but correspond to very large absolute reductions, often on the order of hundreds to thousands of GWh per year, substantially exceeding the absolute energy savings reported for most NbS.
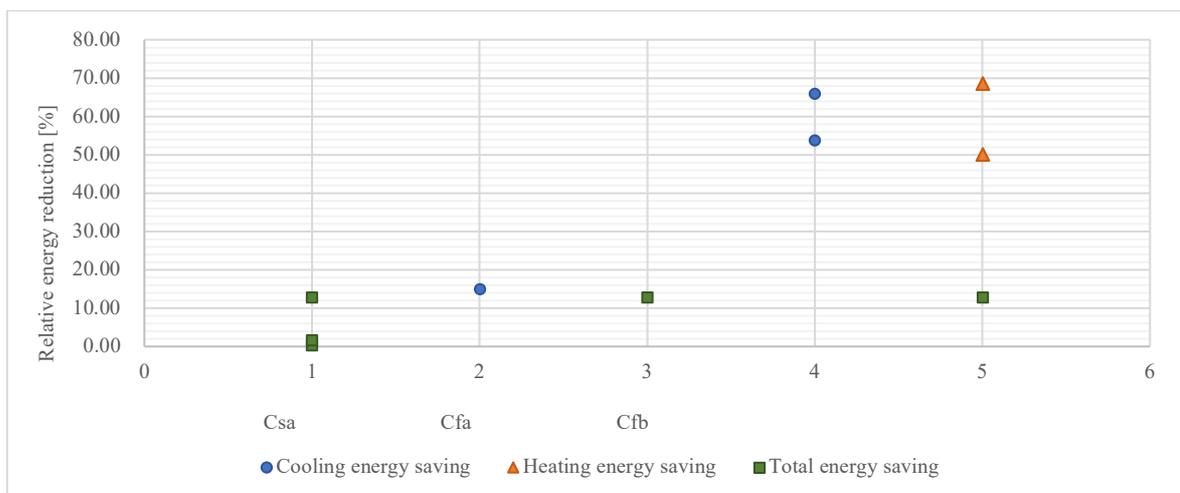
Figure 11: Scatter plot of relative energy saving induced by RES and building renovation across climate zones

2.2.2.5 – Summary of energy performance across NbS types

To enable a quantitative synthesis of reported impacts on energy performance, mean relative energy savings were calculated separately for cooling, heating, and total energy demand by averaging the corresponding relative values reported in Table 1 for each NbS type. Specifically, all reported relative energy-saving values associated with a given NbS and energy end use were grouped together, and their arithmetic mean was computed. The number of individual data points contributing to each mean value (n) is reported in the table integrated below the bar chart in Figure 12. For instance, the mean cooling energy saving of 45.5% for green roofs represents the average of 12 reported relative values extracted from the literature. Reporting n alongside the mean values provides essential context for interpretation, as it indicates the extent of available evidence supporting each aggregated estimate and helps readers assess the robustness and practical relevance of the reported averages, particularly where n is small.

Overall, NbS exhibit distinct performance patterns across energy end uses for cooling demand, green roofs and RES combined with building renovation show the highest mean relative savings (around 45%), supported by comparatively larger sample sizes, whereas urban trees and green walls display more moderate cooling-related savings (approximately 25–30%). For heating demand, similarly high mean relative savings (close to 60%) are observed for green roofs and RES-based renovation strategies; however, these estimates are derived from a smaller number of cases, indicating greater uncertainty. In contrast, reported total energy savings are characterized by both lower mean values and very limited evidence, suggesting a strong dependence on context-specific factors such as climate, building characteristics, and system boundaries. Overall, the synthesis highlights a pronounced research focus on cooling energy performance, while heating and total energy impacts remain underrepresented, and therefore calls for cautious interpretation of aggregated values, particularly where sample sizes are small.

	Green roof	Green wall	Urban trees	RES + building renovation
■ Cooling (n)	12	10	8	3
■ Heating (n)	5	0	1	2
■ Total (n)	12	0	1	3
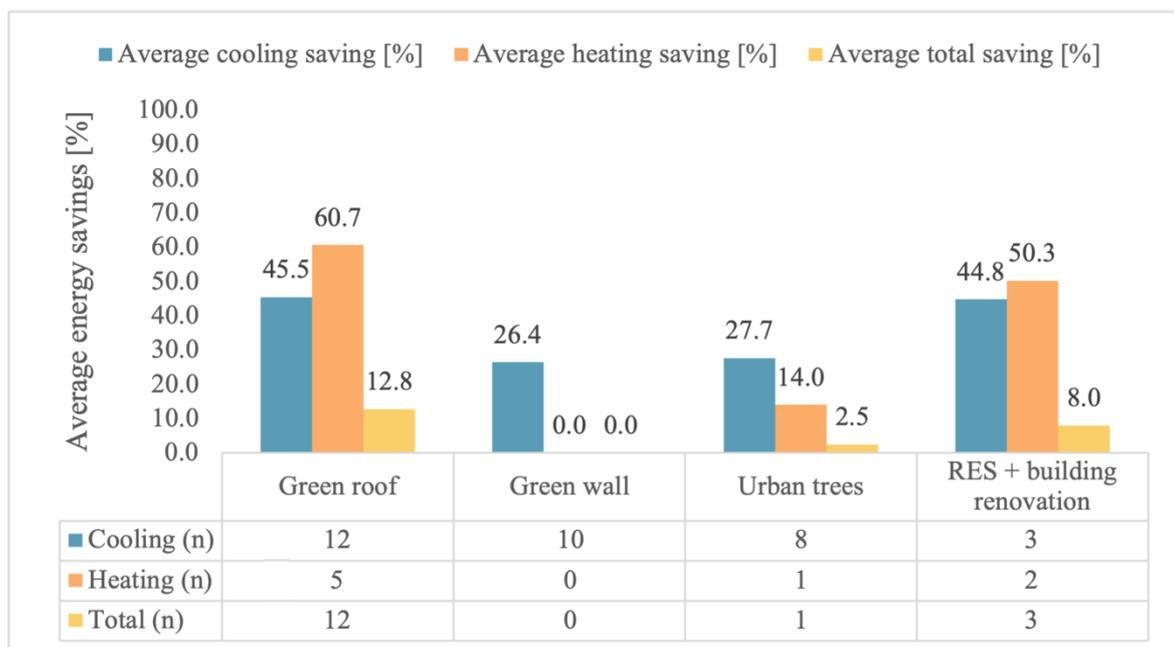
Figure 12: Summary of average relative energy savings across NbS types

2.2.3 – Impacts on CO₂ emissions

The environmental impact of the studied interventions was assessed by quantifying their potential to mitigate CO_2 emissions through two complementary pathways: direct carbon sequestration, which reduces atmospheric CO_2 through photosynthetic uptake and long-term carbon storage in vegetation biomass and, where applicable, in soils (Konopka et al., 2021); and indirect avoided emissions, which arise from microclimate regulation mechanisms—such as shading and evapotranspiration—that lower ambient and indoor temperatures, thereby reducing building cooling energy demand and the associated CO_2 emissions from fossil fuel–based electricity or heat generation (Bevilacqua, 2021).

Table 2 synthesizes reported CO_2 reduction outcomes from the reviewed literature, classified consistently with the energy analysis according to NbS category, Köppen–Geiger climate zone, geographical location, and spatial scale (sample, building, community, or city). For each case, CO_2 impacts are distinguished into direct and indirect components and reported in annualized units (kg CO_2eq/yr), enabling comparison across studies.

To maintain methodological consistency with the energy assessment, only data that could be clearly attributed to a defined intervention scale and time horizon were considered for average calculations, while heterogeneous or aggregated results remain documented in the table for contextual reference. This structured classification allows the subsequent analysis to examine how carbon mitigation performance varies across NbS types, spatial scales, and climatic contexts, and to contrast NbS with conventional energy and building renovation strategies using a unified analytical framework.

Table 2: CO₂ reduction by NbS and conventional solutions

NbS type	Climate zone	Location	Scale	CO₂ saving		References
				Direct [kgCO₂/eq/yr]	Indirect [kgCO₂/eq/yr]	
Green roof	Csa	Valencia, Spain	City	350t/yr	100t/yr	(Zayas-Orihuela et al., 2024)
	Cfa	New York, US	City	$0.38 \sim 1.25$	$1.80 \sim 45.10$	(Engström et al., 2018)
	Cfa	Nanjing, China	Community	0.21	–	(Xi et al., 2022)
	Cfa	Nanjing, China	Building	0.05	4.31	(Yang et al., 2023)
	Cwa	Chengdu, China	Building	6.47	–	(Xiao et al., 2023)
	Cfb	Osijek, Croatia	Building	–	71.00	(Savić et al., 2024)
Green wall	Csa	Gush Dan, Israel	Building	0.16	10.00	(Zuckerman & Lensky, 2023)
	Cfa	Nanjing, China	Building	0.92	–	(Cao et al., 2024)
	Dfb	Kiev,	Building	2.30	–	(Vranayova

NbS type	Climate zone	Location	Scale	CO₂ saving		References
				Direct [kgCO$_2$/eq/yr]	Indirect [kgCO$_2$/eq/yr]	
		Ukraine				et al., 2023)
	Dwa	Goyang, South Korea	Building	–	31.92	(Im & Gil, 2024)
				–	15.03	
Urban tress	Cfa	Nanjing, China	Community	29.92	–	(Xi et al., 2022)
				14.06	–	
	Cfa	Nanjing, China	Street	8.92	–	(Xi et al., 2023)
	Dwa	Beijing, China	City	2.23	–	(Zhang et al., 2014)
	Cfb	Montreal, Canada	Building	0.57	–	(Grossi et al., 2023)
	–	35 major cities, China	City	0.22	–	(Xiao et al., 2023)
RES and building renovation	Cwa	Xianyang, China	Building	–	91.62	(Xin et al., 2024)
				–	114.25	
	Csa	Reggio Calabria, Italy	Building	–	0.53	(Mangano & Laganà, 2024)

2.2.3.1 – CO₂ reduction of green roofs

Green roofs exhibit a complex carbon reduction profile that is strongly dependent on the spatial scale of the intervention. At the building level, indirect avoided emissions associated with reduced energy demand are consistently one to two orders of magnitude higher than direct biological sequestration. For example, in New York, indirect reductions range from 1.8 to 45.1 kg CO_2/m²/yr, whereas direct sequestration is limited to 0.38–1.25 kg CO_2/m²/yr (Engström et al., 2018). Similarly, in Osijek, the integration of green roofs with building reconstruction achieved an indirect reduction of 71.0 kg CO_2/m²/yr (Savić et al., 2024).

In contrast, at the city scale, cumulative biological effects become more prominent. A GIS-based assessment in Valencia showed that greening 50% of the neighborhood roof area could directly sequester approximately 350 t CO_2 per year, exceeding the associated indirect energy-related reduction of about 100 t CO_2/yr (Zayas-Orihuela et al., 2024). This indicates that in mild climates, where operational energy savings are moderate, the biomass-related carbon sink function of NbS may outweigh their thermal regulation benefits when deployed extensively.

Notably, even within intensive green roof systems, direct carbon sequestration capacity varies substantially. In Chengdu, the use of high-biomass tree species in an established state resulted in sequestration rates of 6.47 kg CO_2/m²/yr (Xiao et al., 2023), whereas a newly constructed project in Nanjing reported only 0.05 kg CO_2/m²/yr (Yang et al., 2023). This near two-order-of-magnitude difference highlights the strong dependence of direct carbon

sink performance on vegetation configuration and establishment time, underscoring the presence of pronounced time-lag effects.

2.2.3.2 – CO_2 of reduction green walls

Green walls contribute to decarbonization primarily through indirect means, driven by their significant cooling effects in summer. In Goyang and Gush Dan, indirect emission reductions reached 31.9 kg CO_2/m²/yr (Im & Gil, 2024) and 10.0 kg CO_2/ m²/yr (Zuckerman & Lensky, 2023), respectively. In contrast, the direct sequestration capability of vertical greenery is relatively modest, ranging from 0.156 to 2.3 kg CO_2/ m²/yr. This confirms that for vertical applications, the primary climate value lies in shading and insulation rather than acting as a carbon sink.

2.2.3.3 – CO_2 reduction of urban trees

Urban trees represent the most effective direct carbon sinks among NbS, although their efficiency is highly sensitive to spatial configuration and planting strategies. In Nanjing, optimized combinations of street trees and shelterbelts at the community scale achieved sequestration rates up to 29.9 kg CO_2/m²/yr (Xi et al., 2022), while studies on street canyons reported optimal values of approximately 8.9 kg CO_2/m²/yr under specific spacing conditions (Xi et al., 2022). However, a large-scale review across 35 Chinese cities reported an average sequestration rate of only 0.22 kg CO_2/m²/yr (Xiao et al., 2023), reflecting a dilution effect in generalized urban green spaces compared to targeted, high-density planting configurations.

2.2.3.4 – CO_2 reduction of RES and building renovation

Conventional solutions, specifically RES and technical upgrades, demonstrate the highest potential for indirect avoided emissions, confirming their role as the backbone of energy efficiency. In a case study of a 1,000 square meter exhibition hall in Xianyang, the introduction of an Earth-Air-Cooling system coupled with Photovoltaics significantly reduced daily carbon emissions, achieving an annual avoided emission rate of 91.6 to 114.2 kg CO_2/m²/yr (Xiao et al., 2023).

Overall, indirect emission reductions derived from operational energy savings dominate the decarbonization potential of single-building interventions, with outcomes strongly influenced by the carbon intensity of the local energy supply. While urban trees provide the most effective direct sequestration, green roofs and walls remain indispensable for reducing operational emissions in dense urban environments where ground-level planting opportunities are limited.

2.2.3.5 – Summary of CO_2 reduction across NbS types

Table 3 summarizes the reported average reductions in CO_2 emissions associated with different NbS types, distinguishing between direct and indirect effects. Direct CO_2 emission reductions are reported for green roofs, green walls, and urban trees, with urban trees exhibiting the highest average direct reduction (9.32 kgCO_2eq yr^{-1}), followed by green roofs (2.23 kgCO_2eq yr^{-1}) and green walls (1.13 kgCO_2eq yr^{-1}). No direct CO_2 emission reduction values are reported for RES combined with building renovation.

In contrast, indirect CO_2 emission reductions are substantially higher than direct reductions

across all NbS types for which data are available. Green roofs show an average indirect reduction of 37.65 $kgCO_2eq$ yr^{-1}, while green walls exhibit a lower but still notable value of 18.98 $kgCO_2eq$ yr^{-1}. The highest indirect CO_2 emission reduction is reported for RES combined with building renovation, reaching 68.8 $kgCO_2eq$ yr^{-1}. No indirect CO_2 emission reduction data are available for urban trees.

Overall, the reported results indicate that indirect CO_2 emission reductions generally exceed direct reductions, although the availability of data varies considerably across NbS types and emission pathways.

Table 3: Summary of average CO_2 reduction across NbS types

Average CO_2 emissions reduction	Green roofs	Green walls	Urban trees	RES & building renovation
Direct [kgCO₂eq/yr]	2.23	1.13	9.32	–
Indirect [kgCO₂eq/yr]	37.65	18.98	–	68.8

Chapter 3 – Case study

3.1 – Methodology

3.1.1 – Study area

The Mirafiori district, located in the southern part of Turin, Italy, was selected as the case study area. It represents a transitional urban zone, shifting from the compact historical center toward the more dispersed urban periphery. As shown in Figure 13, the district is divided into Mirafiori Nord (approximately 3.79 million m²) and Mirafiori Sud (approximately 11.49 million m²).

The urban form of Mirafiori is closely tied to the development of the Fiat automobile industry, which shaped a characteristic "factory-town" layout. Mirafiori Sud historically accommodated major industrial facilities with large-span factory structures, whereas Mirafiori Nord developed predominantly as a residential quarter, hosting high-density housing and extensive social housing built for industrial workers. Unlike the historic core of Turin, where buildings are subject to strict preservation regulations, the built environment in Mirafiori mainly consists of post-war functional architecture with limited heritage constraints. This condition makes the district particularly suitable for the implementation of NbS, including green roofs and green walls.
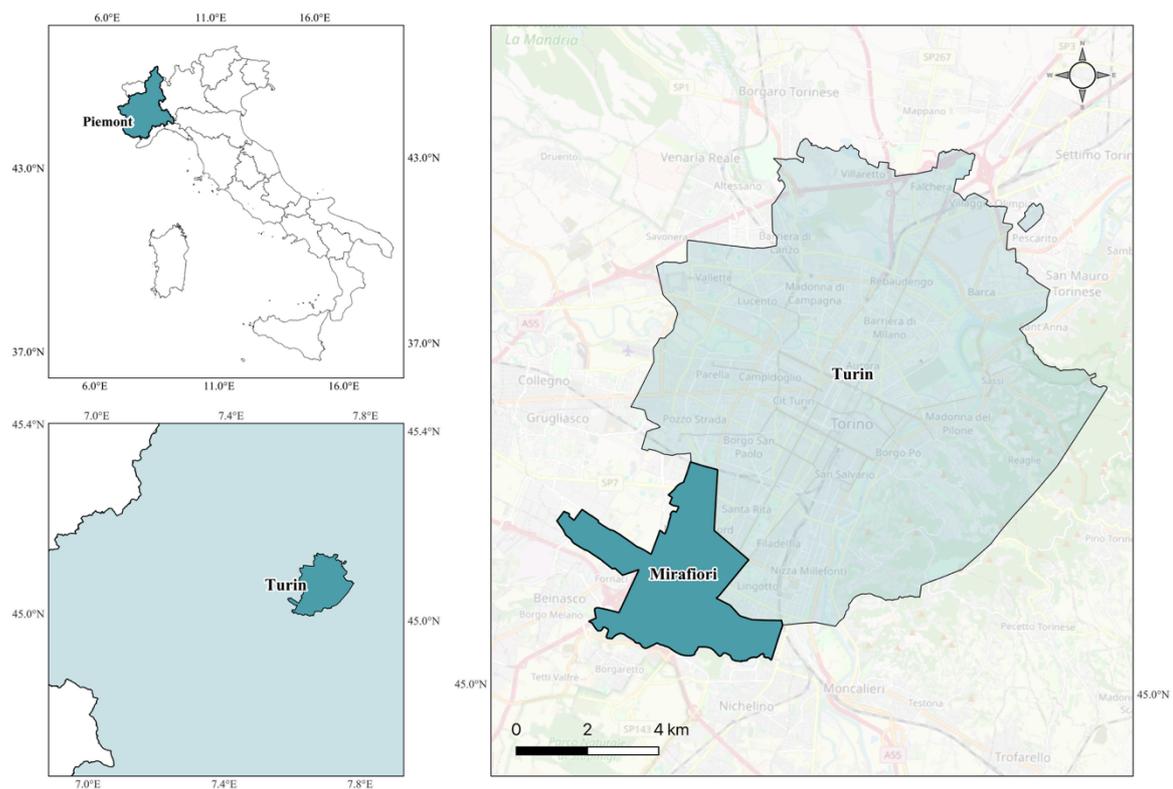

Figure 13: Location of case study area (Mirafiori)

The selection of Mirafiori was further supported by a combination of climatic considerations, environmental challenges, and strategic opportunities. Turin has a humid subtropical climate (Cfa), marked by cold winters and hot, humid summers, which creates dual seasonal energy

demands for heating and cooling. At the same time, Mirafiori faces persistent environmental pressures, including pronounced UHI effects (Ellena et al., 2023), traffic congestion (Mancini, 2014), and air-quality concerns (Campiotti et al., 2025). Its industrial legacy has also contributed to socio-economic disparities, reinforcing the need for ecological interventions capable of improving environmental conditions and enhancing local resilience (De Filippi & Vassallo, 2016).

Despite these challenges, the district also presents clear opportunities for the deployment of NbS. Its regular, modular residential blocks are structurally well suited for the installation of green roofs and green walls, while its extensive open spaces and underused green areas provide substantial potential for new urban greening initiatives.

Mirafiori additionally offers strong policy relevance and excellent data availability. Turin is recognized as an Italian "frontrunner city" within the EU-funded ProGIreg project, which promotes the regeneration of post-industrial urban areas through the implementation of NbS. Within this framework, Mirafiori Sud functions as a key pilot site, providing a highly relevant policy context for the present study. Furthermore, the proximity of the Politecnico di Torino ensures strong academic support. Most importantly, comprehensive, high-resolution geographic and building-energy datasets were made available through the SDG11 Lab, providing a robust analytical foundation and enhancing the methodological reliability of the research.

This study adopts a three-phase methodological framework to assess the spatial potential and renovation benefits of NbS at the district scale (Figure 14).

Part 1 (Suitability analysis) focuses on identifying buildings and areas suitable for different NbS types. Suitability criteria and threshold values for green roofs, green walls, and urban trees were derived from a targeted literature review and implemented through a GIS-based filtering process.

Part 2 (Retrofit analysis) evaluates the energy and carbon-related impacts of the identified NbS interventions. Buildings deemed suitable for green roofs and green walls were first screened to exclude industrial and minor buildings, resulting in a set of selected buildings for retrofit assessment. These buildings were then used to evaluate changes in building energy demand and the associated indirect CO_2 emission reductions. Baseline thermal properties were defined by assigning U-values based on an SVR-based building typology and construction period, and energy demand was calculated for pre- and post-intervention scenarios. In contrast, urban trees were not included in the building energy assessment and were evaluated solely in terms of their direct CO_2 sequestration potential, reflecting their primary mitigation mechanism.

The combined framework enables an integrated assessment of NbS implementation potential, linking spatial suitability with energy demand savings and CO_2 reduction outcomes at the district scale.
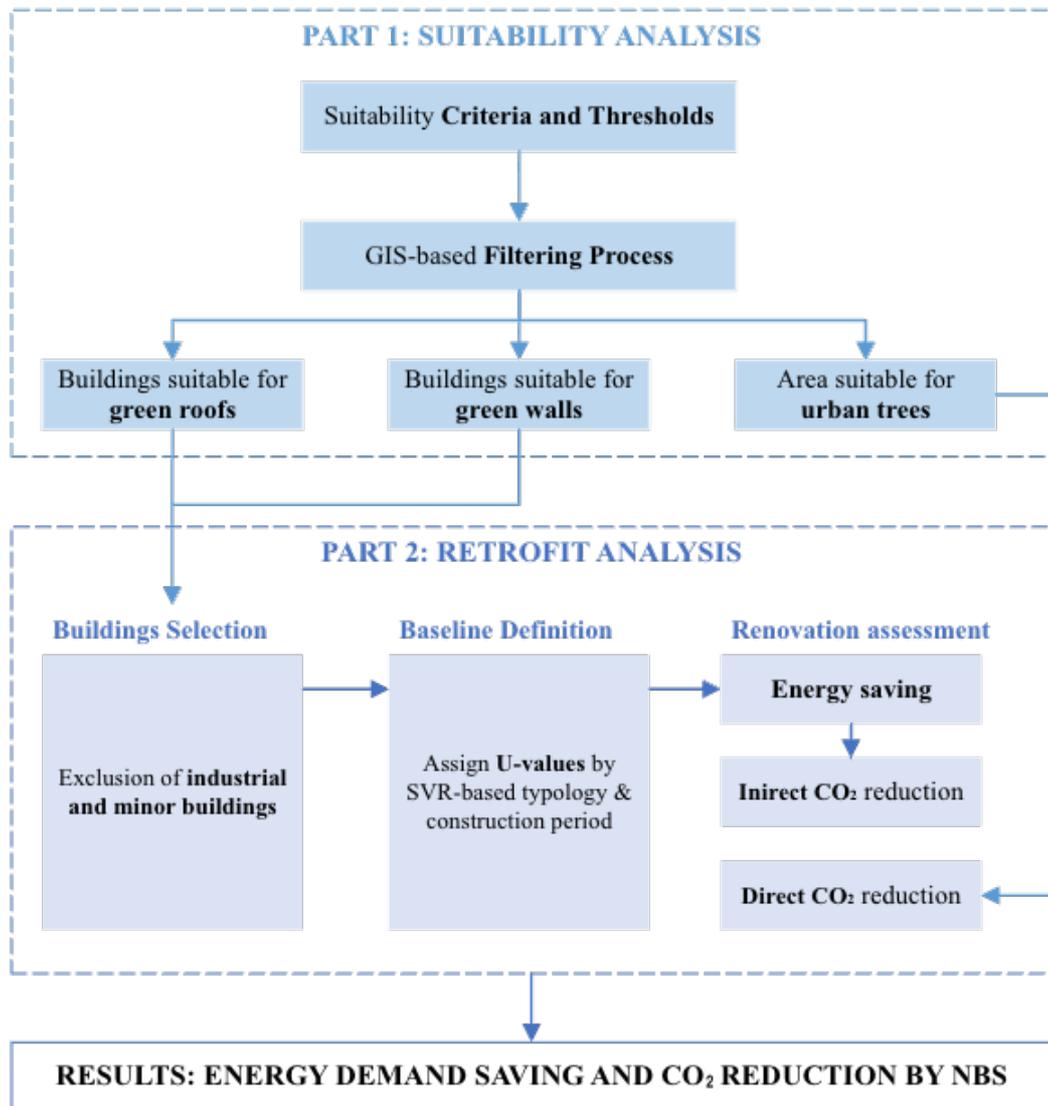
Figure 14: Methodological workflow

3.2.1 – Suitability analysis

3.2.1.1 – Suitability criteria and thresholds

The initial literature review (Chapter 2) provided only fragmented information on spatial suitability criteria for NbS, insufficient to define quantitative thresholds for this study. Therefore, a targeted literature search was conducted to specifically extract criteria for green roofs, green walls, and urban trees. Boolean search strings were constructed for each NbS type (for example, for green roofs: ("suitability" OR "suitable location*" OR "location") AND "green roof*"), which resulted in 11 highly relevant studies. These studies provided a solid basis for establishing localized feasibility thresholds for each NbS type.

(1) Green roofs

For green roofs, five key thresholds were defined (Table 4):

- Construction year: only buildings constructed after 1970 were considered to ensure sufficient structural load-bearing capacity.

- Building height: only buildings between 4 and 25 m were considered (Velázquez et al.,

2019).

- Heritage status: all protected historical buildings were excluded to comply with conservation regulations (Wang, Kong, et al., 2023).

- Minimum roof area: a threshold of 100 m² was adopted to exclude areas occupied by stairwells, elevator shafts, or other non-usable spaces, ensuring economic viability (Zayas-Orihuela et al., 2024).

- Roof slope: slopes no more than 30° were selected, following evidence from previous case studies, to maximize potential coverage while remaining technically feasible (Zayas-Orihuela et al., 2024).

Table 4: Summary of green roof selection criteria and final thresholds

NbS type	Location	Construction year	Building height	Heritage status	Minimum roof area	Roof slope	Reference
Green roof	Thessaloniki, Greece	EGR: before 1980 IGR: after 1980	–	–	–	Flat roof	(Karteris et al., 2016)
Green roof	Madrid, Spain	–	4 -25 m	–	–	–	(Velázquez et al., 2019)
Green roof	Nanjing, China	< 50 years	< 12 floors or < 40 m	Non historical buildings	–	< 20°	(Wang, Le, et al., 2023)
Green roof	Seoul, Korea	⩽ 30 years	–	–	–	Flat roof	(Kim et al., 2021)
Green roof	Valencia, Spain	–	–	–	100 m²	< 10°	(Zayas-Orihuela et al., 2024)
Selected thresholds	Mirafiori, Italy	After 1970	4 - 25 m	Non-historical buildings	100 m²	< 20°	–

(2) Green walls

For green walls were subject to relatively fewer constraints (Table 5):

- Window-to-wall ratio: façades with a WWR ≥ 50% were excluded to ensure sufficient wall surface for vegetation growth, following the threshold suggested by Douglas et al. (2021).

- Green coverage ratio: a minimum green coverage of 25% was adopted, within the recommended range of 24–60% reported in previous studies, with priority given to façades with favorable solar exposure to support plant development (Ling, 2022).

- Heritage status: historical buildings were excluded from potential intervention, in line with common heritage protection practices.

Table 5: Summary of green wall selection criteria and final thresholds

NbS type	Location	WWR (window-to-wall ratio)	Green coverage ratio	Reference
Green wall	Australia	≤ 50%	–	(Douglas et al., 2021)
Green wall	Taipei, China	–	24 - 60%	(Ling, 2022)
Selected thresholds	Mirafiori, Italy	≤ 50%	25%	–

(3) Urban trees

For urban trees, six criteria were defined to identify suitable planting locations (Table 6):

- <u>Land cover</u>: only areas classified as green space or pasture were considered, excluding buildings, roads, and water bodies (Wu et al., 2008).

- <u>Impermeable surface</u>: ≥ 81% to maintain soil permeability and support tree growth (Reitberger et al., 2024).

- <u>Minimum distance to buildings</u>: 0.91 m to avoid structural conflicts (Reitberger et al., 2024).

- <u>Minimum distance to roads</u>: 1 m to ensure safety and accessibility (Kim et al., 2021).

- <u>Minimum distance to existing trees</u>: 2.97 m to reduce competition and allow healthy growth (Reitberger et al., 2024).

- <u>New tree canopy radius</u>: 3.44 m, used to estimate the number of trees that can be planted and their carbon sequestration potential (Reitberger et al., 2024).

Table 6: Summary of urban trees selection criteria and final thresholds

NbS type	Location	Permeable surface	Min. distance to buildings	Min. distance to roads	Min. distance to existing trees	New tree canopy radius	References
Urban trees	Munich, Germany	⩾81%	0.91 m	–	2.97 m	3.44 m	(Reitberger et al., 2024)
Urban trees	Seoul, Korea	–	–	1 m	–	–	(Kim et al., 2021)
Urban trees	Bartın, Turkey	–	0.6 m	0.6 m	0.6 m	–	(Varol et al., 2019)
Urban trees	Los Angeles, USA	–	0.6 m	0.6 m	–	–	(Wu et al., 2008)
Selected thresholds	Mirafiori, Italy	⩾81%	0.91 m	1 m	2.97 m	3.44 m	–

The suitability criteria and threshold values defined for the three NbS types were synthesized into a single visual framework to facilitate comparison. Figure 15 presents a schematic overview of the final thresholds adopted for green walls, green roofs, and urban trees, highlighting the key spatial and morphological constraints applied in this study.
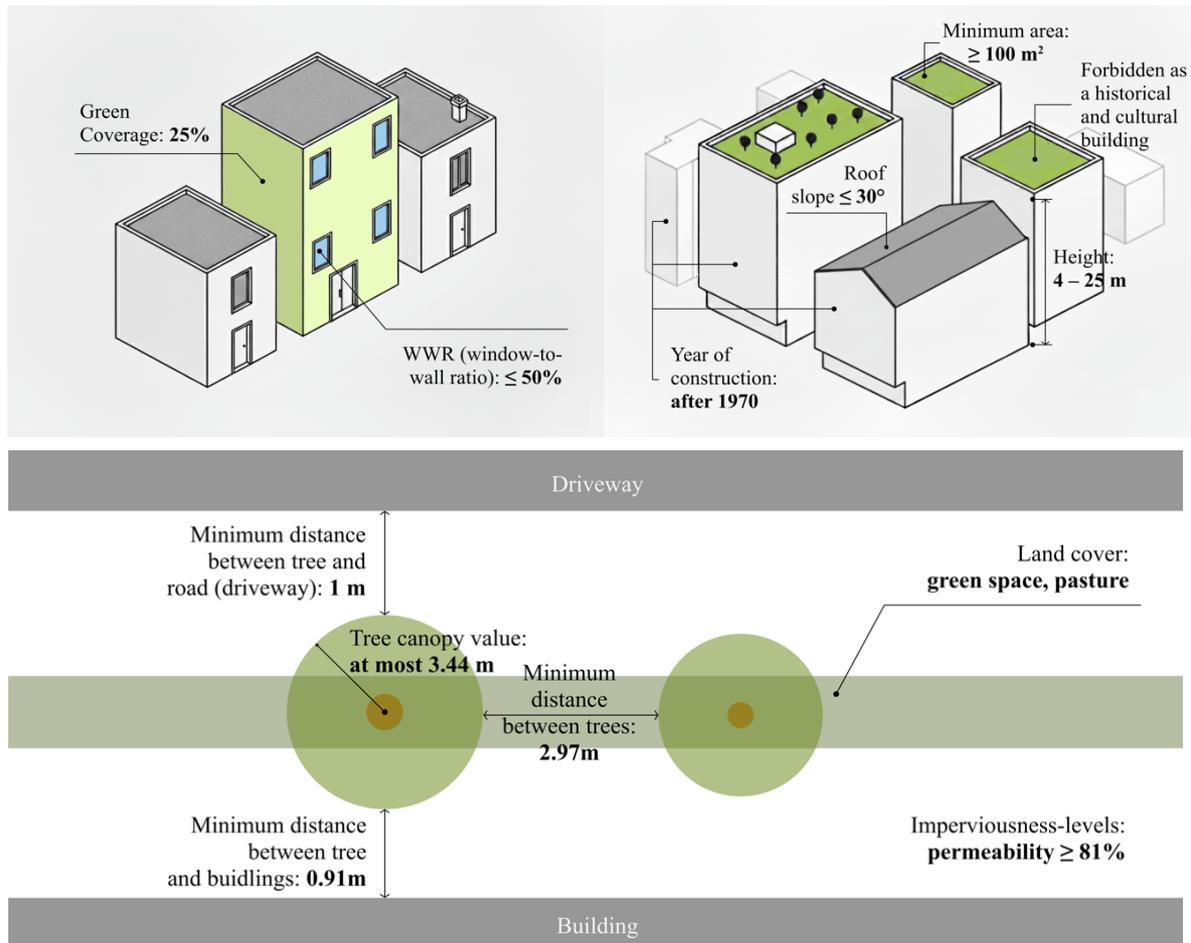
Figure 15: Final threshold values of urban trees, green walls and green roofs

3.2.1.2 – GIS-based filtering process

The suitability criteria and threshold values defined above were operationalized through a GIS-based filtering process using the spatial datasets summarized in Table 7. Each dataset provided the attributes required to translate the criteria into spatial constraints, which were then applied separately for green roofs, green walls, and urban trees. The following sections describe the GIS-based filtering workflows implemented for each NbS type within the study area.

Table 7: Data sources and datasets used in suitability analysis

Dataset	Source	Format	Key attributes	Application
Municipal Technical Map (CTC)	City of Turin	Vector (Shapefile)	– Building footprint – Building height – Construction year – Road network – Land cover – Imperviousness – Existing trees	Green roofs Green walls Urban trees
Roof dataset	SDG11 Lab	Vector (Shapefile)	– Roof slope	Green roofs
Cultural heritage	Geoportale Regione	Vector (Shapefile)	– Heritage status	Green roofs

Dataset	Source	Format	Key attributes	Application
buildings dataset	Piemonte			Green walls
TABULA building database	TABULA WebTool (EU)	Tabular data	– Window-to-wall ratio	Green walls
Administrative boundary	Geoportale Regione Piemonte	Vector (Shapefile)	– Boundary of Mirafiori district	Study area definition

(1) Green roofs

Based on the suitability criteria and threshold values defined in the previous section, a GIS-based filtering process was applied to identify buildings suitable for green roof implementation. The analysis was conducted on vector building layers, following a stepwise screening procedure illustrated in Figure 16. Each decision node in the flowchart represents a specific suitability condition; buildings that meet the criterion proceed to the next step, while those that fail are classified as unsuitable for green roofs.

The most significant reduction in candidate buildings occurs at the building height criterion (4–25 m), where 4887 buildings are excluded. Most of these correspond to minor buildings with heights of approximately 3 m. The second major exclusion is related to the construction year, reflecting the relatively old building stock in Turin, where many buildings were constructed before 1970. Additional constraints concerning heritage status, minimum rooftop area, and roof slope further refine the selection.
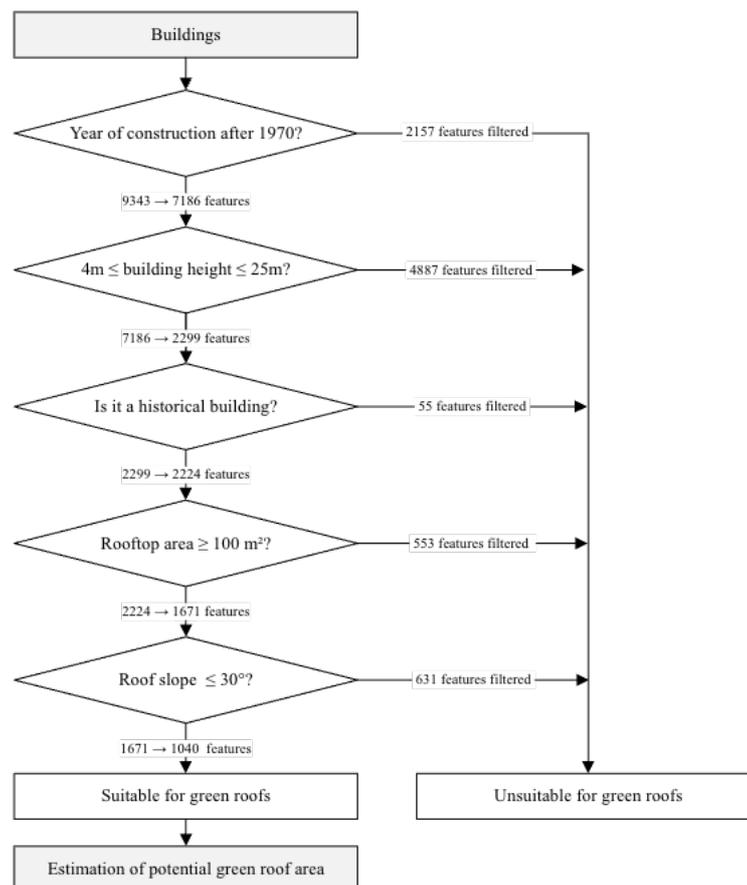
Figure 16: Flowchart of green roof selection

(2) Green walls

Following the same GIS-based workflow adopted for green roofs, a stepwise filtering process was applied to assess the suitability of buildings for green wall implementation, as illustrated in Figure 17. The analysis was performed on vector building layers, with each decision node representing a specific suitability condition. Buildings that fail a given condition are classified as unsuitable for green walls, while those that satisfy the criterion proceed to the next step.
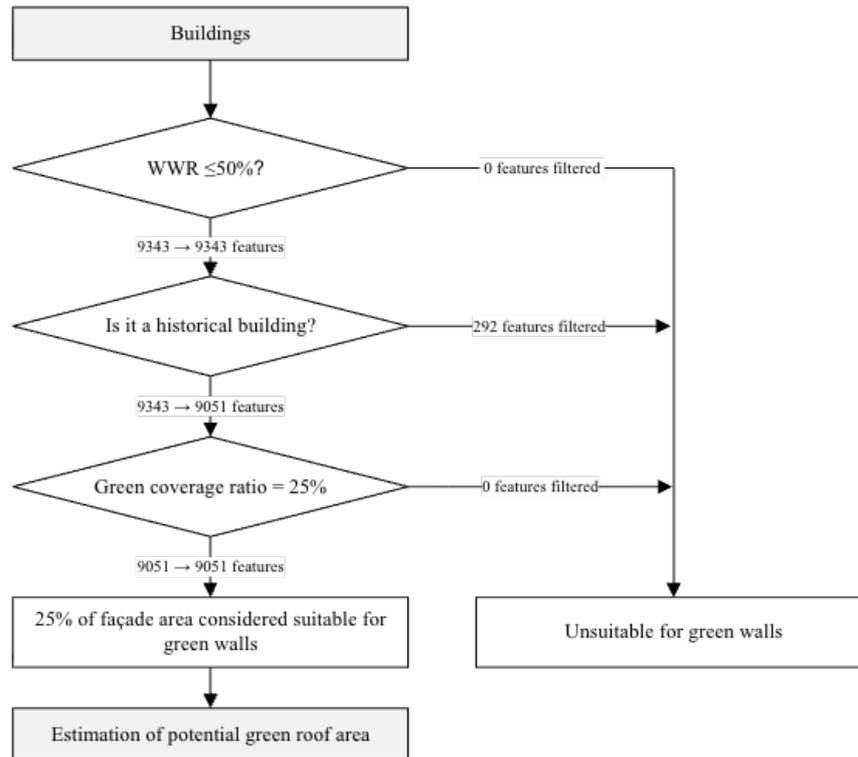
Figure 17: Flowchart of green wall selection

The first screening criterion concerns the WWR, with a threshold of 50%. In principle, this step aims to ensure sufficient opaque façade area for vegetation. For the green wall analysis, the calculation of WWR was initially intended to follow the deep-learning-based automated workflow proposed by Suppa (2025), which relies on Google Street View imagery combined with Rhino-assisted annotation to estimate WWR at façade, building, and district scales. However, the strong dependence of this workflow on licensed Rhino software and Google Street View API credentials posed substantial technical and financial constraints. Given these limitations and the time pressure of the project, an alternative approach based on the TABULA algorithm was adopted.

WWR values for each Italian building typology were derived from the TABULA WebTool, a standardized database of European building typologies providing representative envelope characteristics (Loga et al., 2016), by extracting total façade and window areas. The resulting distribution of WWR values for buildings in the Mirafiori district is reported in Table 8, showing that all typologies fall below the 50% threshold. This outcome is consistent with energy-efficient building design practices in Italy, where early-stage design has traditionally favored relatively low window-to-wall ratios (Méndez Echenagucia et al., 2015).

Consequently, no buildings were excluded at this stage, and all 9,343 features were retained.

Table 8: WWR values for building typologies

Construction year	Single family house	Terraced house	Multi-family house	Apartment block
1918 (al ..)	7.30%	18.29%	11.02%	15.99%
1919-1945	6.83%	19.00%	9.55%	15.55%
1946-1960	8.75%	21.82%	19.21%	13.20%
1961-1970	8.13%	18.08%	8.12%	9.80%
1971-1980	9.18%	13.82%	9.64%	10.93%
1981-1990	10.21%	11.84%	11.34%	12.16%
1991-2000	9.64%	10.54%	14.61%	19.67%
2001-2005	9.64%	10.54%	14.61%	19.67%
2006 onwards	9.72%	10.71%	11.75%	12.00%

The second screening step excludes historical and cultural heritage buildings to avoid potential conflicts with conservation regulations. At this stage, 292 buildings were removed from further consideration, resulting in 9,051 remaining features.

The final step does not introduce additional feature-level exclusions but defines the proportion of façade area assumed to be available for green wall installation. Based on the selected threshold, only 25% of the external wall area of each remaining building is considered suitable for greening. The potential green wall area was calculated using the following equation:

$$S_{GW} = ((P \times H) - S_{COMMON}) \times 25\%$$

Where S_{GW} represents the total final area of green wall coverage suitable for green walls，P is the building perimeter, H is the building height, and S_{COMMON} denotes the wall area shared with adjacent buildings. The coefficient of *25%* corresponds to the green coverage rate adopted in this study.

(3) Urban trees

Unlike green roofs and green walls, whose suitability assessment was primarily building-based, the identification of suitable locations for urban tree planting followed a space-based GIS workflow, focusing on the availability of potential planting areas and their spatial separation from surrounding urban elements (Figure 18).

The analysis started from the land cover layer, where only areas classified as green space or pasture were retained as initial candidate planting zones. These areas were further filtered by soil permeability and only surfaces with a permeability value equal to or greater than 81% were considered suitable for tree planting.

To ensure sufficient space and avoid conflicts with existing urban infrastructure, a series of distance-based constraints were then applied using buffer operations in QGIS. Candidate planting areas were required to maintain a minimum distance of 0.91 m from buildings, 1 m from roads, and 2.97 m from existing trees. The exclusion buffers generated from buildings,

roads, and existing trees were merged and subtracted from the suitable land cover areas using spatial difference operations, resulting in the final potential tree planting areas.
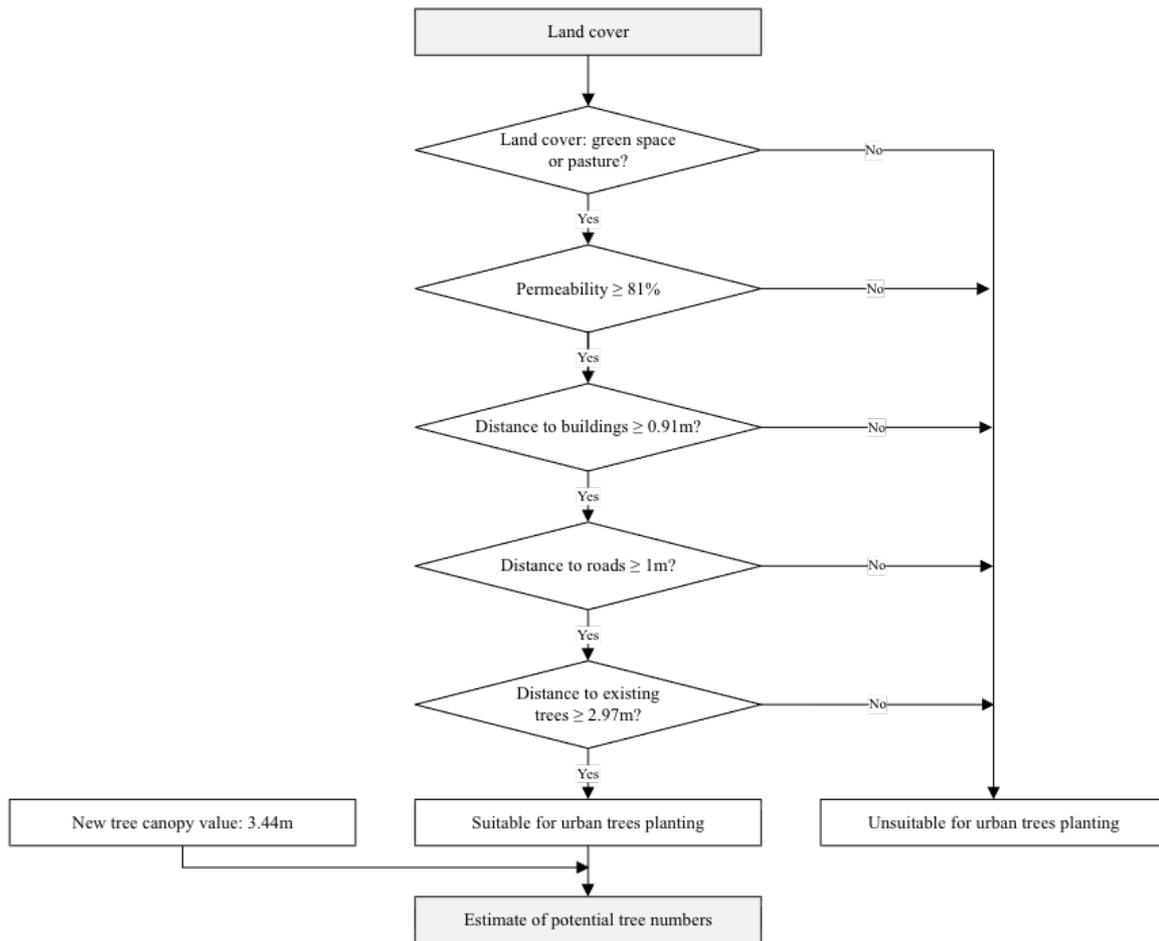
Figure 18: Flowchart of urban trees selection

3.2.2 – Retrofit analysis

Figure 19 summarizes the workflow adopted for the energy and CO_2 assessment. The analysis is structured around a clear distinction between baseline (pre-intervention) and renovation (post-intervention) conditions for building-related interventions. In the baseline assessment, geometric information extracted from the technical building map of the Mirafiori district is used to calculate the Surface-to-Volume Ratio (SVR) and to classify buildings by typology and construction period. These attributes enable the assignment of representative roof and wall thermal transmittance values, which define the reference thermal performance of the building stock.

Climatic inputs are subsequently incorporated to quantify building energy demand. Heating and Cooling Degree Days are used to estimate transmission heat losses, while seasonal solar radiation data support the calculation of solar gains. These components are combined to determine seasonal heating and cooling needs, which are then converted into operational energy demand using appropriate system efficiencies.

The renovation assessment follows the same calculation framework but updates the envelope thermal properties to reflect the implementation of green roofs and green walls. Energy

savings are quantified by comparing baseline and renovation operational energy demand, and the associated indirect CO_2 emission reductions are derived by applying emission factors to the estimated energy savings.

Urban trees are not included in the baseline–renovation assessment workflow, as they do not directly modify building envelope thermal properties. Their contribution is therefore assessed separately in a subsequent section, where CO_2 reduction is quantified exclusively through direct carbon sequestration.
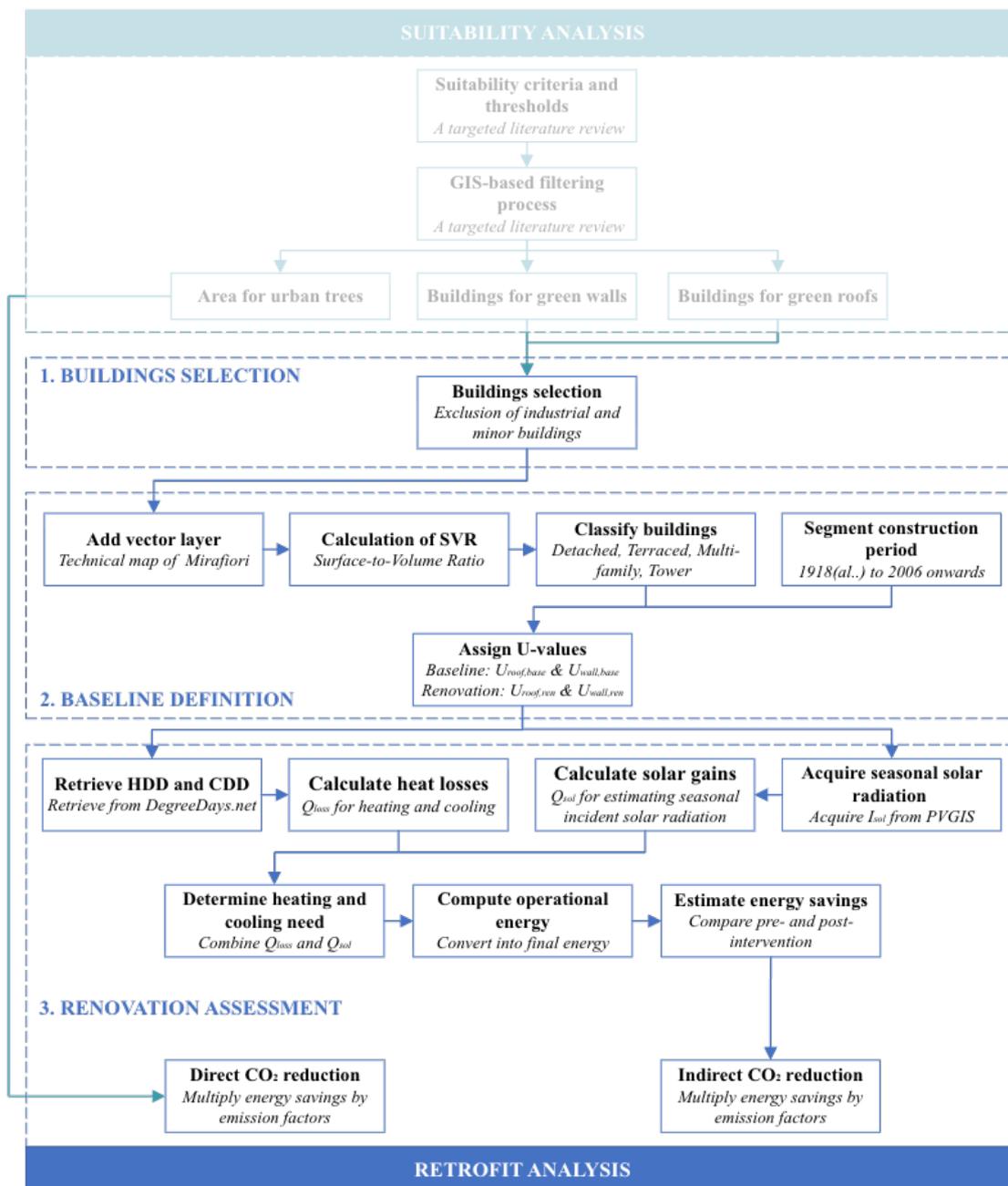
Figure 19: Workflow for retrofit analysis

3.2.2.1 – Buildings selection

The renovation assessment of green roofs and green walls is conducted only for buildings identified as suitable through the spatial suitability analysis and belonging to building

typologies for which operational energy evaluation is relevant. Within this scope, industrial buildings and minor buildings—such as garages and service buildings, as defined by Legislative Decree—are excluded from the energy assessment, as they are generally unheated and do not significantly contribute to space heating or cooling demand (Anselmo et al., 2025).

The exclusion of industrial and minor buildings has a markedly different impact on the available areas for green roof and green wall renovation. As illustrated in Figure 20, industrial buildings contribute a substantial share of the total rooftop area within the study area, while their contribution to the overall external wall surface is comparatively limited. Consequently, the removal of industrial buildings leads to a pronounced reduction in the roof area eligible for retrofit analysis, resulting in a final green roof renovation area predominantly associated with residential buildings. In contrast, the eligible façade area for green wall renovation remains relatively high after the exclusion process, reflecting the more evenly distributed contribution of residential buildings to vertical surfaces. This difference is quantitatively summarized in Table 9.

Table 9: Areas suitable for green roof and green wall retrofit analysis

	Green roofs		Green walls	
	Roof area [m²]	Share [%]	External wall area [m²]	Share [%]
Total area within the study area	3,251,322	100%	4,177,188	100%
Area suitable for NbS intervention	1,594,407	49.04%	1,019,232	24.40%
Area suitable for retrofit analysis	260,934	8.03%	773,238	18.51%

Figure 20: Buildings selected for green roof (left) and green wall (right) retrofit analysis

3.2.2.2 – Baseline definition

The baseline assessment establishes the initial thermal characteristics of the building stock prior to the implementation of NbS. This step provides the reference U-values against which renovation effects—i.e., green roofs and green walls—are evaluated.

(1) Gathering volumetric data

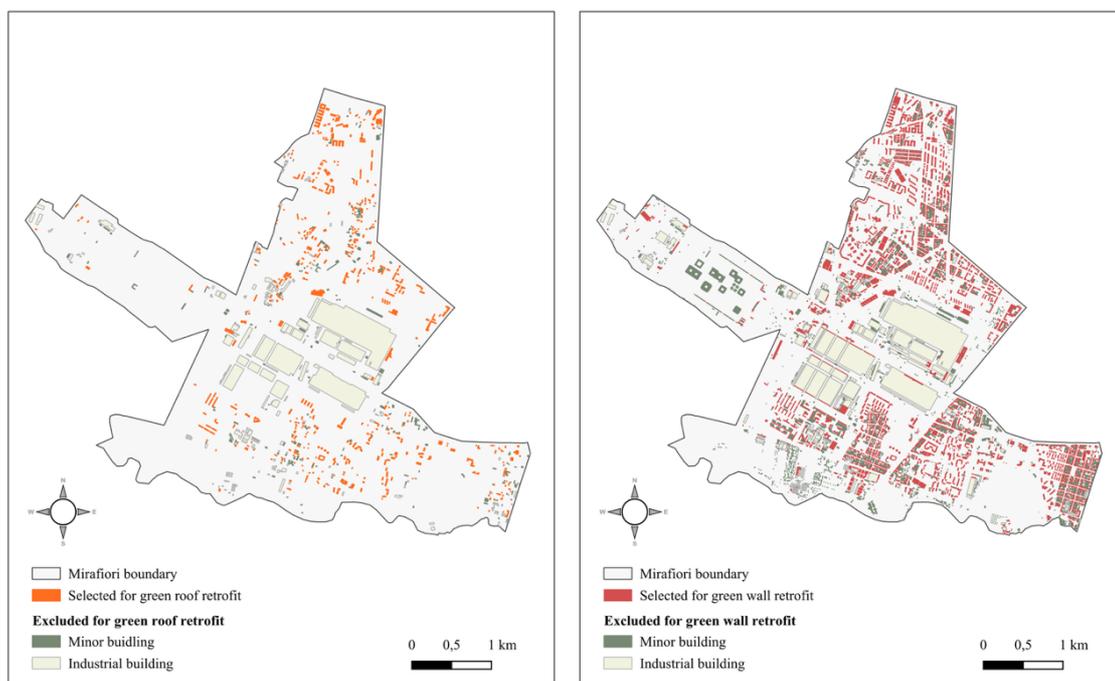Building information for the Mirafiori district was obtained from the Technical Map of the City of Turin (Carta Tecnica Città di Torino). The available attributes included: unique ID, building height, use category, and period of construction.

(2) SVR calculation

The ratio of envelope surface area to conditioned volume is a key indicator of building heat loss characteristics, as it reflects the relationship between the externally exposed thermal envelope and the enclosed heated volume (Reddy et al., 2016). Accordingly, the SVR is defined as:

$$SVR = \frac{S}{V}$$

Where S denotes the heat loss surface of the building envelope and V represents the gross heated volume. SVR is widely used as an indicator of potential heat exchange, with higher values generally corresponding to greater heat losses due to a larger exposed surface area relative to the building volume. In this study, SVR was derived using a GIS-based geometric analysis of building footprints and heights., considering only those portions of the thermal envelope exposed to outdoor conditions. Both the surface area and volume were adjusted to exclude parts contiguous with adjacent buildings, as shared walls do not exchange heat with the exterior.

(3) SVR-based building typology classification

Following the classification proposed by Torabi (2016), buildings were categorized into four SVR-based typologies according to their surface-to-volume (S/V) ratios:

- Detached house: S/V > 0.71
- Terrace house: 0.56 < S/V $\leqslant$ 0.71
- Multi-family house: 0.45 $\leqslant$ S/V $\leqslant$ 0.56
- Tower: S/V $\leqslant$ 0.45

This classification was implemented in QGIS, where each building footprint was attributed with an SVR type and visualized using distinct colors. Figure 21 presents an illustrative SVR typology map for a small area in the vicinity of the intersection between Via Guido Reni and Corso C. G. Allamano in Mirafiori. This location is used solely as a demonstrative example to show the real-world appearance of all four SVR-based building typologies in Mirafiori, highlighting how detached houses, terrace houses, multi-family houses, and tower buildings exhibit distinct geometric configurations and aggregation patterns that are reflected in their different surface-to-volume ratios.
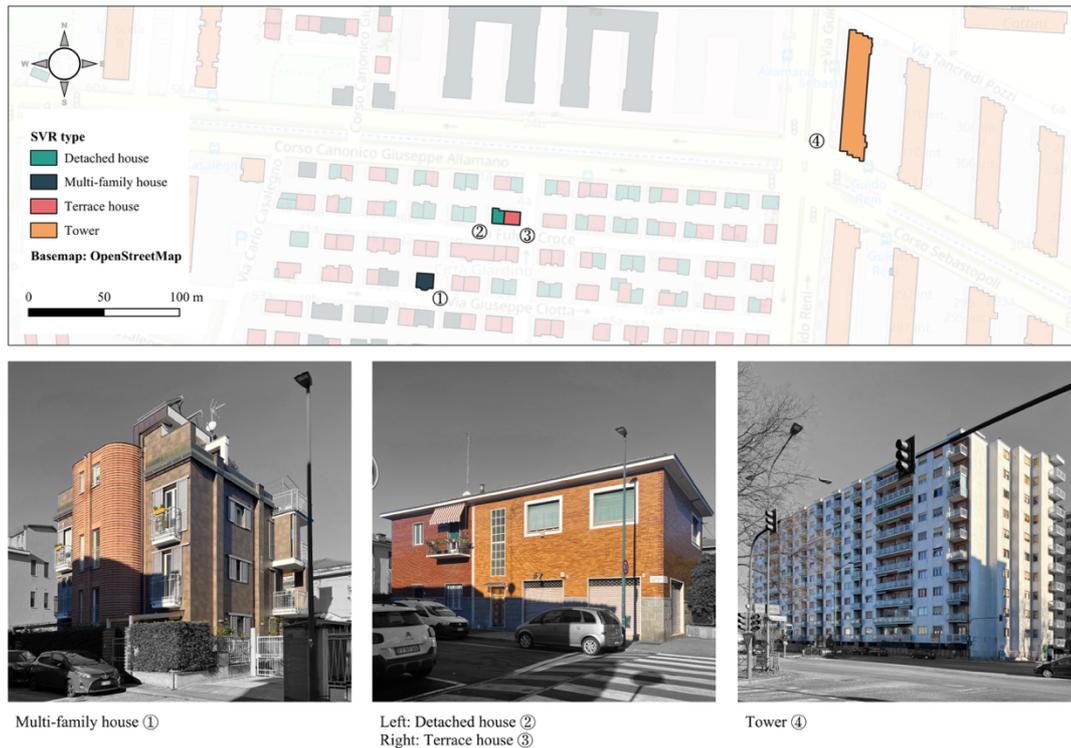
Figure 21: The four SVR-based building typologies in Mirafiori

(4) Assignment of roof and wall U-values

Representative roof and wall U-values were assigned to each building based on the combination of its SVR-based typology and construction year class, using the TABULA building typology database as reference (Loga et al., 2016). For most construction year classes, a direct correspondence with the TABULA temporal classification was available and the associated U-values were assigned accordingly.

An exception was the construction period 1971–1980, which does not exactly match a TABULA time interval. In this case, roof and wall U-values were estimated as the arithmetic mean of the TABULA values for the adjacent periods 1961–1975 and 1976–1990. For buildings with unknown construction year, the modal construction period of the Mirafiori district (1946–1960) was assigned.

The resulting U_{roof} and U_{wall} values were compiled into a lookup table (Table 10) and subsequently assigned to each building selected for the green roof and green wall retrofit analysis in QGIS.

Table 10: Roof and wall U-values [W/m²K] by construction period and building typology

Period of construction	Detached house		Terrace house		Multi-family house		Tower	
	U_{roof}	U_{wall}	U_{roof}	U_{wall}	U_{roof}	U_{wall}	U_{roof}	U_{wall}
1918 (al ..)	1.80	1.61	1.80	1.61	1.41	1.19	1.50	1.34
1919-1945	1.80	1.55	1.61	1.81	1.51	1.34	1.44	1.48
1946-1960	1.80	1.48	1.42	2.01	1.48	1.48	1.42	1,14
1961-1970	2.20	1.48	2.20	1.15	1.10	1.48	1.10	1.15

Period of construction	Detached house		Terrace house		Multi-family house		Tower	
	U_{roof}	U_{wall}	U_{roof}	U_{wall}	U_{roof}	U_{wall}	U_{roof}	U_{wall}
1971-1980	1.67	1.01	1.40	1.01	0.93	0.98	0.93	0.93
1981-1990	1.14	0.76	0.95	0.76	0.75	0.80	0.75	0.76
1991-2000	0.57	0.59	0.57	0.59	0.57	0.59	0.57	0.60
2001-2005	0.57	0.59	0.57	0.59	0.57	0.59	0.57	0.60
2006 onwards	0.28	0.34	0.28	0.34	0.28	0.34	0.28	0.34

As shown in Figure 22 and Figure 23, both roof and wall U-values decrease consistently with newer construction periods across all building typologies. This reflects the progressive tightening of thermal performance requirements in Italian building regulations, particularly after the 1970s and more markedly after 1991. Roofs exhibit a stronger reduction in thermal transmittance compared to walls, explaining their higher potential impact on energy savings when renovation with green roofs. Differences among typologies are more noticeable in early construction periods but become less pronounced in more recent decades, indicating a homogenization of construction standards over time.
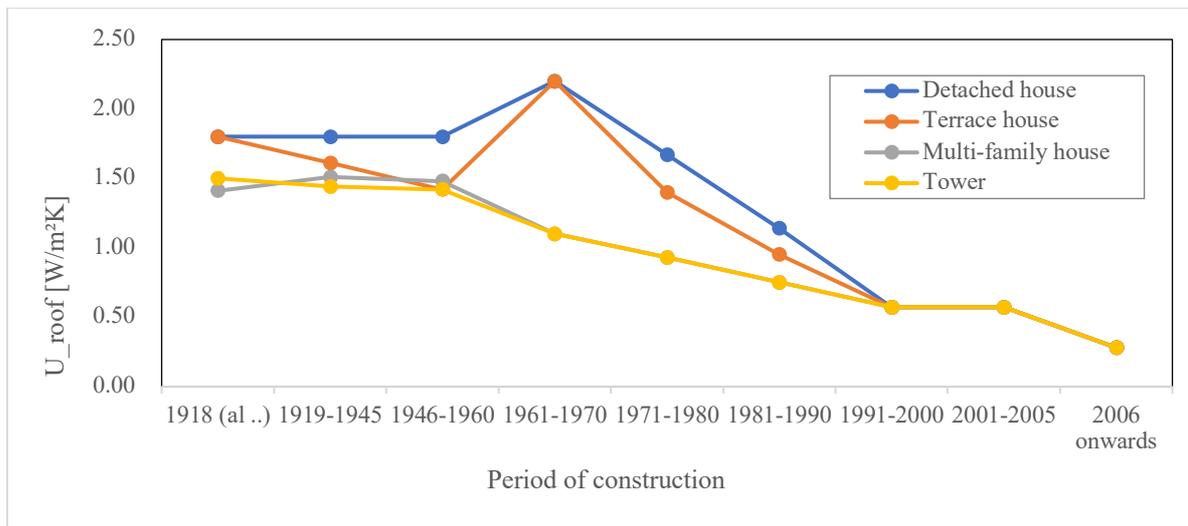

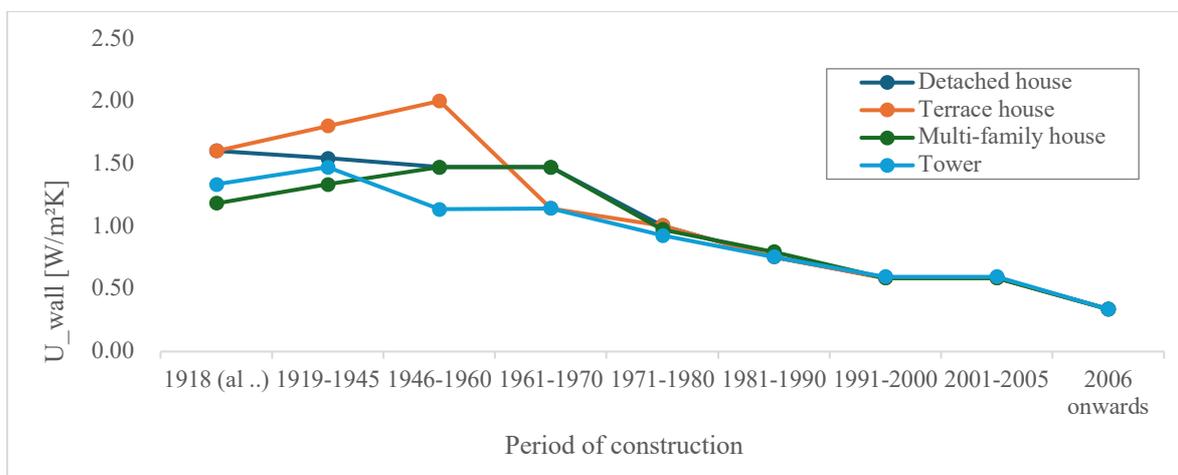*Figure 22: Roof U-values by construction period and building typology*

Figure 23: Wall U-values by construction period and building typology

3.2.2.3 – Renovation assessment: energy saving

Following the determination of baseline roof and wall U-values, thermal transmittance (U, W/m²K) is used as the key parameter to represent the heat transfer performance of building envelope components, with lower values indicating improved insulation. Green roofs and green walls have the potential to enhance building energy performance by modifying envelope thermal properties through their constituent layers, including vegetation and growing media (Harbiankova & Manso, 2025).

In this study, the renovation assessment focuses on quantifying the energy savings resulting from changes in roof and wall U-values associated with the implementation of green roofs and green walls. The specific parameters modified between the baseline and renovation scenarios are summarized in Table 11.

Table 11: Parameters modified between baseline and renovation scenarios

Parameter	Baseline assessment	Renovation assessment
Roof U-value U_{roof}	TABULA-derived $U_{roof,base}$	$U_{roof,ren}$
Wall U-value U_{wall}	TABULA-derived $U_{wall,base}$	$U_{roof,ren}$
Geometry / HDD / CDD / solar radiation / efficiencies	Unchanged	Unchanged

(1) Heat losses

Heat losses for heating and cooling represent the thermal energy exchanged through the building envelope due to temperature differences between indoor and outdoor environments. In this study, heat losses were quantified as a function of the thermal transmittance of the envelope components, the surface area affected by the NbS, and the climatic demand of the heating and cooling seasons, as expressed by the following equations:

$$Q_{losses,heat} = \frac{\sum_i (U_i \cdot A_i) \cdot HDD \cdot 14}{1000} [kWh]$$

$$Q_{losses,cool} = \frac{\sum_i (U_{ex,i} \cdot A_i) \cdot CDD \cdot 14}{1000} [kWh]$$

where U_i and $U_{ex,i}$ denote the thermal transmittance of envelope component i (W/m²K), and A_i represents the area of intervention of the NbS applied to that component (m²). HDD and CDD are the Heating Degree Days and Cooling Degree Days (°C·days), respectively, and the factor 14 is an empirical coefficient used to convert degree-day values into seasonal energy losses. The division by 1000 converts the results from Wh to kWh.

HDD and CDD were obtained from the DegreeDays.net database using a base temperature of 20 °C for the heating season (15 October–15 April) and 24 °C for the cooling season (1 June–31 August), resulting in 2009.6 °C·days and 239.9 °C·days, respectively. For both the baseline and renovation scenarios, all parameters were kept identical except for the thermal transmittance values. For both the baseline and renovation scenarios, all parameters were kept identical except for the thermal transmittance values. In the baseline scenario, roof and wall U-values ($U_{roof,base}$ and $U_{wall,base}$) were assigned based on the combination of SVR-

based building typology and construction period, as described in Table 10. Following the implementation of NbS, U-values were reduced to $U_{roof,ren}$ = 0.22 W/m²K and $U_{wall,ren}$ = 0.26 W/m²K, in accordance with regulatory requirements (Decreto interministeriale 26 giugno 2015, 2015). This distinction enables the calculation of heat losses before and after intervention, which were computed for each selected building using the Field Calculator in QGIS.

(2) Solar gains

Solar gains represent the amount of heat energy transmitted to or absorbed by a building envelope as a result of incident solar radiation. In this study, they were calculated using:

$$Q_{sol} = F_{sh,ob} * \alpha_s * R_{se} * U * A * I_{sol}$$

where $F_{sh,ob}$ is the fixed shading factor, α_s is the solar absorptance of the external surface, R_{se} is the external surface thermal resistance, U is the thermal transmittance of the envelope component, A is the corresponding surface area, and I_{sol} represents the incident solar radiation over the heating or cooling season.

In this study, the fixed shading factor was set to $F_{sh,ob} = 1$, assuming no permanent shading elements. The solar absorption coefficient was taken as $\alpha_s = 0.3$ in the baseline condition and $\alpha_s = 0$ after implementing NbS. The external surface resistance was set to $R_{se} = 0.04$m²K/W. Seasonal solar radiation values I_{sol} were obtained from the PVGIS database using the 2005–2023 average, yielding 455.93 kWh/m² for the heating season and 585.88 kWh/m² for the cooling season. As shown in Figure 24.
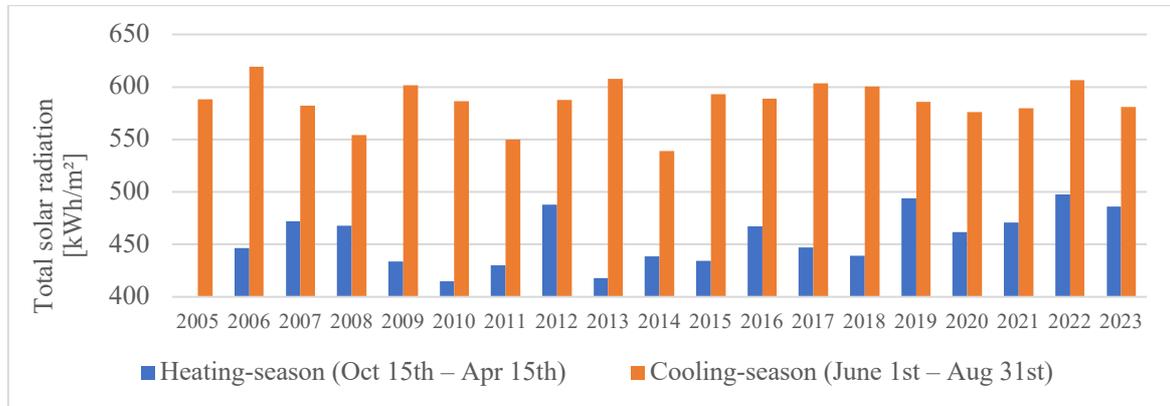
Figure 24: Seasonal incident solar radiation from PVGIS (2005–2023)

(3) Heating and cooling needs

The heating and cooling needs represent the net thermal energy required by the building to maintain indoor comfort conditions during the heating and cooling seasons. They are determined by balancing the transmission losses through the building envelope with the solar heat gains. For the heating season, the net demand $Q_{heating,need}$ is obtained by subtracting the solar gains from the heat losses, whereas during the cooling season the net demand $Q_{cooling,need}$ is obtained by summing the heat losses and the solar gains, as solar radiation acts as an additional heat load. This relationship is expressed in the following equations:

$$Q_{heating,need} = Q_{losses,heat} - Q_{sol}$$

$$Q_{cooling,need} = Q_{losses,cool} + Q_{sol}$$

where $Q_{losses,heat}$ and $Q_{losses,cool}$ represent the heat losses during the heating and cooling seasons, as calculated in the previous step, while Q_{sol} denotes the seasonal solar heat gains through the building envelope, as defined above.

(4) Operational energy demand

The operational energy demand represents the final energy required by the building systems to meet the heating and cooling needs. In this study, the heating and cooling operational energy demands (Q_H and Q_C) were obtained by converting the corresponding thermal energy needs into final energy use through the system efficiencies, as expressed by the following equations:

$$Q_H = \frac{Q_{heating,need}}{\eta_{heat}}$$

$$Q_C = \frac{Q_{cooling,need}}{\eta_{cool}}$$

where $Q_{heating,need}$ and $Q_{cooling,need}$ denote the heating and cooling energy needs previously calculated (kWh); and η_{heat} and η_{cool} represent the efficiencies of the heating and cooling systems. In this study, reference efficiencies were assigned according to the type of heating and cooling system and set to $\eta_{heat} = 0.9$ for natural gas boilers and $\eta_{cool} = 1.5$ for existing electric chillers.

(5) Energy savings

The energy savings associated with the implementation of NbS (green roofs and green walls) were evaluated for both heating and cooling by comparing the operational energy demand before and after intervention for each building. Specifically, heating and cooling energy savings were calculated as:

$$\Delta Q_H = Q_{H,base} - Q_{H,ren}$$

$$\Delta Q_C = Q_{C,base} - Q_{C,ren}$$

where $Q_{H,base}$ and $Q_{C,base}$ denote the heating and cooling operational energy demands in the baseline scenario, and $Q_{H,ren}$ and $Q_{C,ren}$ represent the corresponding values after renovation. This calculation was performed for each building affected by the intervention, yielding the absolute energy savings attributable to green roof and green walls at the building scale. Average heating and cooling energy savings were then obtained by averaging the results across all intervened buildings.

In addition to absolute values, relative energy savings were also evaluated to quantify the percentage reduction in operational energy demand. The percentage energy savings were calculated as:

$$\text{Energy saving (\%)} = \frac{Q_{ren} - Q_{base}}{Q_{base}} \times 100$$

To enable comparison across buildings of different sizes and with results reported in the

literature, energy savings were also normalized by area. Two normalization approaches were adopted. First, energy savings were expressed per unit of Gross Floor Area (GFA), defined as the product of the building footprint area and the number of floors. This indicator allows the assessment of energy savings relative to the total conditioned building area. Second, energy savings were normalized by the area of the implemented NbS, yielding energy savings per unit of intervention area. Both indicators were expressed in kWh/m² and were calculated for heating and cooling energy savings. The use of these two normalized metrics facilitates comparison with previous studies reported in the literature, which adopt either building-based or intervention-based performance indicators.

3.2.2.4 – Renovation assessment: CO₂ reduction

CO₂ reductions were assessed by distinguishing between indirect emission reductions due to operational energy savings (green roofs and green walls) and direct CO₂ removal through carbon sequestration (urban trees). This separation reflects the different mechanisms by which the selected NbS contribute to climate mitigation.

(1) Indirect CO₂ emission reductions

For green roofs and green walls, indirect CO₂ savings were calculated by multiplying the seasonal energy savings by the corresponding emission factors. This approach was applied to derive three CO₂ indicators: total CO₂ reduction, CO₂ reduction per unit of GFA, and CO₂ reduction per unit of NbS area.

$$\Delta CO_{2,heat} = \Delta Q_H \cdot EF_{gas}$$

$$\Delta CO_{2,cool} = \Delta Q_C \cdot EF_{el}$$

where ΔQ_H and ΔQ_C are the heating and cooling operational energy savings (kWh), and EF denotes the emission factor (kgCO₂eq/kWh). Since heating in the study area is predominantly supplied by natural gas, $EF_{gas} = 0.213 \text{ kgCO}_2/\text{kWh}$ was applied. Cooling relies on electricity; therefore, $EF_{el} = 0.235 \text{ kgCO}_2/\text{kWh}$ was used (Institute for Environmental Protection and Research, 2025). Results are expressed in kgCO₂eq.

(2) Direct CO₂ reduction

Urban trees were assessed through direct CO₂ reduction, quantified as net carbon sequestration. Annual CO₂ uptake was estimated by applying a net sequestration rate to the total tree-covered area:

$$CO_{2,direct} = SR_{net} \cdot A_{trees}$$

where $SR_{net} = 0.575 \text{ kg CO}_2/\text{m}^2/\text{yr}$ is the assumed net sequestration rate (Grossi et al., 2023) and A_{trees} is the area associated with urban trees (m²). This yields annual CO₂ removal in kgCO₂/year.

3.2 – Results

3.2.1 – Suitability analysis results

Based on the final thresholds defined in Section 3.2.1 and the corresponding GIS-based filtering process, the suitability analysis yields the following results for green roofs, green

walls, and urban trees in the Mirafiori district. Table 12 summarizes the number of suitable units and the corresponding suitable surface areas for each NbS.

Table 12: Summary of suitability analysis results for NbS in Mirafiori

NbS type	Total units assessed [n]	Suitable units [n]	Total available area before selection [m²]	Suitable area after selection [m²]	Suitable area share [%]
Green walls	9,343	7,898	4,177,188	1,019,232	24.40%
Green roofs	9,343	1,040	3,251,322	1,594,407	49.04%
Urban trees	–	54,193	15,278,677	2,567,416	16.80%

Note: "Units" refers to buildings for green roofs and green walls, and to individual planting spots for urban trees.

The green roof suitability analysis identified a total of 1,040 buildings as suitable for installation. Although this represents a relatively limited number of buildings, the potential is dominated by large industrial structures with extensive rooftop surfaces. As a result, the total suitable green roof area amounts to 1,594,407 m², corresponding to 49.04% of the total roof surface within the study area.

The spatial distribution of suitable and excluded buildings is shown in Figure 25, which combines an overview of the district with a detailed inset of a representative sub-area. In the inset, unsuitable buildings are colored according to their primary exclusion reason.

Figure 25: Buildings suitable for green roofs

In contrast, the green wall assessment resulted in a high number of eligible buildings but a more constrained exploitable surface due to the conservative façade coverage assumption. A total of 7,898 buildings were identified as suitable (Figure 26), corresponding to an estimated green wall area of 4,177,188 m², which represents 24.40% of the total potentially available façade area in the district. Buildings not selected were primarily excluded due to heritage protection constraints associated with historical buildings.
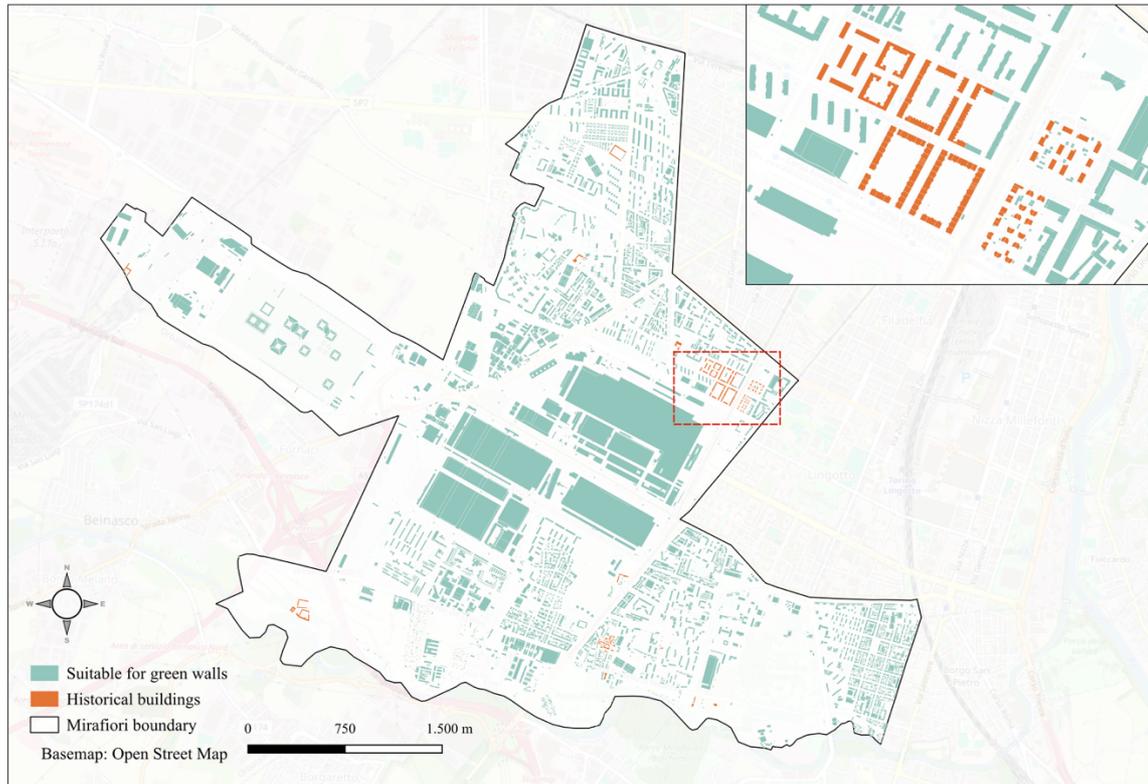
Figure 26: Buildings suitable for green walls

For urban trees, after applying all spatial criteria, a total area of 2,567,416 m² was deemed suitable for tree planting, corresponding to 16.80% of the Mirafiori district. Potential tree locations were generated using a point-in-polygon approach, and each tree was represented by a circular buffer with a radius of 3.44 m, corresponding to the assumed canopy size of newly planted trees. Based on these assumptions, the identified areas could accommodate approximately 54,193 trees. The resulting spatial distribution of suitable planting locations is illustrated in Figure 27.

Figure 27: Areas suitable for urban tree planting

3.2.2 – Retrofit analysis results

3.2.2.1 – Energy saving results

The implementation of green roofs and green walls leads to a substantial reduction in both heating and cooling operational energy demand across the selected buildings in Mirafiori. For both NbS solutions, energy demand after intervention is significantly lower than in the baseline scenario, with cooling demand showing the largest reduction. This suggests that NbS interventions are particularly effective in reducing cooling energy demand, while also providing notable benefits for heating. The detailed comparison of baseline and post-intervention energy demand is reported in Table 13.

Table 13: Area selected for assessment and average operational energy demand

NbS type	Area selected		Baseline scenario		Renovation scenario	
	Absolute [m²]	Share [%]	$Q_{H,base}$ [kWh]	$Q_{C,base}$ [kWh]	$Q_{H,ren}$ [kWh]	$Q_{C,ren}$ [kWh]
Green walls	773,238	18.51	5,717	1,573	1,730	124
Green roofs	260,934	8.03	13,531	3,722	3,099	222

From an energy-saving perspective, green roofs deliver higher absolute reductions in operational energy demand for both heating and cooling compared to green walls (Table 14). However, when savings are expressed in relative terms, both NbS strategies achieve comparable performance, with reductions of approximately 70% for heating and over 90% for cooling. This suggests that, despite differences in scale, green roofs and green walls are

similarly effective in proportionally reducing building energy demand, especially during the cooling season.

Table 14: Summary of energy savings for NbS in Mirafiori

NbS type	Heating energy saving ΔQ_H		Cooling energy saving ΔQ_C	
	Absolute [kWh]	Relative [%]	Absolute [kWh]	Relative [%]
Green walls	3987.09	71.22	1448.64	92.51
Green roofs	10432.02	71.46	3499.79	92.56

When energy savings are normalized by area, different performance patterns can be observed (Table 15). On a gross floor area basis, green roofs achieve higher energy savings, indicating a stronger effect at the building scale. In contrast, green walls show higher energy savings per unit of NbS area, suggesting greater efficiency per unit of installed surface. Overall, these results indicate that green roofs and green walls play complementary roles, with green roofs providing larger overall energy reductions and green walls offering higher efficiency per unit of intervention.

Table 15: Summary of area-normalized energy savings for NbS in Mirafiori

NbS type	Per GFA [kWh/m²]		Per NbS area [kWh/m²]	
	Heating saving	Cooling saving	Heating saving	Cooling saving
Green walls	5.71	1.96	14.21	5.16
Green roofs	7.79	2.60	3.79	1.27

3.2.2.2 – CO₂ reduction results

(1) Indirect CO_2 reduction

CO_2 emissions were first quantified for baseline and renovation scenarios to evaluate the impact of NbS implementation on operational emissions. At the district scale (Table 16 - 1), considering the selected buildings in the Mirafiori area, indirect CO_2 emissions associated with energy use decrease substantially following NbS implementation. In the case of green walls, total CO_2 emissions are reduced from 5,765 t/year in the baseline scenario to 1,444 t/year after intervention, while green roofs achieve a reduction from 2,175 t/year to 412 t/year.

At the building scale (Table 16 - 2), when CO_2 emissions are normalized by GFA, similar reductions are observed. For green walls, average CO_2 emissions decrease from 2.12 to 0.44 $kgCO_2/m²/year$, whereas for green roofs they are reduced from 2.78 to 0.51 $kgCO_2/m²/year$.

When normalized by NbS intervention area to assess mitigation efficiency (Table 16 - 3), green walls show a reduction in average CO_2 emissions from 8.87 to 1.87 $kgCO_2/m²/year$, while green roofs exhibit a decrease from 7.80 to 1.58 $kgCO_2/m²/year$.

Table 16: CO₂ Emissions under baseline and renovation scenarios

Table 16 - 1: Total CO₂ emissions [t/year]

NbS type	Baseline scenario		Renovation scenario	
	Heating	Cooling	Heating	Cooling
Green walls	4,423	1,342	1,339	106
Green roofs	1,669	506	382	30

Table 16 - 2: Average CO₂ emissions per GFA [kg/m²/year]

NbS type	Baseline scenario		Renovation scenario	
	Heating	Cooling	Heating	Cooling
Green walls	1.62	0.49	0.41	0.03
Green roofs	2.13	0.65	0.47	0.04

Table 16 - 3: Average CO₂ emissions per NbS area [kg/m²/year]

NbS type	Baseline scenario		Renovation scenario	
	Heating	Cooling	Heating	Cooling
Green walls	6.80	2.07	1.73	0.14
Green roofs	5.98	1.81	1.47	0.12

Based on these values, indirect CO_2 emission reductions were derived as the difference between baseline and renovation scenarios. At the total scale, green walls achieve an annual CO_2 reduction of 4,320 t CO_2/year, while green roofs result in a reduction of 1,763 t CO_2/year. In both cases, heating energy savings account for more than 70% of the total CO_2 reduction, indicating that reductions in heating demand are the dominant contributor to overall emission mitigation.

At the building scale, when CO_2 reductions are normalized by gross floor area, green walls achieve an average reduction of 1.68 kgCO_2/m²/year, whereas green roofs reach 2.27 kgCO_2/m²/year. This indicates that, although green walls provide larger total CO_2 reductions, green roofs are more effective in reducing emissions per unit of building area.

When normalized by NbS intervention area to assess mitigation efficiency, green walls achieve an average CO_2 reduction of approximately 7.0 kgCO_2/m²/year, while green roofs achieve 6.21 kgCO_2/m²/year. These values indicate comparable performance in terms of CO_2 reduction efficiency per unit of installed area. The corresponding results are summarized in Table 17.

Table 17: Summary of indirect CO₂ reduction for NbS in Mirafiori

NbS type	Total CO₂ reduction [t/year]		CO₂ reduction per GFA [kg/m²/year]		CO₂ reduction per NbS area [kg/m²/year]	
	Heating	Cooling	Heating	Cooling	Heating	Cooling
Green walls	3,084	1,236	1.22	0.46	5.07	1.93
Green roofs	1,287	476	1.66	0.61	4.52	1.70

(2) Direct CO₂ reduction

Direct CO_2 reductions associated with urban trees were quantified based on net annual

carbon sequestration. Across the selected areas in the Mirafiori district, urban trees contribute a total CO_2 reduction of 1,476 t CO_2/year. This reduction corresponds to a total suitable area of 2,567,416 m² and an estimated number of 54,193 trees (Table 18).

When expressed on an area-normalized basis, urban trees achieve an average CO_2 reduction of 0.575 kgCO_2/m²/year. These results indicate that, although the per-unit sequestration rate is relatively modest compared to building-related indirect reductions, urban trees provide a consistent and spatially extensive contribution to direct CO_2 mitigation at the district scale.

Table 18: Summary of direct CO_2 reduction for NbS in Mirafiori

NbS type	Total suitable area [m²]	Total number of trees [n]	Total CO_2 reduction [t/year]	Average CO_2 reduction [kg/m²/year]
Urban trees	2,567,416	54,193	1,476	0.575

Chapter 4 – Discussion and conclusion

4.1 – Discussion

4.1.1 – Energy performance comparison

To enable a meaningful comparison between the Mirafiori case study and the existing literature, energy performance is discussed using both relative (%) and absolute (kWh/m²) indicators. This distinction is essential, as relative values reflect the efficiency improvement compared to a baseline, while absolute values better capture the real magnitude of energy savings and their relevance at the district scale.

(1) Relative energy savings

The relative energy savings obtained in the Mirafiori case study are generally high when compared with the ranges reported in the literature. For both green roofs and green walls, the simulated retrofit scenarios achieve heating and cooling energy reductions exceeding 70% and, in several cases, approaching or surpassing 90%. These values are consistent with the upper-bound results reported in previous building-scale studies conducted in Mediterranean and humid subtropical climates, where envelope-integrated NbS demonstrate strong thermal regulation effects.

Several factors contribute to these comparatively high relative savings. The case study adopts optimized implementation scenarios, assuming full or near-full application of green walls and green roofs on suitable surfaces, which represents a favorable but plausible retrofit condition. In addition, the influence of building construction period plays a key role. As Figure 28 illustrated by the average green wall performance across construction periods, older buildings consistently exhibit higher relative heating and cooling energy savings, while more recent buildings show markedly lower percentage reductions. Since a substantial share of buildings with unknown construction years was assigned to the 1946–1960 category, this assumption contributes to elevating the aggregated relative energy savings at the district scale.

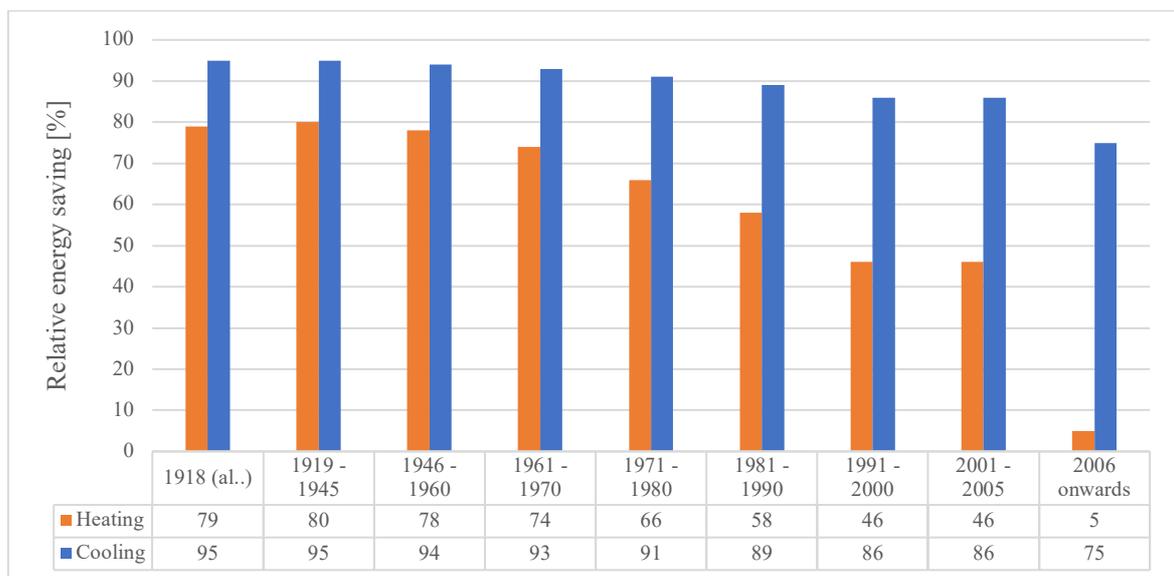|	1918 (al..)	1919 - 1945	1946 - 1960	1961 - 1970	1971 - 1980	1981 - 1990	1991 - 2000	2001 - 2005	2006 onwards
Heating	79	80	78	74	66	58	46	46	5
Cooling	95	95	94	93	91	89	86	86	75

Figure 28: Average relative energy savings of green walls by construction period

Overall, the results indicate that the relative energy savings derived from the Mirafiori case study reflect the upper range of NbS performance under favorable building-age distributions and implementation conditions, rather than representing typical average retrofit outcomes applicable across all urban contexts.

(2) Absolute energy savings

When shifting the comparison to absolute energy savings, clearer differences emerge between the case study and the literature. Table 15 summarizes the area-normalized energy savings for Mirafiori, expressed both per gross floor area (GFA) and per NbS area. For green roofs, the case study reports heating and cooling savings of approximately 7.79 and 2.60 kWh/m² GFA, respectively, while green walls achieve 5.71 and 1.96 kWh/m² GFA. When normalized by NbS area, green walls show higher values due to their smaller intervention area relative to the total building envelope.

These absolute values fall within the lower-to-middle range of those reported in the literature review. Previous studies indicate average absolute cooling savings of around 16–18 kWh/m²·y for both green roofs and green walls, with substantial variability driven by climate, baseline energy demand, and modeling assumptions. The comparatively lower absolute values observed in Mirafiori can be partly explained by the relatively efficient baseline building stock and the district-scale aggregation of results, which tends to smooth extreme values observed in single-building case studies.

This comparison highlights a key insight: very high relative energy reductions do not necessarily translate into equally high absolute energy savings. In Mirafiori, large percentage reductions are achieved on a moderate baseline demand, resulting in absolute savings that are realistic but less extreme than those reported in some literature cases with higher initial energy consumption.

4.1.2 – CO₂ reduction comparison

A similar pattern emerges when comparing CO_2 reduction results. In the literature, green roofs and green walls primarily contribute to CO_2 mitigation through indirect reductions, driven by decreased heating and cooling energy demand, while direct biological sequestration plays a secondary role at the building scale. Average indirect CO_2 reductions reported for green roofs (approximately 38 kg CO_2eq/yr) and green walls (around 19 kg CO_2eq/yr) are consistent with this mechanism.

The Mirafiori case study follows the same trend. CO_2 reductions associated with green roofs and green walls are dominated by avoided operational emissions rather than direct sequestration. The high relative energy savings observed in the case study translate into substantial indirect CO_2 mitigation, reinforcing the role of envelope-integrated NbS as effective strategies for reducing operational carbon emissions in dense urban districts.

For urban trees, the comparison again remains partial. While the case study includes estimates of direct CO_2 sequestration by trees, it does not quantify indirect energy-related CO_2 savings. This reflects a broader limitation identified in the literature, where urban trees are mainly evaluated for their carbon sink function rather than their contribution to building energy reduction. As a result, urban trees emerge as the most effective NbS in terms of direct

CO_2 sequestration, but their role in operational energy and emission reduction remains less clearly defined.

4.2 – Conclusion

This study synthesized quantitative evidence on the potential of NbS, including green roofs, green walls, and urban trees, to reduce building energy demand and CO_2 emissions in urban environments. Approximately 30 peer-reviewed studies reporting energy-saving and carbon reduction outcomes were systematically analyzed, with explicit consideration of their location, climate zone, and spatial scale. On this basis, average values of reported energy savings and CO_2 reductions were derived to support a comparative interpretation across heterogeneous studies.

The literature synthesis indicates that green roofs deliver substantial energy-saving benefits, with average relative reductions of approximately 45% for cooling and 60% for heating. Green walls and urban trees mainly contribute to cooling energy savings, with average reductions exceeding 25%. In terms of carbon mitigation, the reviewed studies show that CO_2 reductions are predominantly achieved through indirect pathways associated with reduced building energy consumption in the case of green roofs and green walls. By contrast, urban trees primarily contribute through direct CO_2 sequestration, which can become significant when implemented at sufficient spatial scale.

These patterns are further supported by the district-scale case study of Mirafiori in Turin. The results demonstrate that the large-scale deployment of green roofs and green walls could substantially reduce district-level building energy demand, with estimated reductions of up to 70% for heating and 90% for cooling, highlighting the strong potential of NbS to enhance urban energy efficiency. In parallel, urban tree implementation provides considerable direct carbon benefits, with approximately 16.8% of the suitable area estimated to deliver a total direct CO_2 reduction of about 1,476 t/yr.

Overall, these findings underline the relevance of NbS as effective strategies for urban climate mitigation, contributing to energy efficiency improvements and CO_2 emission reduction, and supporting broader sustainability objectives, including the SDGs. Future research should focus on addressing the remaining knowledge gaps identified in this study, particularly those related to: (1) improving the harmonization of energy and carbon assessment frameworks to enhance cross-study comparability; (2) investigating potential synergies and interactions among multiple NbS implemented simultaneously within urban systems; (3) extending district-scale analyses to diverse urban contexts to assess the transferability of observed patterns across different climatic and morphological settings; and (4) incorporating long-term and dynamic perspectives that account for vegetation growth, ageing, and evolving climate conditions.

4.3 – Implication

The findings of this study have relevant implications for both academic research and urban policymaking. From a research perspective, the results highlight the value of comparative synthesis based on relative energy savings, which allows heterogeneous studies to be

interpreted within a common analytical framework despite differences in scale, climate, and methodological assumptions. Moreover, the clear distinction identified between energy-driven and carbon-driven mitigation pathways suggests that future NbS research should move beyond isolated performance indicators and explicitly account for the underlying mechanisms through which different NbS contribute to climate mitigation.

From a practical and policy-oriented perspective, the results provide actionable insights for urban planning and retrofit strategies. The differentiated roles of green roofs, green walls, and urban trees imply that NbS selection should be aligned with specific policy objectives, such as reducing building energy demand or enhancing direct carbon sequestration. The district-scale case study further demonstrates that literature-based evidence can be translated into realistic urban contexts, supporting the use of NbS as scalable and complementary measures within urban decarbonization strategies. Overall, the findings can inform decision-makers in prioritizing NbS interventions based on local climatic conditions, urban morphology, and targeted mitigation goals, thereby enhancing the effectiveness of NbS implementation in support of broader sustainability and climate policy objectives.

4.4 – Limitations

The limitations of this study can be summarized into four main aspects along the analytical workflow.

First, the literature review is constrained by the limited availability and comparability of quantitative data, particularly for absolute energy savings. Differences in units, spatial scales, and reporting formats across studies reduce the number of samples that can be normalized and averaged, which affects the robustness of aggregated absolute indicators.

Second, uncertainties in the spatial input data influence the estimation of NbS suitability, especially for green roofs. In the industrial sub-area of Mirafiori, multiple factory buildings are represented as single aggregated footprints rather than as individual structures, which may lead to an overestimation of suitable roof area.

Third, several methodological assumptions in the energy assessment may affect the estimated performance of envelope-integrated NbS. These include the assignment of buildings with unknown construction years to the 1946–1960 period and the use of horizontal solar radiation data for green wall calculations, which does not fully capture façade-specific orientation and shading effects. Together, these assumptions may contribute to higher estimated relative energy savings.

Finally, the scope of the energy analysis does not include the impact of urban trees on building energy consumption. As a result, the contribution of urban trees is limited to direct CO_2 sequestration, while their potential indirect effects on heating and cooling demand are not quantified.

4.5 – Future improvements

Future research can address the limitations identified in this study through improvements in data availability, methodological refinement, and expanded analytical scope.

First, the robustness of literature-based benchmarks can be enhanced by expanding the dataset of comparable studies and adopting more standardized reporting frameworks. Greater consistency in units, temporal resolution, and spatial normalization would improve the reliability of aggregated absolute energy-saving indicators and support more robust cross-study comparisons.

Second, the accuracy of spatial suitability assessments can be improved through the use of higher-resolution and more detailed urban datasets. In particular, disaggregated building footprint data for industrial areas would allow a more precise estimation of available roof surfaces and reduce uncertainty in the evaluation of green roof potential.

Third, future energy modeling efforts could reduce uncertainty by refining key input assumptions. Improved building attribute datasets would allow unknown construction periods to be explicitly identified or probabilistically assigned rather than grouped into a single age category. In addition, façade-specific solar radiation models that account for orientation, vertical inclination, and shading effects could be integrated to better represent the thermal behavior of green walls.

Finally, the analytical scope could be extended to explicitly quantify the impact of urban trees on building energy consumption. Coupling microclimate or urban canopy models with building energy simulations would enable the indirect cooling and heating effects of trees to be assessed alongside their direct CO_2 sequestration benefits, providing a more comprehensive evaluation of Nature-based Solutions.

References

[1] Alexandri, E., & Jones, P. (2008). Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. *Building and Environment*, *43*(4), 480–493. https://doi.org/10.1016/j.buildenv.2006.10.055

[2] Anselmo, S., Boccardo, P., Corgnati, S. P., & Ferrara, M. (2025). Integration of aerial thermography and energy performance certificates for the estimation of energy consumption in cities. *Energy and Buildings*, *336*, 115644. https://doi.org/10.1016/j.enbuild.2025.115644

[3] Ávila-Hernández, A., Simá, E., Xamán, J., Hernández-Pérez, I., Téllez-Velázquez, E., & Chagolla-Aranda, M. A. (2020). Test box experiment and simulations of a green-roof: Thermal and energy performance of a residential building standard for Mexico. *Energy and Buildings*, *209*, 109709. https://doi.org/10.1016/j.enbuild.2019.109709

[4] Azkorra-Larrinaga, Z., Romero-Antón, N., Martin-Escudero, K., & Lopez-Ruiz, G. (2023). Environmentally Sustainable Green Roof Design for Energy Demand Reduction. *Buildings*, *13*(7). Scopus. https://doi.org/10.3390/buildings13071846

[5] Bartesaghi Koc, C., Osmond, P., & Peters, A. (2018). Evaluating the cooling effects of green infrastructure: A systematic review of methods, indicators and data sources. *Solar Energy*, *166*, 486–508. https://doi.org/10.1016/j.solener.2018.03.008

[6] Besir, A. B., & Cuce, E. (2018). Green roofs and facades: A comprehensive review. *Renewable and Sustainable Energy Reviews*, *82*, 915–939. https://doi.org/10.1016/j.rser.2017.09.106

[7] Bettina Wilk, Andreas Vetter, & Inke Schauser. (2021). *Tackling the climate and biodiversity crises in Europe through Urban Greening Plans*. German Environment Agency (Umweltbundesamt).

[8] Bevilacqua, P. (2021). The effectiveness of green roofs in reducing building energy consumptions across different climates. A summary of literature results. *Renewable and Sustainable Energy Reviews*, *151*, 111523. https://doi.org/10.1016/j.rser.2021.111523

[9] Bevilacqua, P., Mazzeo, D., Bruno, R., & Arcuri, N. (2016). Experimental investigation of the thermal performances of an extensive green roof in the Mediterranean area. *Energy and Buildings*, *122*, 63–79. https://doi.org/10.1016/j.enbuild.2016.03.062

[10] Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P. W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W. W. L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., … Péan, C. (2023). *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 [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.* (First). Intergovernmental Panel on Climate Change (IPCC). https://doi.org/10.59327/IPCC/AR6-9789291691647

[11] Campiotti, A., Ricciardi, E., Spano, G., Dominici, L., Comino, E., Riggio, R., Pitasi, F., Ribotta, L., Barbero, S., Sanesi, G., Catalano, C., Calfapietra, C., & Baldacchini, C. (2025). Indoor green walls for improving air quality and human well-being: A case study from a primary school in Turin (Italy). *Nature-Based Solutions*, *8*, 100280. https://doi.org/10.1016/j.nbsj.2025.100280

[12] Cao, S.-J., Zhang, C., Wang, J., Feng, Z., Chen, G., & Haghighat, F. (2024). Low-carbon design towards sustainable city development: Integrating glass space with natural greenery. *Science China Technological Sciences*, *67*(9), 2659–2674. Scopus. https://doi.org/10.1007/s11431-023-2570-x

[13] Cohen-Shacham, E., Cabecinha, E., & Andrade, A. (Eds.). (2025). *Applying the IUCN Global Standard for Nature-based SolutionsTM. 21 case studies from around the globe*. IUCN, International Union for Conservation of Nature. https://doi.org/10.2305/RFTD6180

[14] De Filippi, F., & Vassallo, I. (2016). Mirafiori sud: La città fordista oltre la Fabbrica. Scenari e progetti per (la costruzione di) una nuova identità. *Ri-Vista*, 88-99 Pages. https://doi.org/10.13128/RV-19373

[15] Decreto interministeriale 26 giugno 2015 (2015).

[16] Dong, F., & Asawa, T. (2025). A simulation study on building-scale strategies for urban heat island mitigation and building energy consumption: Case study in Japan. *Building and Environment*, *268*, 112311. https://doi.org/10.1016/j.buildenv.2024.112311

[17] Douglas, A. N. J., Morgan, A. L., Rogers, E. I. E., Irga, P. J., & Torpy, F. R. (2021). Evaluating and comparing the green wall retrofit suitability across major Australian cities. *Journal of Environmental Management*, *298*, 113417. https://doi.org/10.1016/j.jenvman.2021.113417

[18] Ellena, M., Melis, G., Zengarini, N., Di Gangi, E., Ricciardi, G., Mercogliano, P., & Costa, G. (2023).

Micro-scale UHI risk assessment on the heat-health nexus within cities by looking at socio-economic factors and built environment characteristics: The Turin case study (Italy). *Urban Climate*, *49*, 101514. https://doi.org/10.1016/j.uclim.2023.101514

[19] Engström, R., Howells, M., Mörtberg, U., & Destouni, G. (2018). Multi-functionality of nature-based and other urban sustainability solutions: New York City study. *Land Degradation and Development*, *29*(10), 3653–3662. Scopus. https://doi.org/10.1002/ldr.3113

[20] European Commission. (2019). *The European Green Deal*. European Commission.

[21] European Commission. (2021). Forging a climate-resilient Europe—The new EU strategy on adaptation to climate change.

[22] European Environment Agency (Ed.). (2021). Nature-based solutions in Europe: Policy, knowledge and practice for climate change adaptation and disaster risk reduction. Publications Office of the European Union. https://doi.org/10.2800/919315

[23] Gómez, G., Frutos, B., Alonso, C., Martín-Consuegra, F., Oteiza, I., De Frutos, F., Castellote, M. M., Muñoz, J., Torre, S., Fermoso, J., Torres, T., Antón, M. A., Batista, T., & Morais, N. (2021). Selection of nature-based solutions to improve comfort in schools during heat waves. *International Journal of Energy Production and Management*, *6*(2), 157–169. Scopus. https://doi.org/10.2495/EQ-V6-N2-157-169

[24] Grossi, F., Ge, H., Zmeureanu, R., & Baba, F. (2023). Feasibility of Planting Trees around Buildings as a Nature-Based Solution of Carbon Sequestration—An LCA Approach Using Two Case Studies. *Buildings*, *13*(1). Scopus. https://doi.org/10.3390/buildings13010041

[25] Harbiankova, A., & Manso, M. (2025). Integrating green roofs and green walls to enhance buildings thermal performance: A literature review. *Building and Environment*, *270*. Scopus. https://doi.org/10.1016/j.buildenv.2025.112524

[26] Hayes, M., Steurs, W., Cossu, S., & Iglesias, H. M. (2022). *European Green Deal policy guide*.

[27] IEA. (2024). *Empowering Urban Energy Transitions – Analysis*. https://www.iea.org/reports/empowering-urban-energy-transitions

[28] Im, J., & Gil, K. (2024). Research on effects of reducing temperature and CO2 emissions by green wall: Case study of G city. *Ecological Engineering*, *208*, 107382. https://doi.org/10.1016/j.ecoleng.2024.107382

[29] Institute for Environmental Protection and Research. (2025). *Italian Greenhouse Gas Inventory 1990-2023. National Inventory Document 2025* (No. 411/25). Institute for Environmental Protection and Research. https://www.isprambiente.gov.it/en/publications/reports/italian-greenhouse-gas-inventory-1990-2023-national-inventory-document-2025

[30] Jia, S., Weng, Q., & Wang, Y. (2024). The Potential of Nature-Based Solutions in Urban Heat Mitigation and Building Energy Savings. In *Handbook of Geospatial Approaches to Sustainable Cities* (pp. 109–136). CRC Press; Scopus. https://doi.org/10.1201/9781003244561-9

[31] Karteris, M., Theodoridou, I., Mallinis, G., Tsiros, E., & Karteris, A. (2016). Towards a green sustainable strategy for Mediterranean cities: Assessing the benefits of large-scale green roofs implementation in Thessaloniki, Northern Greece, using environmental modelling, GIS and very high spatial resolution remote sensing data. *Renewable and Sustainable Energy Reviews*, *58*, 510–525. https://doi.org/10.1016/j.rser.2015.11.098

[32] Kim, H., Oh, K., & Lee, D. (2021). Establishment of a Geographic Information System-Based Algorithm to Analyze Suitable Locations for Green Roofs and Roadside Trees. *Applied Sciences*, *11*(16), 7368. https://doi.org/10.3390/app11167368

[33] Ko, Y. (2018). Trees and vegetation for residential energy conservation: A critical review for evidence-based urban greening in North America. *Urban Forestry & Urban Greening*, *34*, 318–335. https://doi.org/10.1016/j.ufug.2018.07.021

[34] Komninos, N. (2022). Net Zero Energy Districts: Connected Intelligence for Carbon-Neutral Cities. *Land*, *11*(2). Scopus. https://doi.org/10.3390/land11020210

[35] Konopka, J., Heusinger, J., & Weber, S. (2021). Extensive Urban Green Roof Shows Consistent Annual Net Uptake of Carbon as Documented by 5 Years of Eddy-Covariance Flux Measurements. *Journal of Geophysical Research: Biogeosciences*, *126*(2), e2020JG005879. https://doi.org/10.1029/2020JG005879

[36] Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World Map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift*, *15*(3), 259–263. https://doi.org/10.1127/0941-2948/2006/0130

[37] Li, M., Remme, R. P., Van Bodegom, P. M., & Van Oudenhoven, A. P. E. (2023). *Solution to what? Global assessment of nature-based solutions, urban challenges, and outcomes*. Ecology. https://doi.org/10.1101/2023.12.07.570577

[38] Ling, T.-Y. (2022). Rethinking greening the building façade under extreme climate: Attributes consideration for typo-morphological green envelope retrofit. *Cleaner and Circular Bioeconomy*, *3*, 100024. https://doi.org/10.1016/j.clcb.2022.100024

[39] Liu, H., Kong, F., Yin, H., Middel, A., Zheng, X., Huang, J., Xu, H., Wang, D., & Wen, Z. (2021). Impacts of green roofs on water, temperature, and air quality: A bibliometric review. *Building and Environment*, *196*. Scopus. https://doi.org/10.1016/j.buildenv.2021.107794

[40] Loga, T., Stein, B., & Diefenbach, N. (2016). TABULA building typologies in 20 European countries—Making energy-related features of residential building stocks comparable. *Energy and Buildings*, *132*, 4–12. https://doi.org/10.1016/j.enbuild.2016.06.094

[41] Mancini, S. (2014). Time Dependent Travel Speed Vehicle Routing and Scheduling on a Real Road Network: The Case of Torino. *Transportation Research Procedia*, *3*, 433–441. https://doi.org/10.1016/j.trpro.2014.10.024

[42] Mangano, G., & Laganà, D. (2024). A New Workflow for Achieving Climate Neutrality in Circular Energy Clusters. Simulations of Regenerative Design Combining Nature Based Solutions and Solar Energy Technologies in Urban Environment. 1189 LNNS, 49–63. Scopus. https://doi.org/10.1007/978-3-031-74723-6_5

[43] Manso, M., & Castro-Gomes, J. (2015). Green wall systems: A review of their characteristics. *Renewable and Sustainable Energy Reviews*, *41*, 863–871. https://doi.org/10.1016/j.rser.2014.07.203

[44] Mastouri, H., Bahi, H., Radoine, H., & Benhamou, B. (2020). Improving energy efficiency in buildings: Review and compiling. *Materials Today: Proceedings*, *27*, 2999–3003. https://doi.org/10.1016/j.matpr.2020.03.270

[45] Méndez Echenagucia, T., Capozzoli, A., Cascone, Y., & Sassone, M. (2015). The early design stage of a building envelope: Multi-objective search through heating, cooling and lighting energy performance analysis. *Applied Energy*, *154*, 577–591. https://doi.org/10.1016/j.apenergy.2015.04.090

[46] Nejat, P., Jomehzadeh, F., Taheri, M. M., Gohari, M., & Abd. Majid, M. Z. (2015). A global review of energy consumption, CO_2 emissions and policy in the residential sector (with an overview of the top ten CO_2 emitting countries). *Renewable and Sustainable Energy Reviews*, *43*, 843–862. https://doi.org/10.1016/j.rser.2014.11.066

[47] Pérez, G., Rincón, L., Vila, A., González, J. M., & Cabeza, L. F. (2011). Green vertical systems for buildings as passive systems for energy savings. *Applied Energy*, *88*(12), 4854–4859. https://doi.org/10.1016/j.apenergy.2011.06.032

[48] Prades-Gil, C., Viana-Fons, J. D., Masip, X., Cazorla-Marín, A., & Gómez-Navarro, T. (2024). Methodology to assess the impact of urban vegetation on the energy consumption of residential buildings. Case study in a Mediterranean city. *Energy Conversion and Management: X*, *24*. Scopus. https://doi.org/10.1016/j.ecmx.2024.100706

[49] Reddy, T. A., Kreider, J. F., Curtiss, P. S., & Rabl, A. (2016). *Heating and Cooling of Buildings: Principles and Practice of Energy Efficient Design* (3rd ed.). CRC Press. https://doi.org/10.1201/9781315374567

[50] Reitberger, R., Pattnaik, N., & Lu, Y. (2024). Urban tree placement analysis: A GIS-based approach for identifying suitable planting locations in Munich. https://doi.org/10.15480/882.13517

[51] S. Cascone. (2022). The energy-efficient design of sustainable green roofs in Mediterranean climate: An experimental study. *Energy and Buildings*, *273*. Scopus. https://doi.org/10.1016/j.enbuild.2022.112427

[52] Sailor, D. J. (2008). A green roof model for building energy simulation programs. *Energy and Buildings*, *40*(8), 1466–1478. https://doi.org/10.1016/j.enbuild.2008.02.001

[53] Santamouris, M. (2014). On the energy impact of urban heat island and global warming on buildings. *Energy and Buildings*, *82*, 100–113. https://doi.org/10.1016/j.enbuild.2014.07.022

[54] Savić, S., Krstić, H., Šećerov, I., & Dunjić, J. (2024). Decreasing the energy demand in public buildings using nature-based solutions: Case studies from Novi Sad (Republic of Serbia) and Osijek (Republic of Croatia). *Energy, Sustainability and Society*, *14*(1). Scopus. https://doi.org/10.1186/s13705-024-00455-2

[55] Taha, H., Akbari, H., & Rosenfeld, A. (1991). Heat island and oasis effects of vegetative canopies: Micro-meteorological field-measurements. *Theoretical and Applied Climatology*, *44*(2), 123–138.

https://doi.org/10.1007/BF00867999

[56] Torabi, S., Mutani, G., & Lombardi, P. L. (2016). GIS-Based Energy Consumption Model at the Urban Scale for the Building Stock. *ResearchGate*. 9th international conference on energy efficiency in commercial buildings and smart communities. https://www.researchgate.net/publication/301566375_GIS-Based_Energy_Consumption_Model_at_the_Urban_Scale_for_the_Building_Stock

[57] Turhan, C., Atalay, A. S., & Gokcen Akkurt, G. (2023). An Integrated Decision-Making Framework for Mitigating the Impact of Urban Heat Islands on Energy Consumption and Thermal Comfort of Residential Buildings. *Sustainability (Switzerland)*, *15*(12). Scopus. https://doi.org/10.3390/su15129674

[58] UNFCCC. (2015). *Paris Agreement*. United Nations Framework Convention on Climate Change.

[59] United Nations. (2015). Transforming our world: The 2030 Agenda for Sustainable Development (p. 41). United Nations.

[60] Varol, T., Gormus, S., Cengiz, S., Ozel, H. B., & Cetin, M. (2019). Determining potential planting areas in urban regions. *Environmental Monitoring and Assessment*, *191*(3), 157. https://doi.org/10.1007/s10661-019-7299-1

[61] Velázquez, J., Anza, P., Gutiérrez, J., Sánchez, B., Hernando, A., & García-Abril, A. (2019). Planning and selection of green roofs in large urban areas. Application to Madrid metropolitan area. *Urban Forestry & Urban Greening*, *40*, 323–334. https://doi.org/10.1016/j.ufug.2018.06.020

[62] Vranayova, Z., Tkachenko, T., Lis, A., Savchenko, O., & Vranay, F. (2023). *GREEN BUILDINGS IN PURSUIT OF HEALTHY AND SAFE HUMAN LIVING ENVIRONMENT*. *5*(1), 204–211. Scopus. https://doi.org/10.2478/czoto-2023-0022

[63] Wang, Y., Kong, F., Yin, H., Su, J., & Sun, H. (2023). Identifying the right building roofs for greening from the perspective of socio-ecological demands in a 3D urban landscape. *Landscape and Ecological Engineering*, *19*(3), 351–362. https://doi.org/10.1007/s11355-023-00559-5

[64] Wang, Y., Le, H., Gotmare, A. D., Bui, N. D. Q., Li, J., & Hoi, S. C. H. (2023). *CodeT5+: Open Code Large Language Models for Code Understanding and Generation*. 1069–1088. https://doi.org/10.48550/arXiv.2305.07922

[65] Wu, C., Xiao, Q., & McPherson, E. G. (2008). A method for locating potential tree-planting sites in urban areas: A case study of Los Angeles, USA. *Urban Forestry & Urban Greening*, *7*(2), 65–76. https://doi.org/10.1016/j.ufug.2008.01.002

[66] Xi, C., Ding, J., Wang, J., Feng, Z., & Cao, S.-J. (2022). Nature-based solution of greenery configuration design by comprehensive benefit evaluation of microclimate environment and carbon sequestration. *Energy and Buildings*, *270*, 112264. https://doi.org/10.1016/j.enbuild.2022.112264

[67] Xi, C., Han, L., Wang, J., Feng, Z., Kumar, P., & Cao, S.-J. (2023). How can greenery space mitigate urban heat island? An analysis of cooling effect, carbon sequestration, and nurturing cost at the street scale. *Journal of Cleaner Production*, *419*. Scopus. https://doi.org/10.1016/j.jclepro.2023.138230

[68] Xiao, Z., Ge, H., Lacasse, M. A., Wang, L., & Zmeureanu, R. (2023). Nature-Based Solutions for Carbon Neutral Climate Resilient Buildings and Communities: A Review of Technical Evidence, Design Guidelines, and Policies. *Buildings*, *13*(6). Scopus. https://doi.org/10.3390/buildings13061389

[69] Xin, G., Feng, Z., Zhang, X., Wang, J., & Cao, S.-J. (2024). Low-carbon environmental control system for storage of earthen relics in exhibition hall: From the perspectives of nature based solution. *Indoor and Built Environment*, *33*(6), 1100–1117. Scopus. https://doi.org/10.1177/1420326X241234490

[70] Yang, S., Kong, F., Yin, H., Zhang, N., Tan, T., Middel, A., & Liu, H. (2023). Carbon dioxide reduction from an intensive green roof through carbon flux observations and energy consumption simulations. *Sustainable Cities and Society*, *99*. Scopus. https://doi.org/10.1016/j.scs.2023.104913

[71] Yungstein, Y., & Helman, D. (2023). Cooling, CO2 reduction, and energy-saving benefits of a green-living wall in an actual workplace. *Building and Environment*, *236*. Scopus. https://doi.org/10.1016/j.buildenv.2023.110220

[72] Zayas-Orihuela, M., Bastida-Molina, P., Gómez-Navarro, T., & Montagud-Montalvá, C. (2024). How green can it be? A methodology for calculating green roof retrofit potential in Valencia. *Energy and Buildings*, *324*. Scopus. https://doi.org/10.1016/j.enbuild.2024.114893

[73] Zhang, B., Xie, G., Gao, J., & Yang, Y. (2014). The cooling effect of urban green spaces as a contribution to energy-saving and emission-reduction: A case study in Beijing, China. *Building and Environment*, *76*, 37–43. https://doi.org/10.1016/j.buildenv.2014.03.003

[74] Zhao, Z., Ye, H., Wang, K., Lin, T., Zhang, G., & Lin, M. (2024). Building energy consumption

reduction driven by the accessibility to greenspace ecological effect. *Ecological Indicators*, *160*. Scopus. https://doi.org/10.1016/j.ecolind.2024.111750

[75] Zuckerman, N., & Lensky, I. M. (2023). Thermal performance of vertical greenery systems (VGS) in a street canyon: A real-scale long-term experiment. *Building and Environment*, *244*. Scopus. https://doi.org/10.1016/j.buildenv.2023.110750